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Investigating Properties of Electrically Conductive Textiles: A Review

Raziskave lastnosti elektroprevodnih tekstilij: pregled

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Abstract

Electro-conductive textiles are mostly fabrics that have conductive elements or electronics integrated into them to achieve electrical characteristics. They have acquired considerable attention in applications involving sensors, communications, heating textiles, entertainment, health care, safety etc. To produce electro-conductive textiles, several techniques, e.g. chemical treating with conductive polymers on various textile materials, or using different technologies, e.g. knitting, weaving, embroidery techniques to include conductive threads into fabric interconnections etc., are being used. Electro-conductive fabrics are flexible enough to be adapted to quick changes in any particular application, beginning with wearable purposes and sensing needs as specified by many different groups. The ability of electro-conductive textiles to conduct electricity is the most essential property they must possess. In addition, the applications that may be worn should have stable electrical, thermal and mechanical qualities. The most recent developments in the field of electro-conductive textiles represent the aim of this review, which analyses these properties, including the investigation of methods that are used to obtain conductive textiles, their electrical properties, thermal properties, and beyond that, the scientific methods that are used to measure and investigate electro-conductive textiles. We also focused on the textile materials used in studies, as well as the technologies used to make them conductive, which may be a guide for different interested groups for use in a variety of smart applications.
Keywords: electro-conductive textiles, electrical resistivity, electro-thermal behaviour

Izvleček

Elektroprevodne tekstilije so večinoma tekstilije, v katere so vgrajeni prevodni elementi ali elektronika za doseganje električnih lastnosti. Veliko pozornosti so pridobili v aplikacijah, ki vključujejo senzorje, komunikacije, grelne tekstilije, zabavo, varovanje zdravja in varnost. Za izdelavo elektroprevodnih tekstilij se uporabljajo številne tehnike, kot je kemična obdelava s prevodnimi polimeri na različnih tekstilnih materialih ali uporaba različnih tehnologij, kot so pletenje, tkanje, tehnike vezenja za vključevanje prevodnih niti v strukturo ploskovnih tekstilij idr. Elektroprevodne ploskovne tekstilije so dovolj upogibljive, da se lahko prilagodijo hitrim spremembam v kateri koli posebni aplikaciji, začenši z namenom nošenja in potrebami zaznavanja, ki jih določajo različne skupine. Sposobnost elektroprevodnega tekstila za prevajanje električnega toka je najpomembnejša lastnost, ki jo mora ta imeti. Poleg tega morajo aplikacije, ki so nosljive, imeti stabilne električne, toplotne in mehanske lastnosti. Namen tega pregleda je podati analizo najnovejšega razvoja na področju elektroprevodnih tekstilij, vključno z raziskavo metod, ki se uporabljajo za pridobivanje prevodnih tekstilij, njihovih električnih lastnosti, toplotnih lastnosti in poleg tega znanstvenih metod, ki se uporabljajo za mer-

jenje in raziskovanje elektroprevodnih tekstilij. Pregled se osredinja tudi na tekstilne materiale in tehnologije, ki so jih avtorji uporabili za dosego prevodnosti, kar je lahko vodilo različnim zainteresiranim skupinam za uporabo v različnih pametnih aplikacijah.
Ključne besede: elektroprevodne tekstilije, električna upornost, elektrotoplotno obnašanje

1 Introduction

Over the last decades, smart textiles have become popular as a concept. In order to manufacture wearable textile systems, electro-conductive textiles are needed. These textiles are materials which can conduct electric current [1]. They are made by means of different methods, e.g. using conductive fibres, yarns, coatings, polymers or inks, with the most common manufacturing techniques (cf. Figure 1) [2–4]. Furthermore, Figure 2 depicts the percentage of e-textile players who use various types of textile material.

Different conductive yarn manufacturers can be found on the market, and their growth and development have followed a traditional path. As new electro-conductive materials have become available on the market, manufacturers have found different ways of developing and improving the properties of conductive fibres and yarns [5–7].

As a building block for intelligent textile components, electrically conductive yarns must offer stable and reliable electrically conductive properties while maintaining textile properties, which ensure good processing and pleasant wearing comfort. The reliability and stability requirements may vary depending on the application.

