



Sustainable eco-design approach for next-generation wearable e-textiles

Marzia Dulal^{a,b}, Shaila Afroj^{a,c,*}, Nazmul Karim^{a,d,**}

^a Centre for Print Research (CFPR), University of the West of England, Bristol, BS16 1QY, UK

^b Department of Textile Engineering Management, Bangladesh University of Textiles, Tejgaon Industrial Area, Dhaka, 1208, Bangladesh

^c Department of Engineering, Faculty of Environment, Science and Economy, University of Exeter, EX4 4QF, Exeter, UK

^d Department of Fashion and Textiles, Winchester School of Art (WSA), University of Southampton, Southampton, SO23 8DL, UK

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ABSTRACT

Wearable e-textiles offer a cutting-edge approach to personalised health monitoring. However, challenges in material sustainability, production processes, and end-of-life management hinder their broader adoption. This study introduces the first eco-design approach to wearable e-textiles, emphasising the integration of the three constructs: sustainable design, performance measurement, and end-of-life solutions throughout the product lifecycle. Understanding market demands and customer expectations is crucial for the viability of this eco-design strategy. By integrating these constructs, eco-design ensures that wearable e-textiles meet functionality expectations while minimising environmental impact. This research examines the current state of wearable e-textiles using Partial Least Squares Structural Equation Modeling (PLS-SEM) to validate these constructs. It explores key elements such as sustainability parameters, manufacturing processes, and potential applications, as perceived by experts through a focused survey using purposive sampling and descriptive statistics. The study demonstrates a significant correlation between these constructs involved in sustainable wearable e-textile design. Specifically, performance measurement plays a partial role in mediating this relationship, contributing to the advancement of design practices that prioritize sustainability in wearable e-textiles. Finally, it discusses the theoretical, managerial, and societal implications, emphasising the importance of sustainable eco-design strategies for e-textiles in driving scientific advancements and benefiting both academia and industry.

1. Introduction

From the dawn of civilisation onward, people have covered themselves with textiles for warmth and body safeguarding. Widely regarded as one of the earliest forms of self-augmentation, textiles have played a vital role in human development. The advancement of wearable technology has arrived at a turning point. The next phase of textile wearables has begun with the success of the whole e-textile industry, which is projected to reach a market size of US\$1.4 billion by 2030 (Shi et al., 2023). E-textiles can store and generate energy (Liao et al., 2022), as well as sense (Yan et al., 2022), actuate (Maziz et al., 2017), measure (Rajappan et al., 2022) and display (Shi et al., 2021). These textile wearables are expected to bring extra features to improve our everyday experience, overall wellness, and wear comfort (Barber, 1991). They show potential for use in environmental monitoring, gaming, health-care, and sports training, among other sectors (Hossain et al., 2023; Meena et al., 2023), because of their emerging qualities such as light

weight, flexibility, stretchability and responsiveness to stimuli, enhancing comfort and overall wellness (Akter et al., 2024). However, significant obstacles include production technical difficulty, confined element cross-compatibility, short service times for product life, and insufficient supply chains, all of which increase e-textile product cost and slow down consumer uptake. Additionally, significant environmental costs remain associated with the mass manufacture of e-textiles. E-textiles are currently produced using a variety of integrated technologies (Fig. 1c), such as embroidered circuits, flexible and elastic printed circuit boards, and integrated textile circuit boards for data processing, interconnection, power supply, and actuation. These components make the sorting and recycling procedures for electronic waste (e-waste) generated from e-textiles more difficult since they combine textile and electronic components (Elisabeth et al., 2022).

During the past ten years, there has been an average annual growth of 2 million metric tonnes in the volume of worldwide e-waste. According to projections, the volume of e-waste will reach ~74.7 million

* Corresponding author. Department of Engineering, Faculty of Environment, Science and Economy, University of Exeter, EX4 4QF, Exeter, UK.

** Corresponding author. Department of Fashion and Textiles, Winchester School of Art (WSA), University of Southampton, Southampton, SO23 8DL, UK.

E-mail addresses: s.afroj@exeter.ac.uk (S. Afroj), nazmul.karim@oton.ac.uk (N. Karim).

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metric tonnes (Fig. 1a), almost doubling in just 16 years from 2014 (Ruiz, 2023). Additionally, the textile industry is considered one of the largest polluters of the environment, contributing ~92 million textile waste every year, which is thrown away in landfills (Fig. 1b) (Ruiz, 2024). The difficulties in recycling e-textiles, or textiles coupled with electrical components, worsen this issue. These numbers demonstrate the growing difficulty in managing e-textile waste and the urgent need for enhanced End-of-life solutions (EoLs) and environmentally friendly production methods in the sector. To generate fresh concepts that serve a purpose, an eco-design research method (Fig. 1d) highlights a cyclical process that starts with an ideation phase along with the screening and includes concept testing and validation, directly influencing the design. Hence, sustainable design is not only an option but also a need for the future of e-textiles. This study aims to explore the processability of end-of-life (EoL) options and address sustainability challenges and environmental impacts by investigating design approaches incorporating advanced materials and methods to develop sustainable and efficient wearable e-textiles. Additionally, it seeks to investigate the current state-of-the-art in wearable e-textiles in order to comprehend market needs and develop study resources and processes within facilities. This will ensure that ongoing efforts remain in line with the most recent expectations of the market. To achieve this, a combination of

qualitative and quantitative methods is used for the collection of measurable responses, which can be analyzed to identify patterns, trends, and relationships (Valaei et al., 2017) within the context of wearable e-textiles and gain a comprehensive grasp of choices for new technologies and their usage (Chen and Ye, 2023). In terms of sustainability aspects, insights will be applied to future research and development by adapting methods to evaluate the performance attributes of e-textiles as well as preferences thoroughly. Thus, the study employs a mixed-methods approach to achieve the purpose in the sustainable wearable e-textiles field. The mixed-methods approach enables the integration of data from multiple sources to examine similar constructs (Wang et al., 2021), allowing for a comprehensive analysis of this untapped area with significant potential (Reamer et al., 2022). By incorporating both qualitative and quantitative features with an applied focus, this approach offers a thorough investigation. This dual strategy not only broadens and deepens the study but also ensures that the results are firm and thorough, providing a well-rounded perspective on the developments and practical applications of sustainable wearable e-textiles. This study examines the current trend in the wearable e-textiles field and tests the conceptual framework, stating that the sustainable design construct is linked to the resolution of EoL processabilities through the PLS-SEM for eco-design of the next-generation wearable

