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Investigation on a smart textile heating concept for energy consumption-optimised heat transfer

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ABSTRACT

Conventional non-stationary artificial heating methods, such as infrared radiators, have various deficits: The heat fields are small, their range is short, and the installation options are limited. In addition, they are environmentally harmful due to high emissions. To make in- and outdoor areas usable at lower temperatures, an energy consumption-optimized heat transfer is required. In this work we are investigating on an innovative, intelligent, modular textile for indoor and outdoor use. The use of conductive wires, sensors and a data-driven control circuit in the textile enables targeted heat radiation, which can be expanded as required thanks to its modular design. This reduces emissions and precisely controls energy consumption. By developing a demonstrator, the concept of the layered structure of the textile module, including unidirectional radiation and sensor technology, is being investigated. The conductive wires are incorporated into a flexible carrier material using a modified embroidery machine. In the process, the carrier material must meet the previously defined design requirements that are based on the material investigation and preliminary tests on embroidery feasibility. The structure of the intelligent textile is constructed, realized as a prototype, and validated. Through the combination of a heat source and flexible support material, it is possible to bring a competitive product to the market.

Keywords
e-textiles,
smart textiles,
heating,
energy efficiency,
integration technique

1 Introduction

The European electric heating radiator market recorded an estimated value of more than € 700 million in 2021. According to a Skyquest report, the market value is expected to reach € 1,5 billion by 2030, representing an annual growth rate of over 8% [1]. The most frequently used products are infrared radiant heaters and patio heaters.

Infrared heaters, predominantly utilized in the catering industry, are typically either portable or attached under awnings and operate using electricity. Conventional heat sources for outdoor catering suffer from several drawbacks, including limited heat coverage and range and complex handling. Moreover, for the use of wall-mounted emitters (IR emitters), connection options to energy sources are limited. The presence of connection cables lying on the floor poses a tripping hazard and they can be damaged by the movement of chairs and tables. Patio heaters, when operating at maximum power, can emit up to 3.5 kg of CO_2 per hour. Considering an average weekly usage of 40 hours over approximately 25 weeks per year, a single patio heater can produce up to 4 tons of CO_2 [2,3. In summary, traditional heating solutions are environmentally unfriendly due to higher emissions and necessitate additional mounting options and space [4].

Considering these environmental issues and the limitations of conventional heat sources, there is a need to develop an environmentally friendly solution that ensures effective heat transfer. In this context, a novel smart textile technology that reduces the negative impact of conventional heat sources and optimizes energy consumption is investigated on.

2 Technology overview and embroidery process

2.1 Advantages of thermal radiation over convection

Thermal radiation is a method of heat transfer in which heat is transferred through electromagnetic waves. Unlike heat conduction and convection, heat radiation or infrared can propagate even in a vacuum. Infrared is non-ionizing electromagnetic radiation within in the wavelengths of 780 nm to 1 mm. Within this wide waveband, it is often subdivided further into three regions, with IR-A from 700 nm-1400 nm, IR-B in the range of 1400 nm-3000 nm and IR-C covering the widest area of 3000 nm-1 mm [5]. Thermal energy transport through radiation differs from convection in that it is not reliant on any carrier medium [6]. Convection involves heating the surrounding air, as seen with traditional radiators. The heated air rises due to its lower density and displaces colder air towards the ground, creating an air circulation that stirs up dust and distributes it in the surrounding environment. In the case of heaters that emit heat through electromagnetic waves (infrared heaters), the convection effect is minimal, resulting in a more even distribution of heat [6]. Infrared radiation directly heats surfaces instead of heating the surrounding air or medium.

2.2 Challenges in embroidery of conductive fibers

Achieving precise fiber placement is crucial for optimizing the material properties of conductive composites, as accurate orientation enhances strength, stiffness, and other desired characteristics. However, the fragility of carbon fibers for instance limits their design possibilities with traditional textile manufacturing techniques like knitting, weaving, or braiding, complicating the control of electro-thermal behavior and heat distribution, thereby restricting applications like Joule heating [7-9]. Embroidery, in contrast, allows for the control of processing parameters, resulting in fabrics with carbon fibers embedded that exhibit excellent electro-thermal performance and uniform heat distribution, making them suitable for applications such as indoor climate control [7,10-13].