Electro-conductive textiles can be made using traditional techniques, e.g. knitting, weaving, sewing and embroidering. When it comes to smart textiles that monitor vital functions and also need to be close to the human body, like a second skin, the knitting technology can be chosen [9–12]. The latter can provide a textile structure that can conform to the shape of our body by giving the wearer a comfortable feeling while moving freely. In this way, a knitted fabric can be stretched when subjected to a force and return to its original shape when the force is removed. When this technology combines textiles with electrically conductive materials, it is

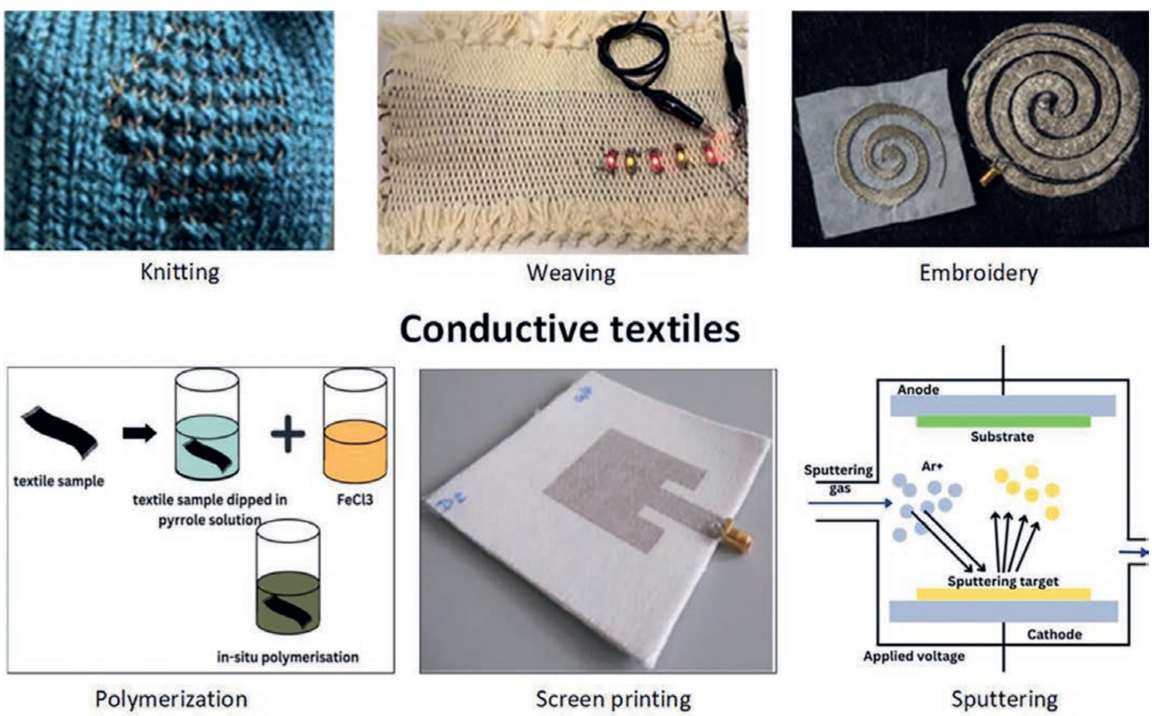

Figure 1: Different manufacturing techniques of conductive textiles:
a) knitting, b) weaving, c) embroidery. d) coating methods, d) screen printing, e) magnetron sputtering