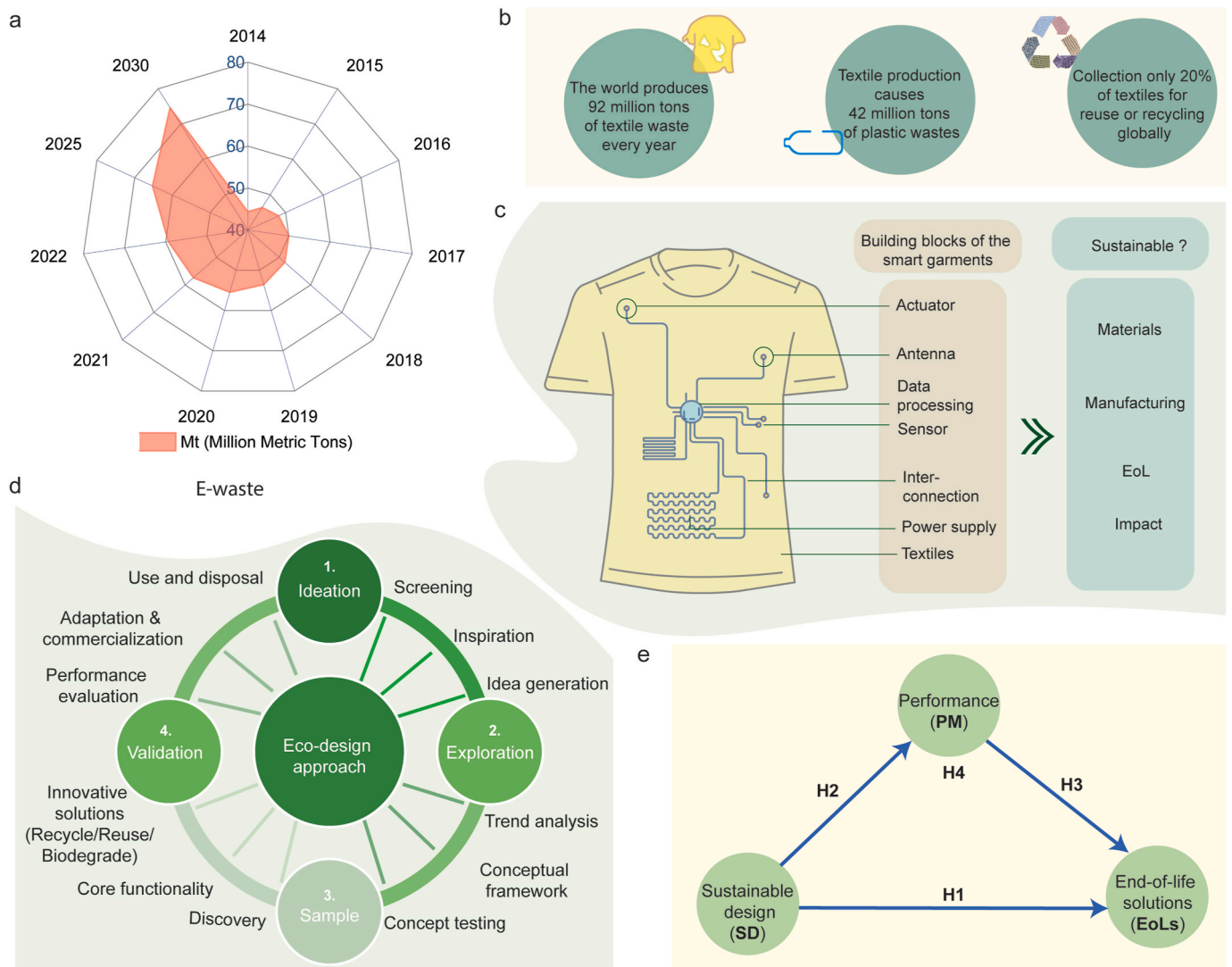


Fig. 1. Addressing the urgent need for eco-friendly wearable e-textiles. a) E-waste generation in total annual global. b) Key statistics of global textile waste, c) Schematic of the building blocks of wearable e-textiles and their sustainability considerations. d) The overall eco-design research approach toward sustainable wearable e-textiles. e) Conceptual framework of sustainable design approach for next-generation wearable e-textiles.

e-textiles. In outline, with an emphasis on the growing need for sustainability (Dulal et al., 2024; Dulal et al.; Islam et al., 2024a,b), the research's main objective was to examine market trends and comprehend expert opinions in the wearable e-textiles industry. It sought to investigate the relationships between important aspects of sustainable design and performance as well as their potential impact on the processability of EoL alternatives. The study looks into these connections in an effort to offer directions for the development of effective and environmentally friendly wearable e-textiles. A thorough investigation of the possibilities and viability of sustainable practices in this rapidly evolving industry is made possible by this integrated approach.

2. System overview

Wearables are designed to be worn on various parts of the human body, depending primarily on their intended application and the specific requirements for data collection or output. Modern devices have advanced from the earliest healthcare devices and typical activity trackers (Ometov et al., 2021). The sustainable design approach can advance in promoting user adoption and establishing a circular economy (Brandão and Verissimo, 2024), essential for wearable technology to live up to its cutting-edge potential (Dutta and Bansal, 2024; Murrugesan et al., 2024). With the advancement of wearable e-textiles, electronic waste (e-waste) generation poses significant environmental and health risks. Managing e-waste is challenging due to poor infrastructure, limited resources, and short device lifespans (Gaur et al., 2024; Gollakota et al., 2020), integrated by electronics in textiles, complicating recycling and increasing the risk of contamination and pollution, necessitating global e-waste strategies and advanced recycling technologies as end-of-life solutions via sustainable design (Elisabeth et al., 2022). Numerous review papers were published to present the wearable electronic-centric design, market growth, challenges and potential uses (Azeem et al., 2025; Islam et al., 2024a,b; Kan and Lam, 2021; Naeem et al., 2023; Yang et al., 2024; Younes, 2023). In a report of IDTechEx (Skyrme, 2023), they contextualized the narrative around the e-textiles industry, which narrowly focused on the breakdown of the preferred material choice, such as conductive, fibres, inks, and polymers in e-textile manufacturing across 256 players. In contrast, this survey takes a broader approach, covering various aspects of the e-textile industry beyond just materials, including sustainability, applications, and preferences. It discusses preferred forms of e-textiles, application areas, and desired functions, offering a more comprehensive view of experts from different areas of expertise like research and design, material science, wearable and flexible electronics and sustainability analytics.

This study introduces new elements not covered in any survey reported in e-textiles, such as highlighting the importance of sustainability, including specific aspects like recyclability and eco-friendly materials, waste reduction, socially responsible consumption, etc., which are absent in any previous surveys. This sustainable perspective is missing in the reported studies (Consulting, 2021; Hayward, 2019; Meena et al., 2023; Yang et al., 2019), where the types of materials used by e-textile players, technological analysis and the global e-textiles and smart clothing market analysis and forecast were mostly focused. However, quantitatively, there is no extensive study investigating the field of wearable e-textiles toward sustainability which can give distribution statistics in terms of preferences and sustainability aspects parameters. Before sustainable design can be widely adopted and its impact on EoL understood, it is important to study the key factors influencing wearable e-textiles. Conducting a survey in this field, which combines wearable electronics and textiles, facilitates a comprehensive understanding of evolving research in sustainable wearable e-textiles. It provides valuable data on current trends, preferences, and challenges, offering a wide perspective to guide future innovations and effectively address gaps in sustainability practices. This will help gather detailed insights, validate theoretical constructs, and advance exploratory research to investigate new hypotheses, providing a comprehensive

view of developments in sustainable wearable e-textiles. The survey was newly developed in the field of sustainable wearable e-textiles for exploring the trend of the current state of the art about integration, performance, wearable form, functionalities, functions, and sustainability parameters. It was specifically tailored to address specific aspects of end-of-life solutions related to sustainable design through the perception of experts in the field of material science, wearable, flexible electronics, industrialist and sustainability analyst. Statistical analyses, including Cronbach's alpha, confirm internal consistency for reliability and validity in reporting.