Despite these advantages, automating the embroidery process presents significant challenges. Developing reliable robotic systems capable of handling delicate fibers and following intricate paths is highly challenging. These systems must ensure the precise and consistent placement of fibers without causing damage. Additionally, modifications to the feed units of embroidery machines are often necessary to facilitate the introduction of electrically conductive fibers, further complicating the process [14]. Maintaining consistent stitching patterns across the entire surface is also demanding, complicating the fabrication of uniformly conductive textiles. Addressing these challenges is essential for the successful automation of conductive fiber embroidery.

3 Intended technological development of the process

The smart textile-based heating system aims to incorporate an intelligent control circuit that utilizes data processing to optimize energy consumption. The layered structure of the heated textile is designed to ensure that heat is radiated only outwards. Motion sensors integrated into the system determine the positions where people are present, enabling localized heating. Leveraging the sensor data, the data evaluation system determines the number and locations of individuals to maximize the energy efficiency of the system through targeted use.

3.1 Innovative textile-based heating system with directional heating

For the development of the carrier medium, the identification of suitable materials and their evaluation for compliance with safety requirements such as fire protection is crucial. For this, substrates such as glass, ceramic and aramid fabric are taken into consideration [15]. An additional aluminum coating to enhance thermal radiation reflection in the target area can be considered. The key challenge lies in developing a flexible radiation medium that allows for the generation of the required infrared radiation. Typically, materials like metal and ceramics are used in panel heaters but adapting them to a flexible state is necessary. The identified solution involves utilizing the large-format feed units of the embroidery machine to deposit a combination of wires and metallic fibers onto a special carrier material enabling the desired radiation.

3.2 Optimized control system for directional heat and localized heating

The system under development is multifaceted. It initially utilizes motion sensors to identify areas requiring heat, such as zones with customer presence. The system then employs advanced algorithms to calculate the necessary local heating output. A crucial function is to determine the optimal heating behavior, factoring in heating cycles and local conditions to prevent overheating by dynamically adjusting heating parameters accordingly.

For the smart sensing and control Passive InfraRed (PIR) sensors are utilized, commonly used in motion detection. To complement this, sensors for human presence detection, capable of sensing stationary heat signatures, are integrated. These sensors provide more comprehensive data, allowing for precise control over heating areas. Temperature sensors near heating zones act as a safety measure, ensuring operation within safe temperature ranges. All sensor data is fed into single-board computers (SBCs), where algorithms optimize heating performance or efficiency. This necessitates advanced integration of electronic components into the textile, involving new storage modules and software extensions in the existing EPCwin/CAD system. The integration of human presence detection sensors improves the system’s robustness in heating activation. A feedback loop with multiple sensors enables precise temperature control in specific zones.

4 Evaluation methodology and framework

The aim creating an intelligent textile designed for energy-optimized heat transfer is to overcome several challenges: ensuring targeted heat radiation in specific areas through sensor integration, the conception of the modular structure of the textile, eliminating the need for time-consuming assembly and disassembly of heat sources in daily operations, and avoiding on-site emissions by using infrared radiation as the heat carrier. Additionally, the incorporation of a control circuit combined with sensor integration allows for precise control over energy consumption, significantly boosting the efficiency of the heat source.

To meet this goal, a flexible medium for radiating infrared heat is integrated into a pliable carrier material through a specially adapted embroidery machine and technique. This carrier material not only retains traditional textile characteristics like lightness and protection from the elements but also includes a reflector layer for directing thermal radiation to specific areas unidirectionally. Additionally, it securely holds the heating wires necessary for generating heat. Initial experiments with state-of-the-art infrared heating technologies have been carried out. Careful selection and rigorous testing of materials, using tests tailored to specific applications, ensure that stringent safety standards are met for the materials in use. Following the material research and initial trials with embroidery, the structure of the smart textile is conceptualized and implemented as a modular textile prototype, which is then put through validation processes. To assess the different concepts, a test bench and an evaluation framework have been developed.