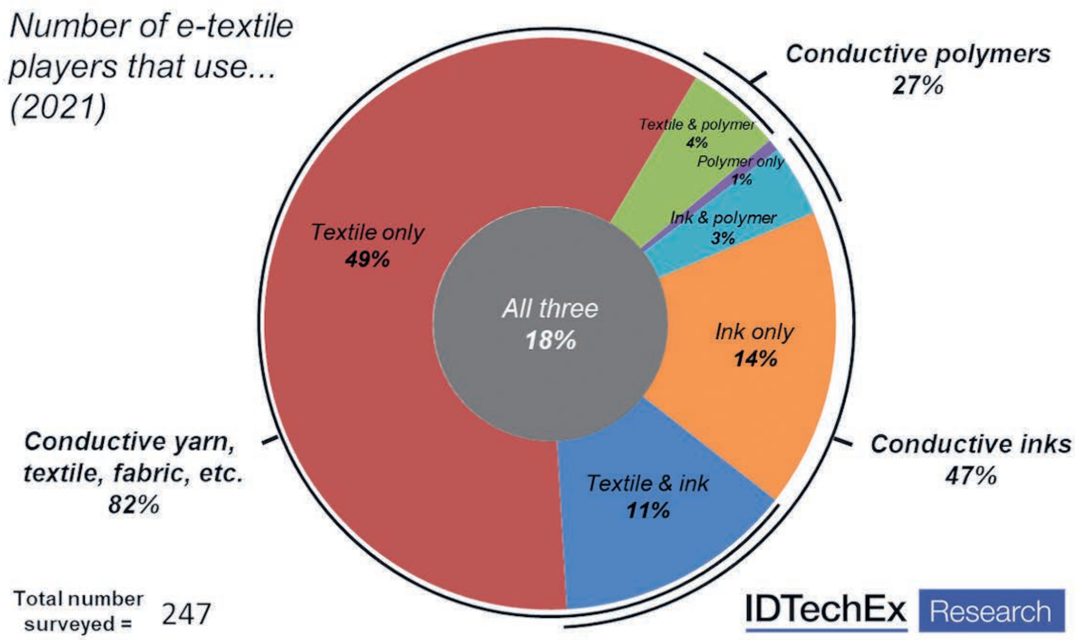

Figure 2: Percentage of e-textile players using different types of material (Image source: E-Textiles 2021–2031, IDTechEx Research [8])

important that the knitted fabric is combined with elastic yarn without loop formation during its use.

The second method to obtain conductive textiles is to chemically treat the fibres/yarns/fabrics to make them conductive. This can be achieved by coating them in different processes, e.g. electroless deposition, electroplating, physical vapour deposition (PVD), chemical vapour deposition (CVD) and conductive polymer coating, the latter being used more on textiles, which is the focus of this article. Conductive polymers, e.g. polypyrrole, polyaniline or polythiophene, are applied to textile surfaces with in situ polymerisation.

The first electronic textile introduced to the market was the ICD+ (Industrial Clothing Design Plus) jacket in 2000 by Levi Strauss & Co. and Philips Research Laboratories [13], which could house an MP3 player and a mobile phone. When the jacket goes into the washing machine for maintenance, all appliances and cords must be removed. From the textile point of view, the challenge for researchers (even nowadays) is to produce as many components as possible from textile materials. Therefore, it was necessary to develop electro-conductive textiles that can be obtained in several ways, e.g. by integrating conductive fibres or yarns, by applying conductive coatings or by using conductive inks [2, 4, 14].

Electro-conductive textiles have emerged as a new trend in recent decades. Based on the above, we study electrical and thermal properties of conductive textiles obtained with various chemical processes, in particular polymerisation, carbon-based technologies, or technologies such as knitting, weaving, embroidery, sewing and needle felting.

It is of crucial importance to study the properties of textile materials to predict their future applications, human comfort and lifespan due to aging factors. Table 1 shows a chronological overview of published work focusing on the properties of conductive textiles and their applications. The overview continues with the analysis of conductive fabrication process, methods of measuring electrical resistance, thermo-mechanical properties and modelling techniques as an approach to simulate the electrical behaviour of conductive textiles. In the end, the applications of conductive textiles as electrical devices, e.g. sensors and antennas, are mentioned.