3. Conceptual framework and hypothesis development

To adopt a circular approach, it is imperative to complete the loop and include sustainability into the selection of materials, manufacturing processes, and device configurations for all these prospective uses. Nonetheless, product longevity and sustainable ease of disassembly and recycling must be closely correlated, and product design should support regeneration. Key performance (PM) attributes such as flexibility, durability, washability, and comfort, alongside seamless integration of electronic functions, are critical. The aim is to develop e-textiles that not only last longer, reducing the reliance on raw materials and waste generation, but also integrate electronic capabilities without compromising the e-textile's performance. For this reason, it is necessary to assess the state of e-textiles in sustainable design (SD) options, such as employing more environmentally friendly materials and manufacturing processes and addressing EoLs, mediating through PM. Providing a framework is the essential component of this developing sector through mixed-mode research. In the development of smart and sustainable wearable e-textiles, the apparent trend and framework will push towards the creation of adapted, simpler, and widely available devices that closely interact with our bodies. Therefore, it is crucial first to understand the integration strategies, influencing factors, selected forms, primary application areas, necessary functions, and sustainability concerns to make sure that the framework in sustainable wearable e-textiles is tailored to user requirements and market demands by addressing and examining survey responses for next-generation wearable e-textiles. The identification of comprehensive and adaptive design qualities in wearable technology has been made available by investigating constructs and measurement items. Surveys with wearable technology-experienced populations were targeted, and a sample size was used to investigate these parameters. To learn more about the sustainability aspects of the wearable e-textiles design process, qualitative analysis of responses was used to acquire insights. Hence, a conceptual framework was developed (Fig. 1e) to represent the relationship of EoLs approach for wearable e-textiles initiated with SD need to be established for these smart fabrics to achieve their full potential while minimising their negative environmental effects and to investigate how sustainable e-textile design can support the easy EoLs at the end of their useful life through h PM. The study results presented in this study provide wearable e-textile designers with a new conceptualisation approach that incorporates a set of design constructs and their measurement items in the design process, which are helpful in comprehending the design process itself. The following statements are thus developed as four hypotheses to investigate the correlation among the constructs and validate the framework.

Hypothesis 1. (H1): SD has a positive influence on EoLs.

Hypothesis 2. (H2): SD has a significant influence on the PM of wearable e-textiles.

Hypothesis 3. (H3): PM has a significant influence on EoLs.

Hypothesis 4. (H4): PM can positively mediate the relationship between SD and EoLs.

4. Methodology

4.1. Variable measurement and questionnaire design

In the current research, the survey method was employed which is a popular approach for gathering data on wearable technology and its applications (El-Toukhy et al., 2023; Miyakoshi and Ito, 2024). This

involved setting structured questions (Supporting information, Questionnaire S1) to collect data and using software tools to analyse the results. The goal is to find the descriptive statistics and derived relationships between the variables. The survey underwent ethical approval and got approval CATE-2324-244 from the UWE Research Ethics Committee. Using the Qualtrics platform, a questionnaire based on the variables and objectives was generated, and the link was sent to

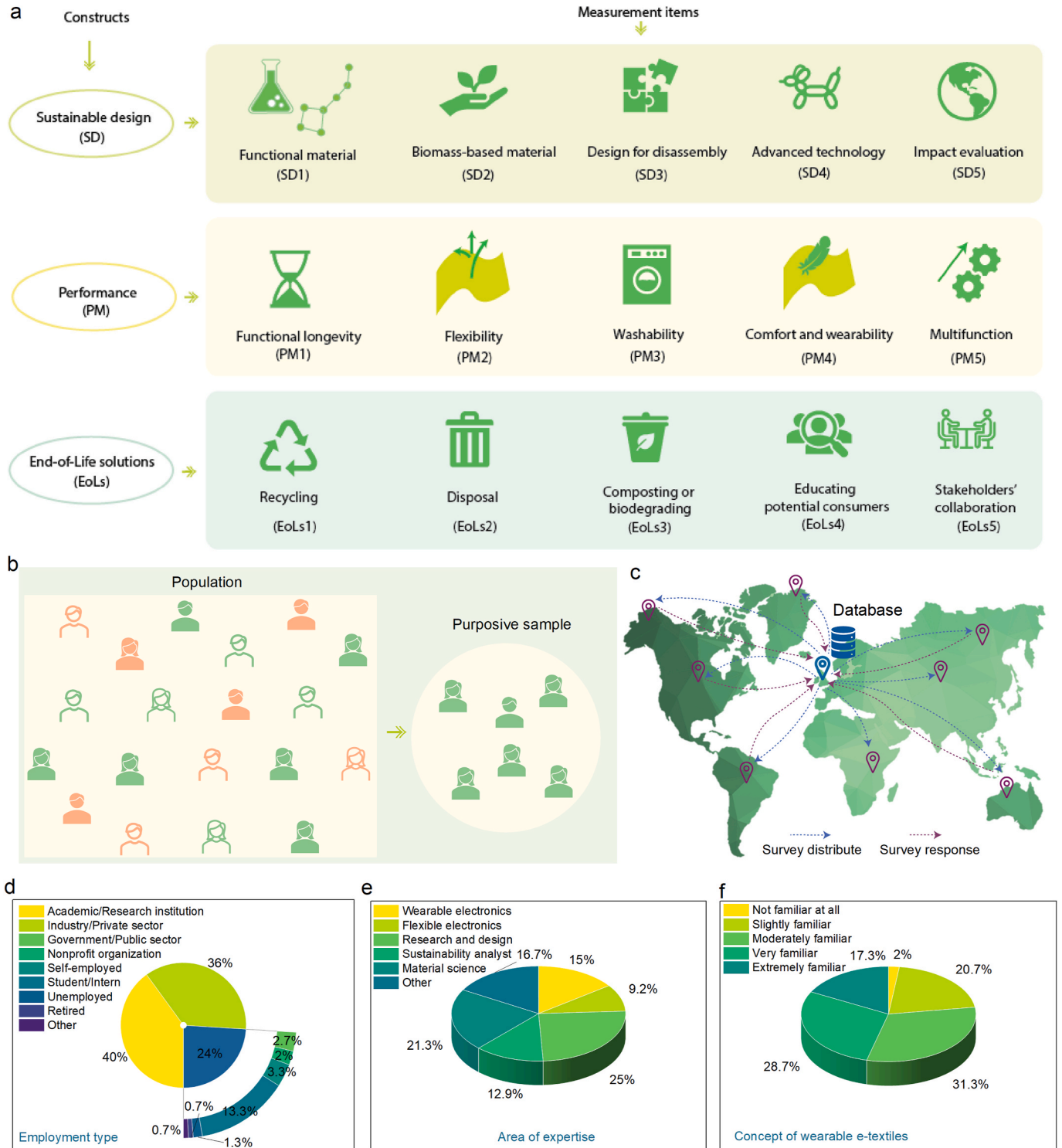


Fig. 2. Methodological framework. a) Schematic and indication of measurement items for constructs. b) Schematic of purposive sampling. c) Schematic for distributing survey forms to participants who are dispersed out around the globe and gathering data from them. d) Employment type, e) Area of expertise, and f) Familiarity with the concept of wearable e-textiles of the respondents.