4.1 Realization of the test bench

The evaluation of the smart textile-based heating concept necessitates the development of a robust test bench designed to simulate real-world conditions and provide accurate measurements. The test bench was constructed with dimensions of 600 mm in width, 1200 mm in length, and 800 mm in height (Fig. 1).

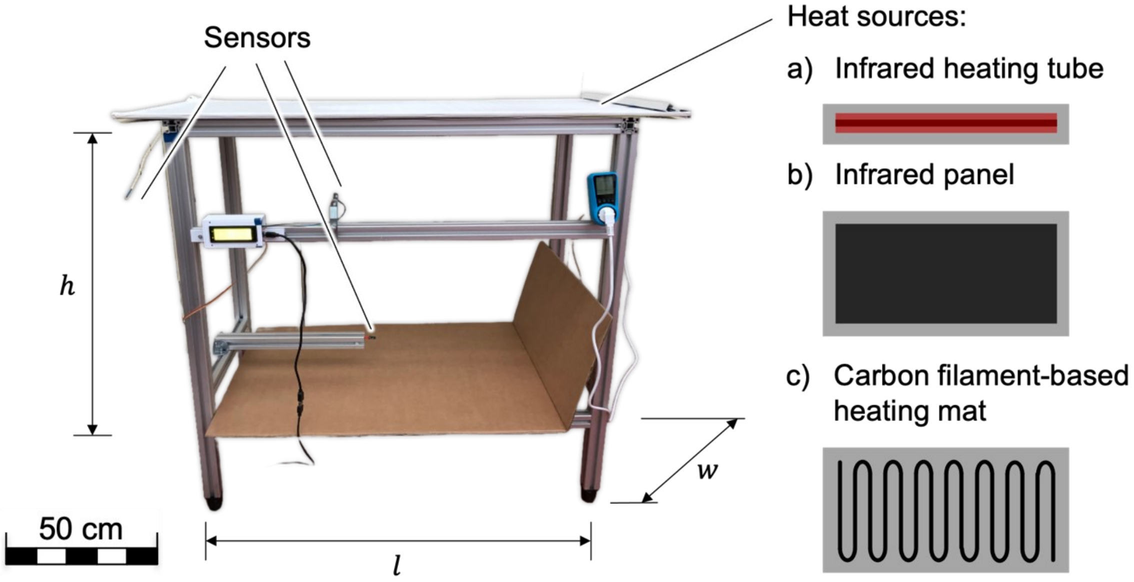

Fig. 1 Test bench and heat sources.

The bench is equipped with three precise temperature sensors: two MLX90614 infrared sensors for capturing the surface temperatures of both the heat source and the heated object, and one MAX6675 thermocouple for recording ambient air temperature. The specifications are listed in Table 1.

Table 1. Test bench parameters.

Specifications	**Values**
Mechanical	Dimensions (l x w x h) – 1200 mm x 600 mm x 800 mm
	Material – aluminum profile
Electrical	Supply voltage – 230 VAC, 50 Hz
	Rated power (for all sources) – 1000 W
Sensors	2 x MLX90614 sensors
	MAX6675 + K type thermocouple
	Arduino ATMega328p
	TCA9548A I2C expander
	LCD – 20x4 HD44780 IC

4.2 Design of experiment

The design of the experiment was structured to evaluate the heating performance of three state-of-the-art technologies: an infrared heating tube, an infrared panel, and a carbon filament-based heating mat. The evaluation focused on key performance metrics, including heating efficiency, temperature distribution, and the impact of environmental factors. Each heating technology was tested three times, under multiple conditions to determine its effectiveness (Table 2). The conditions included the use of heat source reflectors to enhance heat distribution and side reflectors to contain the heat within a specified area. Additionally, tests were conducted under both calm conditions and simulated windy conditions using a fan to assess the impact of airflow on heating performance. This setup ensured comprehensive temperature monitoring throughout the experiments. Each test was conducted multiple times over a 25 minute period, starting from ambient room temperature, with temperature data recorded at 5 second intervals. The data collected was stored in an Excel spreadsheet for detailed analysis. This methodical approach enabled the accurate assessment of each heating technology's performance under controlled conditions.

Table 2. Design of experiment.