Table 1: Chronological overview of papers published on electro-conductive textiles

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Hersh, S. P. 1952 [15]	Textile Research Journal	Electrical Resistance Measurements on Fibres and Fibre Assemblies	Poorly conducting hydrophobic synthetic fibres, such as nylon, Dynel and Dacron	Static electricity, resistance measurement
Azoulay, J. 1988 [16]	IEEE Transactions on Electrical Insulation	Anisotropy in Electric Properties of Fabrics Containing New Conductive Fibres	2/1 warp-faced twill fabric containing 10% new conductive fibre	Surface resistance measurement, anisotropy
Berberi, P. 1998 [17]	Textile Research Journal	A New Method for Evaluating Electrical Resistivity of Textile Assemblies	Textile assemblies	Electrical resistivity, volume resistivity
Meoli, D. 2002 [18]	Journal of Textile and Apparel, Technology and Management	Interactive electronic textile development: A review of technologies	Smart fabrics, interactive textiles	Review the possibilities to develop smart textiles
Tappura, K. 2003 [19]	Journal of Electrostatics	Computational modeling of charge dissipation of fabrics containing conductive fibres	Twenty different fabrics with base fabric cotton and polyester	Analyse electrostatic properties in conductive fibres and discharging properties
Kaynak, A. 2003 [20]	Polymer International	Effect of synthesis parameters on the electrical conductivity of polypyrrole-coated poly(ethylene terephthalate) fabrics	Coated fabrics polypyrrole, poly(ethylene terephthalate) (PET)	Conductive resistance measurement, temperature affection on conductivity
Xue, P. 2004 [21]	Textile Research Journal	Electromechanical Behavior of Fibres Coated with an Electrically Conductive Polymer	Polymer fibres coated with conductive polymer, polypyrrole (PPy). PPy-coated PA6 fibres and PPy-coated Lycra fibres	Electrochemical behaviour, electrical resistance, electromechanical model, resistance as function of strain, damage level, relative humidity, air temperature.
Dhawan, A. 2004 [22]	Textile Research Journal	Woven Fabric-Based Electrical Circuits: Part I: Evaluating Interconnect Methods	Fabric-based electrical circuits, woven textile structures	Develop fabric-based electrical circuits
Wu, J. 2005 [23]	Synthetic Metals	Conducting polymer coated lycra	Conducting polymer using pyrrole, nylon lycra	In situ polymerisation process is used to produce conductive polymer nylon lycra
Varesano, A. 2005 [24]	Polymer Degradation and Stability	A study on the electrical conductivity decay of polypyrrole coated wool textiles	Wool fibres coated with electrically conducting polypyrrole (PPy)	Electrical conductivity stability due to dry cleaning and other factors
Kim, B. 2006 [25]	Journal of Applied Polymer Science	Polyaniline-coated PET conductive yarns: Study of electrical, mechanical, and electro-mechanical properties	Conductive polymer and polyethylene terephthalate (PET) yarns, polyaniline (PANI)	Electrical, mechanical, and electro-mechanical properties of PET conductive yarns
Gasana, E. 2006 [14]	Surface and Coatings Technology	Electroconductive textile structures through electroless deposition of polypyrrole and copper at polyaramide surfaces	Polyaramide fabrics, metal coated textile fibres, pyrrole monomer	Polymerisation of polyaramide textile structures using polypyrrole combined with copper metallisation