possible respondents. There were only closed-ended questions on the questionnaire. The questionnaire was divided into 3 sections; in the first section, the questions about the respondent's profile were set; in the second section, general preferences for wearable e-textiles were set from which the current trend is shown; and in the final section, a 5-point

Likert scale (Fig. 4c) was employed to determine the connection between constructs based on the respondents' choice to validate the hypothesis developed and the model. For every construct size, the measurement elements range from 1—“No significance” to 5—“Extreme significance”. After reviewing the literature, five items for SD



Fig. 3. The current trend of wearable e-textiles. Respondents' preferences: a) Integration method of electronics into textiles, b) Factors influencing to choose the method, c) Form of wearable e-textiles more appealing, d) Applications that offer more opportunities for the growth and adoption of wearable e-textiles. e) Likable functions or features in wearable e-textiles, f) Sustainability importance in wearable e-textiles, g) Important sustainability aspects for initialising in wearable e-textiles.

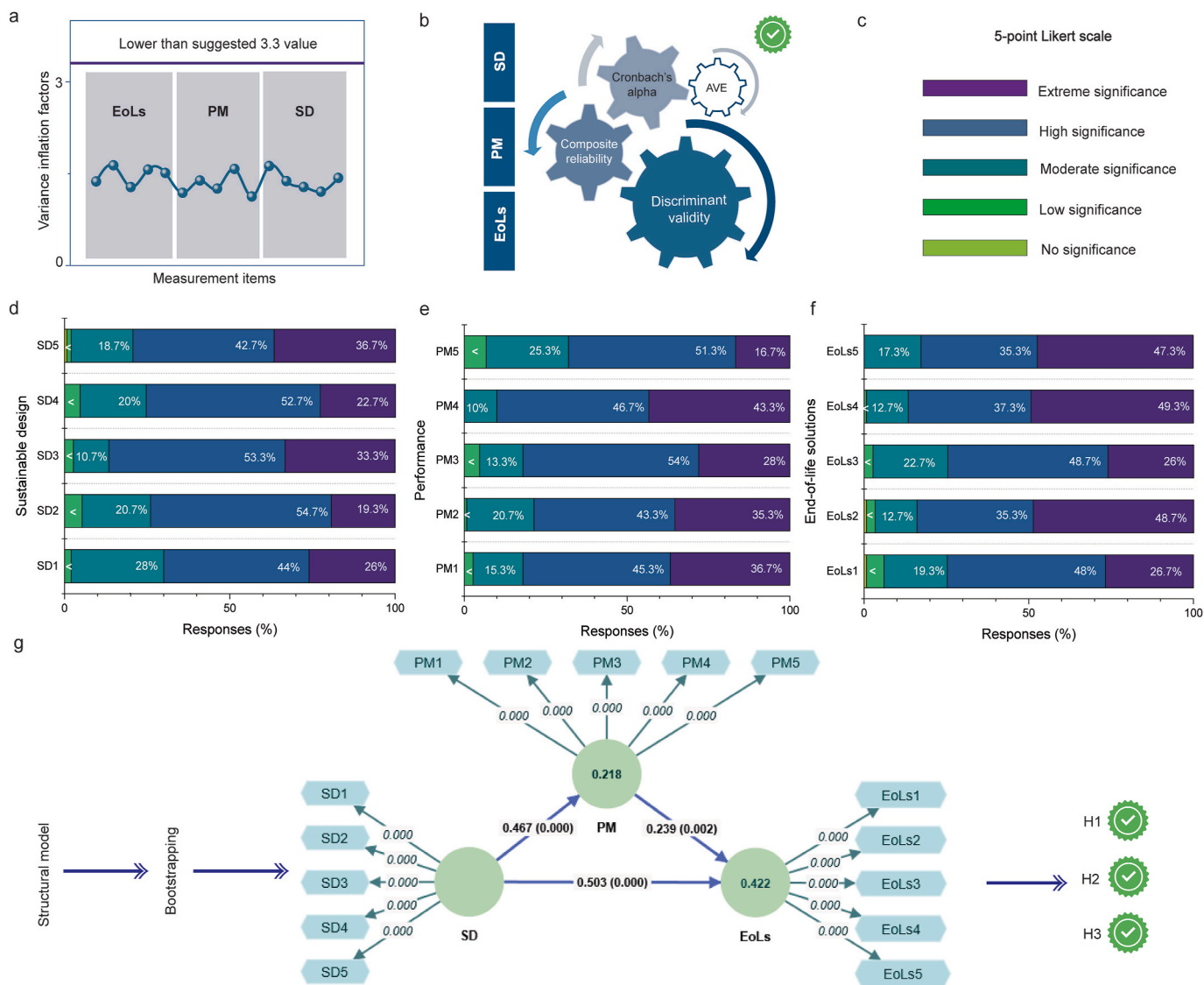


Fig. 4. Model testing. a) Collinearity test of the constructs by VIF. b) Schematic of measurement model acceptance. c) The legend of the 5-point Likert scale is used in (d–f). Responses in percentage on a scale of 1–5, indicating the level of significance of the constructs comprising measurement items for sustainable wearable e-textiles: d) Sustainable design, e) Performance and f) EoLs. g) Graphical output of bootstrapping with inner model path coefficient (p-value), outer model p-value, and constructs R².

(Dulal et al., 2022; Köhler, 2013; McLaren et al., 2017; Naeem et al., 2023; Saunders, 2022; Shi et al., 2023; Veske and Ilén, 2021), five items of PM (Ismar et al., 2020; McLaren et al., 2017; Wu et al., 2021) and five items of EoLs (Beemer et al., 2023; Garbacz et al., 2021; Kasaw et al., 2021; Vasquez and Vega, 2019) were chosen. Fig. 2a presents measurement items for construct details.