Heat source	**Reflector**	**Ventilator**
Infrared heating tube	With	With
		Without
	Without	With
		Without
Infrared panel	With	With
		Without
	Without	With
		Without
Carbon filament-based heating mat	With	With
		Without
	Without	With
		Without

The primary parameters measured were the surface temperature of the heating elements, the temperature of the heated object, and the ambient air temperature. By comparing temperatures with and without the use of reflectors and under varying airflow conditions, the experiment aimed to identify the optimal configuration for each heating technology.

5 Results

The infrared heating tube, specifically a halogen lamp, was evaluated for its rapid heating capabilities and high-temperature output. The results indicated that the IR heating tube reached a surface temperature of over 1400 °C within a short time frame. The use of a reflector significantly enhanced the heated surface temperature, in accordance with the inverse square law. Because of how effective the reflector is in directing and focusing the heat, the IR lamp was always tested with a reflector [16]. The presence of airflow, simulated by a fan, reduced the heated surface temperature (Fig. 2), highlighting the sensitivity of the IR heating tube to airflow.

As we see from the graph, the IR Lamp can produce a temperature difference of around 14 to 20 °C when comparing heated surface to the different ambient temperature readings, although the delta is reduced significantly when airflow is present. These findings suggest that while they are the best performing in static wind, they are not ideal in windy conditions. Furthermore, they are fragile, need reflectors, get very hot – which makes them so unsafe for close human proximity – and they are difficult to implement in a textile base.

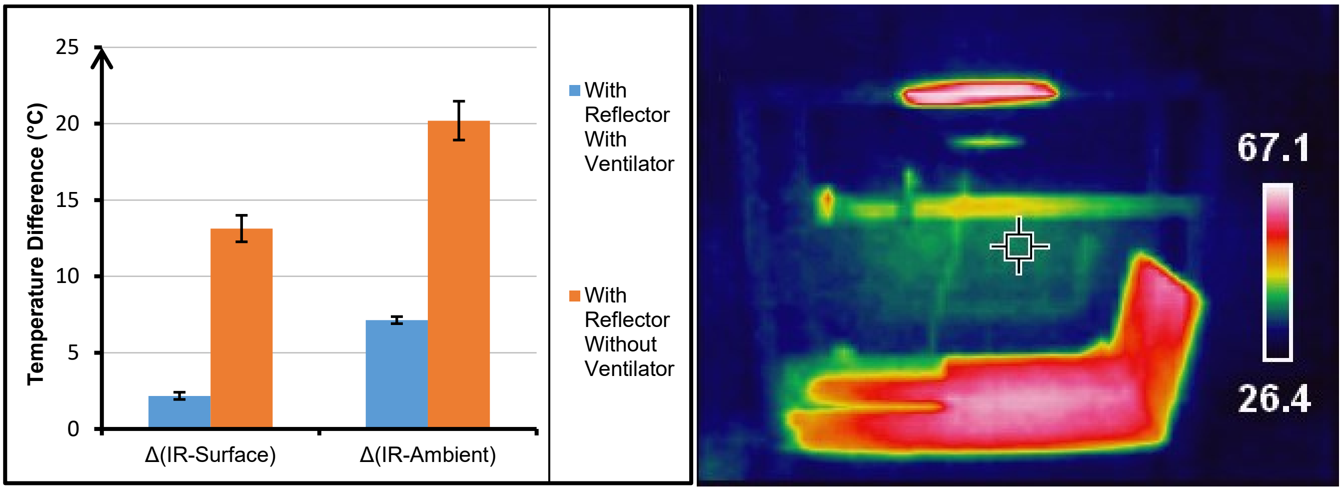

Fig. 2. Averaged temperature difference between the surface of the demonstrator and the ambient temperature for the infrared heating tube.

Infrared panels, which operate by emitting IR-B and IR-C radiation [5], were assessed for their heating efficiency and aesthetic integration. The panel tested in this study featured hidden heating elements and provided a steady heat output. The reflector slightly improved the heating efficiency. Notably, the IR panel maintained a relatively stable performance under windy conditions, with minimal reduction in surface temperature (Fig. 3). Since the heating is more evenly spread, the temperature delta is not very high, but the heating is still apparent on the heat sink and the wind performance is also more consistent. The combination of efficiency, stability, and aesthetic appeal makes IR panels a viable option for residential and commercial heating solutions.