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Wang, J. 2006 [26]	Journal of the Textile Institute	Thermal conductivity studies on wool fabrics with conductive coatings	Wool fabrics, PPy-coated, Anthraquinone-2-sulfonic acid (AQSA) sodium salt monohydrate 97% was the dopant and iron chloride hexahydrate ($FeCl3 \cdot 6H2O$) as the oxidising agent	Surface resistivity measurements, thermal conductivity measurements, investigation the relation between electrical conductivity and thermal conductivity
Asanovic, K. 2007 [27]	Journal of Electrostatics	Investigation of the electrical behavior of some textile materials	Textiles, wool, hemp, cotton, pan, flax, jute	Electrical behaviour, dielectric loss tangents and relative dielectric permeabilities
Locher, I. 2008 [28]	Textile Research Journal	Enabling Technologies for Electrical Circuits on a Woven Monofilament Hybrid Fabric	Woven fabric with embedded copper wires	Electrical proprieties, frequency transmission, transmission lines, electronic circuits
Banaszczyk, J. 2009 [29]	Quantitative InfraRed Thermography Journal	Infrared thermography of electroconductive woven textiles	Woven stainless steel sheet (Bekintex)	Current distribution modelling, anisotropy, IR thermography
Banaszczyk, J. 2009 [4]	FIBRES & TEXTILES in Eastern Europe	Current Distribution Modelling in Electroconductive Fabrics	Woven electroconductive textiles sheets	Model current distribution of woven conductive textiles using resistive networks
Latifi, M. 2010 [30]	Technical Textile Yarns	Electro-conductive textile yarns	Electro-conductive yarn, metallic fibre, electro-conductive polymers, composite fibres	Manufacturing process of electro-conductive yarns
Gu, J. F. 2010 [31]	Smart Materials and Structures	Soft capacitor fibres using conductive polymers for electronic textiles	Conductive polymer-based fibre	High capacitance fibres frequency analysation
Schwarz, A. 2010 [3]	Surface and Coatings Technology	Gold coated para-aramid yarns through electroless deposition	Para-aramid yarns, (Teijin Aramid). polypyrrole PPy and copper coatings	Gold, polypyrrole and copper coated para-aramid yarns proved to offer good electroconductive properties and endurable due to washing
Li, L. 2010 [32]	Textile Research Journal	A Resistive Network Model for Conductive Knitting Stitches	Conductive knitting yarn	Resistance of knitting yarn, electrical modelling
Ding, Y. 2010 [33]	ACS Applied Materials and Interfaces	Conductivity trends of PEDOT-PSS impregnated fabric and the effect of conductivity on electrochromic textile	Stretchable fabric (SPANDEX), cotton, polyester, Lycra, rayon were treated with PEDOT-PSS conductive polymer	Electrical conductivity measurements
Kazani, I. 2011 [34]	Textile Research Journal	Van Der Pauw method for measuring resistivities of anisotropic layers printed on textile substrates	Woven textile substrates, screen printed	Van Der Pauw method for electrical resistance measurement
Yoon, B. 2011 [35]	Fibres and Polymers	Designing waterproof breathable materials based on electrospun nanofibres and assessing the performance characteristics	Layered fabric structures based on electrospun nanofibre	Examine waterproofness and breathability performances

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Petersen, P. 2011 [36]	Textile Research Journal	Electronic textile resistor design and fabric resistivity characterization	Highly conductive metallic coated thread knitted into fabric	Electrical resistance characterisation for different knitting methods
Kacprzyk, R. 2011 [37]	Fibres and Textiles in Eastern Europe	Measurements of the volume and surface resistance of textile materials	Textile materials	Surface and volume resistance measurement
Patel, P. C. 2012 [38]	IEEE International Conference on Power System Technology, POWERCON	Applications of electrically conductive yarns in technical textiles	High conductive fibres, metal fibres, electro-conductive yarns etc.	Electromechanical properties of conductive yarns and fibres
Tokarska, M. 2013 [39]	Indian Journal of Fibre and Textile Research	Measuring resistance of textile materials based on Van der Pauw method	Electro-conductive Shieldex® fabric	Van Der Pauw resistance measurement, surface resistance measurement, anisotropy
Yen, R. H. 2013 [40]	International Journal of Numerical Methods for Heat and Fluid Flow	Numerical study of anisotropic thermal conductivity fabrics with heating elements	Electrically conductive yarns	Numerical analysis, temperature control, temperature uniformity
Hamdani, S. 2013 [41]	Materials	Thermo-mechanical behavior of textile heating fabric based on silver coated polymeric yarn	Conductive silver yarn	Heating of conductive textiles, thermography of conducting elements, heating due to knitting methodology
Tokarska, M. 2013 [42]	Journal of Materials Science: Materials in Electronics	Electrical properties of flat textile material as inhomogeneous and anisotropic structure	Electro-conductive plain-weave polyester woven fabric	Electrical resistance as function of electrode placement, electrode properties
Odhiambo, S. 2013 [43]	Mixed Design of Integrated Circuits and Systems	Comparison of Commercial Brands of PEDOT : PSS in Electric "Capattery" Integrated in Textile Structure	PEDOT:PSS are used in making "capatteries" and Ag coated yarns and stainless steel filament yarn used as electrodes	Measuring discharging characteristics of capattery
Stoppa, M. 2014 [44]	Sensors	Wearable electronics and smart textiles: A critical review	Conductive fabrics, Smart textiles	Reviewing materials, methods of manufacturing, energy consumption, ergonomics etc.
Wegene, J. 2014 [45]	Industrial and Engineering Chemistry Research	Conducting leathers for smart product applications	Conductive leather	Infrared spectroscopy, Fourier transform, electron microscopic analysis
Capineri, L. 2014 [46]	Procedia Engineering	Resistive sensors with smart textiles for wearable technology: From fabrication processes to integration with electronics	Conductive fabrics using copper wire, steel wire	Fabrication of smart textiles, sensors
Tokarska, M. 2014 [47]	Autex Research Journal	Determination of fabric surface resistance by Van der Pauw method in case of contacts distant from the sample edge	Antioxidant silver fibre shielding rip-stop fabric, silver fibre shielding canvas fabric	Surface resistance measurement, Van der Pauw, electrode placement