4.2. Sample and data collection

In this survey method study, particularly in the preliminary phase, understanding constructs within the specialised domain of wearable e-textiles was concentrated. Due to the challenges of defining the total population size in this emerging field, purposive sampling to engage with recognised experts was employed (Fig. 2b). The selection of a sample of experts typically involves techniques such as purposive sampling (Hasson et al., 2000; Janssen et al., 2013). The representation of a range of viewpoints and perspectives is crucial because the objective of this study is to foster exploration and comprehension across several categories. As a result, we were looking for participants with a range of job titles and areas of expertise (Fig. 2d and e). To this end, a

multifaceted purposive sampling strategy was adopted to ensure e-textile competence experts from a variety of backgrounds (wearable electronics, flexible electronics, research and design, sustainability analyst, material scientist etc.) were included in the study. The selection of expert respondents was guided by their relevance, knowledge, and active involvement in the fields of material science, wearable electronics, flexible electronics, sustainability analysis, research, and design. This ensured that the participants possessed the necessary expertise to contribute valuable insights and validate the theoretical constructs under investigation. The purposive sampling method was chosen because it allowed the deliberate targeting of a specific, informed audience critical to advancing exploratory research employing PLS-SEM and analyzing current trends. SEM is a multivariate statistical method that is increasingly being used in social sciences to analyse causal relationships among latent variables as well as relationships between latent and observed variables (Hair Jr et al., 2021). SEM is an appropriate technique for testing the validity and unidimensionality of observed variables, confirming whether they adequately measure what they are supposed to measure, and generating reliable information about unobserved variables (Cheung et al., 2024; Russo and Stol, 2021).

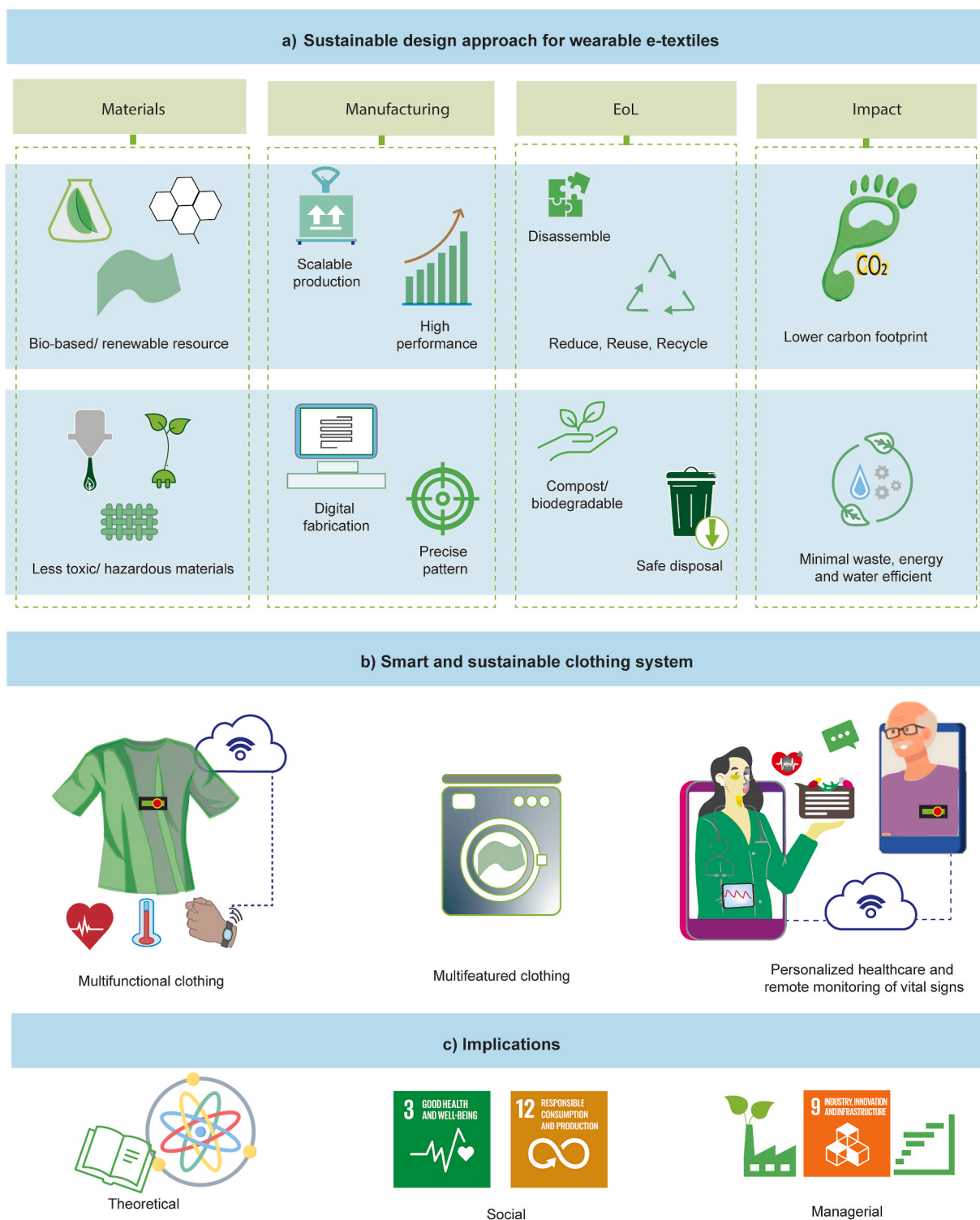


Fig. 5. Measurement items application and implications. a) Sustainable design approach for wearable e-textiles. b) Smart and sustainable clothing system. c) Implications: theoretical, social, and managerial.

Second, model fit is evaluated to determine how well the model represents the data (Adedeji et al., 2016). When considering the statistical power of data analysis in covariance-based methods, particularly SEM, sample size is essential. A recently proposed method was used for calculating the minimum sample size based on three indicators: standard statistical power, effect size, and level of significance (Westland, 2010). The study utilized an online statistical tool developed by Daniel Soper, which helps calculate the minimum sample size required for

reliable results. This tool employs an algorithm that considers several key factors: a medium effect size of 0.3, representing a moderate impact, a statistical power of 0.8 to ensure adequate sensitivity in detecting effects, and a significance level of 0.05, which indicates the acceptable probability of Type I error. These criteria were used to determine the lower bound for the necessary sample size in the study. With 15 measurement items and 3 constructs, the results indicate that a minimum sample size of 119 would be adequate to achieve statistical power for

precision in this analysis. The observed variables representing measurement items (latent variables) in the present study are extracted from the literature review and theoretical concept. Purposive sampling was adopted to achieve the target population. To mitigate potential biases inherent in purposive sampling, several measures were implemented such as diversity of sources, cross-sector representation, clear selection criteria and adequate sample size. Utilising online platforms for data collection enables targeted access to a diverse and geographically dispersed (Fig. 2c) expert population, ensuring the relevance and richness of the data for preliminary model testing and theory development. This approach reduced the risk of over-representation from any single region or demographic. Respondents were drawn from a balanced mix of academic/research institutions, industry professionals, and end-users, ensuring varied perspectives across the domains of interest, such as material science, wearable electronics, flexible electronics, sustainability analysis, research, and design. Potential respondents were evaluated based on their professional background and relevance to the research topics. This ensured that only individuals with pertinent expertise were included. With 150 valid responses obtained, the sample size was deemed sufficient for PLS-SEM analysis and preliminary model testing, enhancing the reliability of the findings. By implementing these strategies, the research ensured the selection of a well-qualified respondent pool while minimising biases and enhancing the richness and relevance of the collected data for model validation and theory development.