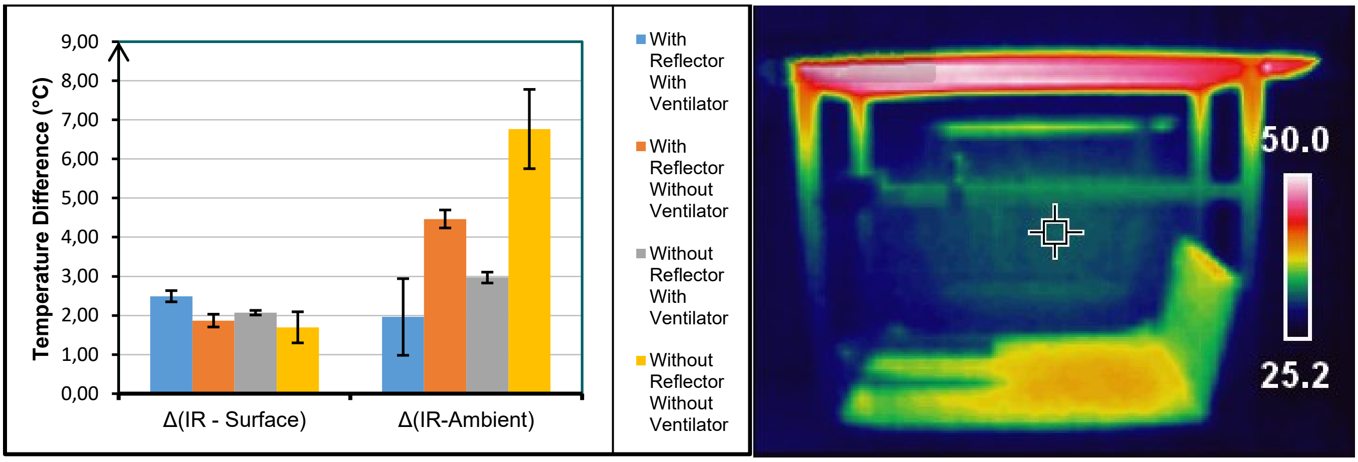

Fig. 3. Averaged temperature difference between the surface of the demonstrator and the ambient temperature for the infrared panel.

The carbon filament-based heating mat represents an advanced approach to integrating heating elements with textiles. Unlike traditional metallic wire heaters, carbon filaments offer greater flexibility and superior heat distribution properties. The heating mat demonstrated significant improvements in heat distribution with the use of reflectors. Additionally, the carbon filament heating mat maintained its performance under windy conditions, showing only a slight reduction in surface temperature (Fig. 4). These results underscore the potential of carbon filament-based heating mats for a wide range of applications, particularly in scenarios where flexible, durable, and efficient heating solutions are required. The adaptability of this technology makes it particularly promising for both indoor and outdoor applications, including smart textile-based heating systems.