4.3. Respondent's profile

Fig. 2d–f represents the respondent's profile and their concept in the field of wearable e-textiles. A significant 40 % of responses in Fig. 2d are from academic or research institutes, laying a solid foundation for future research and development in the wearable e-textiles sector. This is especially helpful for SD because academic settings often place a high value on creative solutions, such as developing eco-friendly procedures and sustainable materials. To advance the commercial presence of sustainable e-textiles for future generations, the industry/private sector response is essential as respondents, which accounts for 36 % of the total responses. The government/public sector, which is involved in policy creation and the promotion of sustainable practices, can make a valuable choice, accounting for 2.7 % of the total responses. Fig. 2e reveals that the predominant expertise lies in research and design (25 %), pivotal to crafting a comprehensive and sustainable wearable e-textiles design approach opinion. Since wearable and flexible electronics expertise make up 15 % and 9.2 % of total responses, respectively, experts in these fields may be able to give their choice to make textile electronics more integrated, less wasteful, and energy efficient. Additionally, 12.9 % of sustainability analysts underscore the presence of significant knowledge contributing towards sustainable wearable textiles, with the rest of the respondents coming from various other professional backgrounds. Many respondents have some familiarity (31.3 % moderately, 28.7 % very, and 17.3 % extremely) with wearable e-textiles, suggesting that this group understands well and may be willing to embrace sustainable practices (Fig. 2f). However, some responders (2 % not familiar) and those who are only slightly familiar (20.7 %) with the concept remain. This indicates that more professionals need to be made more aware of the advantages and usage practices of sustainable e-textiles to increase their level of comprehension and engagement.

4.4. Data analysis procedure

Two software tools were used in this study to analyse the datasets and uncover relationships between variables that influence design, functionality, and user behavior. Firstly, IBM SPSS Statistics V29 was used as it provides robust statistical analyses to identify patterns, trends and descriptive statistics, which are crucial for understanding user preferences and design impacts (Williams et al., 2024). PLS-SEM by SmartPLS v.4.1.0.0 software was utilized for exploring theoretical

constructs and validating models (Subhaktiyasa, 2024), enabling a deeper understanding of the interconnected aspects of wearable e-textiles: SD, PM and EoLs. Also, this widely recognised PLS-SEM approach was employed (Hair Jr et al., 2014) to support the theory with empirical data. With its high degree of flexibility for the link between theory and data (Yang et al., 2022), PLS-SEM offers a powerful tool for wearable technology research. These tools complement each other, enabling comprehensive and accurate insights into this evolving research area. The study focuses on exploring complex, multivariate relationships between SD, PM, and EoLs considerations. PLS-SEM is particularly well-suited for exploratory research (Russo and Stol, 2021) because it handles complex models with multiple latent variables and relationships (Gao et al., 2024; Ramli et al., 2018). The primary objective of this research is not direct optimisation but rather the development and validation of a theoretical framework. PLS-SEM facilitates the simultaneous analysis of measurement and structural models, making it an ideal tool for testing theoretical constructs and hypotheses (Richter and Tudoran, 2024). Unlike traditional covariance-based SEM, PLS-SEM emphasizes prediction and variance explanation (Vaithilingam et al., 2024). This aligns well with the study's goal to understand how key factors in sustainable design influence performance and end-of-life considerations, providing actionable insights for future optimisation efforts. PLS-SEM's robustness in handling comparatively smaller sample sizes make it a realistic alternative for ensuring valid and reliable findings considering the nature of the data and the use of purposive sampling.

4.5. Current trend analysis

The fields of nano and microtechnology are expected to progress, resulting in a more personalised and human-centred wearable technology that could revolutionise social interactions and environmental awareness through clothes and everyday living. Thus, this study aims to provide insight into the recent e-textile preferences. It offers information on product attributes and prerequisites that must be fulfilled to preserve the sustainability of e-textiles. Employing experts' knowledge and experience to evaluate wearable e-textile trends would help to bridge the gap between conceptual research and innovative, practical solutions, resulting in cutting-edge, socially responsible, and economically feasible goods. Respondents' preferences for incorporating electronics into textiles to form e-textiles were initially ascertained through the survey in Fig. 3a. When asked which approach they found most appealing or preferred, the majority of respondents (22.5 %) chose woven or knitted electronics, with printed electronics coming in second at 21.3 %. With 19.8 % and 19.4 % of the responses, respectively, embedded and embroidered or stitched electronics were almost equally popular. Only 10.7 % of respondents chose that coated electronics were their favourite option. 6.3 % of the responses were unsure about their preference.

Participants were then asked which factors of their chosen method of incorporating electronics into textiles they appreciated the most in Fig. 3b. Comfort and wearability were found to be the most important aspects, with 24.8 % of respondents emphasising their significance. 20.8 % of total responses were other important factors, such as durability and washability. Additional aspects that were noted by respondents were cost-effectiveness, flexibility/stretchability, and integration of multiple functionalities. These variables were given almost similar weights, with 15.2 %, 14.9 %, and 14.9 % of responses mentioning them, respectively. In the context of wearable e-textiles, responses for aesthetic design are the least chosen factor, with only 9.3 % of respondents selecting it.

As seen in Fig. 3c, smart clothing is the most appealing type of wearable e-textiles, as indicated by 40.7 % of responses. This means that the creation of clothing that integrates technology in a subtle and comfortable should be the top priority for future innovation. As the second most popular category, wearable accessories (24.5 %) showed a strong interest in clothing-accessory items with technological

enhancements. A strong desire for integrating technology in the healthcare and medical device sectors is indicated by the data, which reveals a notable preference for e-textiles, accounting for 41.8 % of all those responding. The development of e-textiles should prioritize sports and fitness applications, as shown by the interest expressed by nearly one-third of the respondents (32.9 %), as shown in Fig. 3d. Besides applications, health and fitness monitoring is the most popular choice (28 %), as shown Fig. 3e.

When asked about the importance of sustainability in wearable e-textile items, 47.3 % of participants stated it was very important, while another 37.3 % said it was extremely important, Fig. 3f. This indicates a broad agreement among respondents regarding the importance of sustainability in the development of wearable e-textiles. After that, participants were asked to choose the components of sustainability that, in their opinion, are most important when starting wearable e-textile projects. 24 % of the responses prioritised eco-friendly materials, as shown in Fig. 3g. Another important factor that stood out was recyclability, as highlighted by 20.3 % of responses. The product’s long lifespan attracted attention: 18.7 % of total responses. Waste reduction and energy efficiency were ranked fourth and fifth, respectively, with 14.5 % and 14.1 % of responses. Furthermore, 8.3 % of responses emphasised the importance of a socially responsible approach.

The results of the survey indicate that future research and development in wearable e-textiles should concentrate on designing products that are not only functional but also meet preferences for comfort, durability, and discreetly integrated technology from the expert point of view. Prioritising should be given to woven or knitted electronics and printed electronics, as they were the respondents’ topmost preferred option. Given that wearability and comfort were found to be the most desirable qualities, they should be built with these in mind. Furthermore, adding characteristics that make these materials more washable, and durable would solve important user concerns. Future research and development efforts should place more of an emphasis on these areas due to the high demand for wearable technology and smart clothes, especially in the fitness and healthcare industries. Furthermore, employing eco-friendly materials and improving the products’ longevity and recyclability should be the top priorities when it comes to sustainability in the design and production processes. This strategy helps to achieve the overarching objective of reducing the e-textile industry’s environmental impact while simultaneously satisfying consumer needs. Following these paths will probably increase the market acceptability and success of upcoming breakthroughs in next-generation wearable e-textiles.

Table 1
Total variance explained.

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
	1	4.655	31.032	31.032	4.655	31.032
2	1.461	9.740	40.772			
3	1.129	7.527	48.298			
4	1.047	6.978	55.277			
5	0.973	6.488	61.765			
6	0.844	5.627	67.392			
7	0.802	5.346	72.738			
8	0.717	4.779	77.518			
9	0.645	4.302	81.819			
10	0.580	3.864	85.683			
11	0.532	3.550	89.233			
12	0.453	3.018	92.252			
13	0.438	2.917	95.168			
14	0.388	2.585	97.754			
15	0.337	2.246	100.000			

5. Sustainable design approach validation

5.1. Method bias measurement

The existence of method bias is the main contributor to measurement error, which leads to an inaccurate relationship between measurement items. Because of its roots, the systematic error variance can significantly affect study outcomes and result in inaccurate conclusions (Habib et al., 2021). Finding the underlying causes of common method bias (CMB) is, therefore, essential. The CMB was tested using two approaches. Initially, the principal axis factor analysis (PAF) (Harman, 1976) was observed using Harman’s one-factor test. Following the test, the overall variance of a single construct came out to be 31.03 % (Table 1), a figure that is below the suggested 50 % (Podsakoff et al., 2003). Secondly, the entire collinearity test of the constructs was used to assess the CMB in variance inflation factors (VIF) (Fig. 4a), and the results showed a value that was lower than the suggested 3.3 (Kock, 2015). Thus, this investigation has avoided any CMB.

5.2. Measurement model

The study examined construct reliability, convergent validity, and discriminant validity (Hair Jr et al., 2021) necessitated for measuring the model (Fig. 4b). At first, construct reliability was determined by examining the composite reliability and Cronbach’s alpha. All of the second-order constructs’ composite reliability (CR) values from the measurement in this study fell between 0.786 and 0.839 (Table 2), meeting the acceptable standard of 0.60 (Aibinu and Al-Lawati, 2010). Cronbach’s alpha (CA) values were found between 0.657 and 0.760. A higher value implies high reliability. A value of 0.60–0.70 is acceptable for exploratory research, while 0.70 to 0.95 is regarded as satisfactory to good (Aibinu and Al-Lawati, 2010). The fact that both numbers are greater than the 0.60 recommended threshold in this type of exploratory research indicates that the construct’s measurement model is accurate and well-fitting to the model. The average variance extracted (AVE) ranges between 43.2 % and 51.2 %, which is close to the recommended

Table 2
Measurement model-quality criteria.

	Cronbach’s alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
EoLs	0.760	0.768	0.839	0.512
PM	0.657	0.691	0.786	0.432
SD	0.730	0.731	0.822	0.481

level of 0.5. According to [Fornell and Larcker \(1981\)](#)([Aibinu and Al-Lawati, 2010](#)), the average variance extracted may be a more conservative estimate of the validity of the measurement model, and “on the basis of composite reliability alone, the researcher may conclude that the convergent validity of the construct is adequate, even though more than 50 % of the variance is due to error”. Since the composite reliability of the three constructs is well above the recommended level, the internal reliability of the measurement items is acceptable. The constructs’ considerable differences from one another are validated by discriminant validity. The Fornell-larger criterion, cross-loading, and Heterotrait–monotrait ratio (HTMT) were used to evaluate discriminant validity. As the diagonal elements in this study, the square root of AVE is greater than the off-diagonal correlation in the rows and columns, indicating that the Fornell-Larcker criterion is satisfied ([Table 3](#)) ([Fornell and Larcker, 1981](#)). If the measurement items’ outer loading on the corresponding construct is higher than the loadings of all other constructs, the cross-loading examination is considered successful. All measuring items have higher loading on their intended construct, according to the study’s cross-loading matrix results ([Table 4](#)). In summary, [Table 5](#) shows that the correlations’ HTMT was below 0.9, which is considered satisfactory ([Yang et al., 2023](#)) Thus, the cross-loading matrix, HTMT, and Fornell-Larcker criterion results are taken together to verify that the data’s discriminant validity is satisfied.

5.3. Structural model and hypothesis testing

The structured model (also known as the hypothetical model) was constructed in accordance with the study’s objectives to evaluate the links between the constructs and variables found in the responses ([Fig. 4d–f](#)). Tests were conducted on the hypothesis from two-step contexts, including the significance of direct route analysis with set variables, where the path coefficient significance was determined using 5000 bootstrapping samples. The PM mediation effects between SD and EoLs were then examined. To measure the structural model’s explanatory power, the R² value was used as a dependent variable ([Fig. 4g](#)). An R² value ranges from 0 to 1, with a higher value representing a higher level of accuracy in prediction.([Al-Emran et al., 2019](#)). The predictive validity is confirmed by the structural model, explaining 21.8 % of the variance in PM and 42.2 % of the variance in EoLs. Using t-statistics and the path coefficient (β), the study examines the relationship between the independent and dependent variables. According to [Table 6](#), there is a direct and positive significant relationship of SD on EoLs (β = 0.503, t = 8.155, p < 0.05), PM (β = 0.467, t = 6.445, p < 0.05) successively. Therefore, H1 and H2 are accepted. Likewise, there exists a positive correlation between PM and EoLs (β = 0.239, t = 3.080, p < 0.05). Thus, the hypothesis H3 is approved. As a result, wearable e-textiles with higher SD and PM capacity will be closely linked to EoLs.

5.4. Test for mediation effect

In compliance with recommendations ([Preacher and Hayes, 2008](#)), a mediation analysis was performed to assess the mediating role of PM on the linkage between SD and EoLs. Path coefficient direct path of the independent and mediating variable (i.e., iv-mv) and mediating and dependent variable (i.e., iv-mv) is used for negotiating effect analysis. The bootstrapping’s path coefficients were used to determine the importance of the signalling impact ([Hair Jr et al., 2014](#)). In addition, the size of the mediating effects has been assessed using the variance

Table 3
Latent variable descriptive, correlations, and discriminant validity.

	EoLs	PM	SD
EoLs	0.716		
PM	0.474	0.657	
SD	0.615	0.467	0.694

Table 4
Item cross-loading matrix of the constructs.