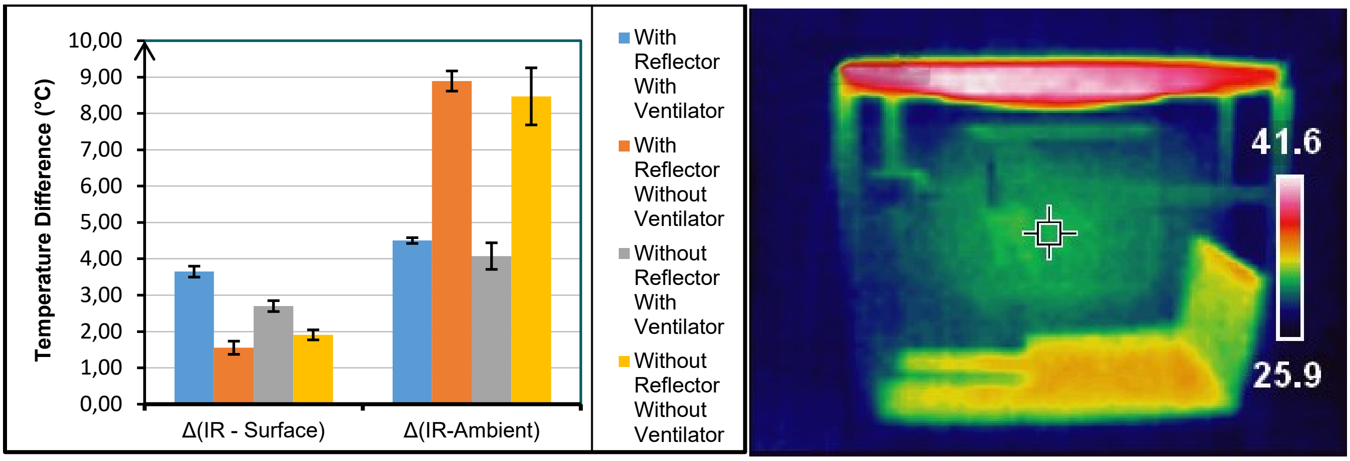

Fig. 4. Averaged temperature difference between the surface of the demonstrator and the ambient temperature for the carbon filament-based heating mat.

The comparative analysis of the three heating technologies revealed distinct advantages and limitations for each. The IR heating tube excelled in rapid heating and high-temperature output but was less effective in windy conditions. The IR panel provided a balance of efficiency, stability, and aesthetic integration, making it suitable for controlled indoor environments. The carbon filament-based heating mat offered the best combination of flexibility, durability, and performance, demonstrating significant potential for smart textile applications. Overall, the carbon filament-based heating mat emerged as the most versatile and effective solution for our specific application of outdoor heating, offering a promising path forward for the development of innovative, energy-efficient heating systems.

6 Conclusion

A textile-based heating system presents a novel and efficient solution for diverse heating areas. By integrating sensors and conductive fibers, it can achieve targeted heating performance. The utilization of infrared radiation as a heat carrier, along with an AI-based control circuit and sensor integration, can enhance heat source efficiency, reduce emissions, and enable precise energy consumption control.

The experimental evaluation of three heating technologies – infrared heating tubes, infrared panels, and carbon filament-based heating mats – under varying conditions has provided comprehensive insights into their performance. The results indicate that carbon filament-based heating mats offer a superior combination of flexibility, durability, and performance, making them an optimal choice for smart textile applications. This technology not only maintains traditional textile characteristics but also integrates advanced functionalities such as targeted heat distribution and modular design.

Future work will focus on realizing and evaluating the integrated smart textile system as a whole and optimizing the production process for scalability to ensure an efficient manufacturing. Additionally, further development of the sensor suite for smart heating control will be pursued to enhance the system's responsiveness and adaptability. This systematic approach aims to deliver a market-oriented demonstrator that extends the benefits of energy-efficient heating to a broader audience.

Author contributions

R. Oberlé, B. Shazimani: conceptualization, formal analysis, investigation, writing; R. Boich: methodology, project administration, funding acquisition; T. Gries: supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