	EoLs	PM	SD
EoLs1	0.671	0.289	0.440
EoLs2	0.783	0.366	0.457
EoLs3	0.623	0.300	0.353
EoLs4	0.741	0.331	0.453
EoLs5	0.749	0.399	0.483
PM1	0.353	0.662	0.338
PM2	0.313	0.720	0.289
PM3	0.207	0.557	0.262
PM4	0.393	0.812	0.381
PM5	0.248	0.481	0.238
SD1	0.413	0.308	0.751
SD2	0.373	0.333	0.688
SD3	0.484	0.350	0.695
SD4	0.337	0.388	0.623
SD5	0.505	0.243	0.707

Table 5
Heterotrait–monotrait ratio (HTMT).

	EoLs	PM	SD
EoLs			
PM	0.658		
SD	0.815	0.672	

Table 6
Bootstrapping results for structural model evaluation.

Hypothesis	Path	Path coefficient	T statistics	P values	Decision
H1	SD -> EoLs	0.503	8.155	0.000	Accepted
H2	SD -> PM	0.467	6.445	0.000	Accepted
H3	PM -> EoLs	0.239	3.080	0.002	Accepted

accounted for (VAF). [Table 7](#) displays the mediating effect’s findings. The outcomes showed that the total effect of SD on EoLs was significant (β = 0.615, t = 10.483, p < 0.05). With the inclusion of the mediating variable (PM), the impact of SD on EoLs became significant (β = 0.503, t = 8.155, p < 0.05). The indirect effect of SD on EoLs through PM was found to be significant (β = 0.112, t = 2.554, p < 0.05). Although findings support the hypothesis of H4, this shows that the relationship between SD and EoLs is complementary-partial mediation by PM, as indirect and direct effects do not have opposite signs([Demming et al., 2017](#)). This means that PM explains some, but not all of the influence that SD has on EoLs. Complimentary-partial mediation by PM adds to the direct effect of SD on EoLs, providing additional insights into how SD influences EoLs. The VAF by the mediator (PM) is 18 %, which is relatively low. This indicates that while PM does mediate the relationship between SD and EoLs, it accounts for a relatively small portion of the total effect of SD on EoLs. The majority (82 %) of the effect is either due to the direct influence of SD on EoLs or potentially other factors not mediated by PM.

5.5. Analysis of the model’s significance

The structural model and hypothesis results highlight the significance of measurement items, indicating that advances in SD and PM capabilities are substantially correlated with improvements in the EoLs for wearable e-textiles by the acceptance of H1, H2 and H3. The significant direct effects of SD on PM and EoLs highlight how important the SD approach is to improving wearable e-textiles’ EoLs and PM capabilities. The results validate the proposed hypothesis (H4), demonstrating a specific relationship between SD and EoLs, with PM as a partial mediator. However, the mediation effect is relatively minor, with only 18 %

Table 7
Summary of mediation results.

Total effect (SD- > EoLs)		Direct effect (SD- > EoLs)		Indirect effects of SD on EoLs (H4: SD- > PM- > EoLs)				
Coefficient	p-value	Coefficient	p-value	Coefficient	SD	t-value	p-value	BI [5 %; 95.0 %]
0.615	0.000	0.503	0.000	0.112	0.044	2.554	0.005	0.041, 0.181

of the total effect impact EoLs being explained through PM. This indicates that while PM contributes to understanding how SD impacts EoLs, significant direct effects or other mediating factors are at play. The complementary nature of the mediation suggests that including PM in the model offers additional explanatory value beyond the direct relationship between SD and EoLs. The R^2 values support the model's constructs and relationships by showing that it successfully accounts for a sizable percentage of the variance in PM and EoLs. Due to the partial mediation by performance with a lower VAF, future research may examine additional mediators to understand the interplay between SD and EoLs better. Examining additional user experience elements or technological affordances that support learning outcomes may be necessary to achieve this.

6. Implications

6.1. Theoretical implications

The findings of the investigation greatly advance SD's theoretical knowledge of wearable e-textiles. This study adds to the knowledge of user-centred design and sustainable product development by directly connecting SD to advancements in PM and EoLs. Despite its small size, the partial mediation effect of PM offers a balanced viewpoint on how performance tracking contributes to achieving the advantages of SD. It suggests that these constructs are connected and worth further investigation. The validation of the hypothesis (H1, H2, H3, and H4) underscores the importance of incorporating SD principles from the outset to enhance the lifecycle and user engagement of wearable e-textiles. This aligns with and expands upon theories related to sustainable innovation and circular economy, emphasising the need for holistic approaches that consider both the environmental and user-centric aspects of product development.

6.2. Social implications

The findings of the investigation carry significant social implications (Fig. 5c), especially considering Sustainable Development Goals (SDGs)-12 (Responsible Consumption and Production) and 3 (Good Health and Well-Being). By encouraging the development of products that are not only environmentally friendly but also planned with their eventual disposal or recycling in mind, the correlation between SD and enhanced EoLs for wearable e-textiles addresses SDG 12 by lowering waste and promoting responsible consumption patterns. The study indirectly supports SDG 3 by emphasising how wearable e-textiles can support EoLs. This is because increased awareness and engagement with health-monitoring wearables can improve overall health and well-being. The need for advanced SD and PM capabilities essential for developing the next generation of smart textiles that are both ecologically sustainable and user-friendly, demonstrates the emphasis on innovation and sustainable infrastructure (SDG 9).

6.3. Managerial implications

From a managerial point of view, the study provides insightful information to businesses in the wearable e-textiles industry, especially those dedicated to innovation and sustainability, as emphasised in SDG 9 (Industry, Innovation, and Infrastructure). It is suggested that businesses incorporate SD principles at the forefront of their product development initiatives due to the undeniable connection between SD

and PM with EoLs. This entails reducing the adverse effects on the environment and maximising product performance and EoL recyclability or reusability. Even though the mediation effect is minimal, businesses should still consider how PM can act as a mediator between SD features and EoLs considerations. Beyond their environmental impact, consumers can receive additional value from sustainable wearable e-textiles when performance indicators are included in their manufacturing and marketing methods.

7. Conclusion

Gaining insight into the design strategy of current materials and methods as well as their performance and EoLs will propel scientific advancements emphasising cutting-edge device designs, recovery, and synthesis simplicity. Investigating wearable e-textiles' sustainable design dynamics, performance evaluation and EoL options in this work substantially contribute to the field's theoretical, social, and managerial knowledge of sustainability. The research highlights the potential of wearable e-textiles to play a significant role in achieving global sustainability objectives, notably in health, innovation, and responsible consumption, by aligning with key Sustainable Development Goals. The intricate interactions between these variables should be further explored in future studies to improve wearable technology's positive effects on society and the environment and to develop SD practices further.

CRedit authorship contribution statement

Marzia Dulal: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Shaila Afroj:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Nazmul Karim:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.145404>.

Data availability

Data will be made available on request.

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