References

1. Europe Heating Radiators Market Share, Size & Growth Report | 2031. https://www.skyquestt.com/report/europe-heating-radiators-market.
2. Wetter.de. Der Heizpilz des Grauens: Die Wärmestrahler sind riesige Energiefresser und CO2-Produzenten. wetter.de. November 1, 2016. https://www.wetter.de/cms/der-heizpilz-des-grauens-die-waermestrahler-sind-riesige-energiefresser-und-co2-produzenten-4028985.html.
3. Channel, W. Heiße Luft? So steht es um die Energiebilanz von Heizpilzen | The Weather Channel. The Weather Channel. October 18, 2020. https://weather.com/de-DE/wissen/klima/news/2020-10-18-heisse-luft-so-steht-es-um-die-energiebilanz-von-heizpilzen.
4. Schuberth, J.; Börner, M.; Umweltbundesamt. TERRASSENHEIZSTRAHLER Informationen über die nachteiligen Umweltwirkungen; Umweltbundesamt, 2009. https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3735.pdf.
5. Ceramicx Ltd. Preferred infrared wavelengths for comfort heating – White papers – Ceramicx. Ceramicx. https://www.ceramicx.com/information/media/white-papers/preferred-wavelengths-for-comfort-heating/.
6. Dittmann, A.; Fischer, S.; Huhn, J.; Klinger, J. *Repetitorium der Technischen Thermodynamik*; Vieweg+Teubner Verlag Wiesbaden, 1995. DOI: https://doi.org/10.1007/978-3-322-94059-9.
7. Wu, H.; Tan, S.; Zheng, X.; Zhao, Z.; Wang, M.; Ma, Q.; Wu, J.; Li, D. Fabrication of carbon fiber/cement composites with controllable precise patterned structures via facile computerized embroidery. *Materials & Design* **2024**, *242*, 113017. DOI: https://doi.org/10.1016/j.matdes.2024.113017.
8. Yang, Y.; Chen, D.; Cheng, Y.; Sun, B.; Zhao, G.; Fei, W.; Han, W.; Han, J.; Zhang, X. Eco-friendly and sustainable approach of assembling sugars into biobased carbon fibers. *Green Chemistry* **2022**, *24*(13), 5097–5106. DOI: https://doi.org/10.1039/d2gc01075e.
9. Li, X.; Zhao, L.; He, T.; Zhang, M.; Wang, Z.; Zhang, B.; Weng, X. Highly conductive, hierarchical porous ultra-fine carbon fibers derived from polyacrylonitrile/polymethylmethacrylate/needle coke as binder-free electrodes for high-performance supercapacitors. *Journal of Power Sources* **2022**, *521*, 230943. DOI: https://doi.org/10.1016/j.jpowsour.2021.230943.
10. Alshabouna, F.; Lee, H. S.; Barandun, G.; Tan, E.; Cotur, Y.; Asfour, T.; Gonzalez-Macia, L.; Coatsworth, P.; Núnez-Bajo, E.; Kim, J.-S.; Güder, F. PEDOT:PSS-modified cotton conductive thread for mass manufacturing of textile-based electrical wearable sensors by computerized embroidery. *Materials Today* **2022**, *59*, 56–67. DOI: https://doi.org/10.1016/j.mattod.2022.07.015.
11. Huang, Q.; Wang, D.; Hu, H.; Shang, J.; Chang, J.; Xie, C.; Yang, Y.; Lepró, X.; Baughman, R. H.; Zheng, Z. Additive functionalization and embroidery for manufacturing wearable and washable textile supercapacitors. *Advanced Functional Materials* **2020**, *30*(27), 1910541. DOI: https://doi.org/10.1002/adfm.201910541.
12. Zheng, Y.; Jin, L.; Qi, J.; Liu, Z.; Xu, L.; Hayes, S.; Gill, S.; Li, Y. Performance evaluation of conductive tracks in fabricating e-textiles by lock-stitch embroidery. *Journal of Industrial Textiles* **2020**, *51*, 6864S-6883S. DOI: https://doi.org/10.1177/1528083720937289.
13. Ahn, J.; Kim, S. Automated Textile Circuit Generation using Machine Vision and Embroidery Technique. *Textile Research Journal* **2022**, *92*(11–12), 1977–1986. DOI: https://doi.org/10.1177/00405175221075062.
14. Konzilia, J.; Wachter, J.; Egger, M.; Waltl, C.; Fröis, T.; Bechtold, T.; Feix, J. Embroidered carbon reinforcement for concrete. *Buildings* **2023**, *13*(9), 2293. DOI: https://doi.org/10.3390/buildings13092293.
15. Dong, X.-X.; Cao, Y.-M.; Wang, C.; Wu, B.; Zheng, M.; Xue, Y.-B.; Li, W.; Han, B.; Zheng, M.; Wang, Z.-S.; Zhuo, M.-P. MXene-Decorated Smart Textiles with the Desired Mid-Infrared Emissivity for Passive Personal Thermal Management. *ACS Applied Materials & Interfaces* **2023**, *15*(9), 12032–12040. DOI: https://doi.org/10.1021/acsami.2c21696.
16. Inverse Square Law – Statement, Formula and applications. BYJUS. https://byjus.com/physics/inverse-square-law/.