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Usma, C. 2015 [48]	Procedia Technology	Fabrication of Force Sensor Circuits on Wearable Conductive Textiles	Sn-Ag-Cu (SAC) plated Nylon fabric	Fabrication possibilities of pressure sensors based on conductive textiles
Vásquez Quintero, A. 2015 [49]	Procedia Engineering	Capacitive strain sensors inkjet-printed on PET fibres for integration in industrial textile	PET fibres	Printed strain sensors, sensor measurement
Arogbonlo, A. 2015 [50]	Procedia Technology	Design and Fabrication of a Capacitance Based Wearable Pressure Sensor Using E-textiles	Zell sensor; a Tin/Copper over Silver (Sn/Cu/Ag)-(SAC) plated Nylon Fabric – Shieldex – U.S	Analysis of design parameters for pressure sensor
Felczak, M. 2015 [51]	Fibres and Textiles in Eastern Europe	Lateral and perpendicular thermal conductivity measurement on textile double layers	Fleece produced from blends of 40% flax, 40% steel and 20% polyester	Thermographic measurements, theoretical model and experimental measurements
Lipol, L. 2016 [52]	European Scientific Journal	The Resistance Measurement Method of the Conducting Textiles	Conductive threads through adding: Metal, Carbon, Polyaniline (PANi) – Poly (3, 4-ethylenedioxythiophene) (PEDOT) – Polypyrrole (PPy)	Two and four probe resistance measurements
Karim, N. 2017 [53]	ACS Nano	Scalable Production of Graphene-Based Wearable E-Textiles	Conductive graphene textiles	Sheet resistance and electrical proprieties due to different factors such as washing, mechanical stability analysis
Bahadir, S. 2017 [54]	Textile Research Journal	Modelling of surface temperature distributions on powered e-textile structures using an artificial neural network	Conductive textile yarns, stainless steel, Silver plated PA	Temperature distributions modelling, artificial neural network
Ryan, J. D. 2017 [55]	ACS Applied Materials and Interfaces	Machine-Washable PEDOT:PSS Dyed Silk Yarns for Electronic Textiles	Degummed silk yarn and cotton yarn were treated with water dispersion of PEDOT:PSS	Produced and tested a high conductive silk yarn which was durable to washing and dry cleaning
Alhashmi A., F. 2017 [56]	Journal of Alloys and Compounds	A simple method for fabricating highly electrically conductive cotton fabric without metals or nanoparticles, using PEDOT:PSS	Cotton fabric treated with PEDOT:PSS	Investigating conductive fabric surface morphology, electrical resistance measured using four line probe
Nuramdhani, I. 2017 [57]	Materials	Electrochemical impedance analysis of a PEDOT: PSS-based textile energy storage device	Textile-based energy storage device treated with PEDOT:PSS stainless-steel electro-conductive yarn as the electrodes	Cyclic Voltammetry, electrochemical impedance analysis, equivalent electric circuit model simulation
Chaves, F. A. 2018 [58]	Nanotechnology	Mechanical, in-situ electrical and thermal properties of wearable conductive textile yarn coated with polypyrrole / carbon black composite	Bare and coated cotton yarn using polypyrrole/carbon black composite	Electrical properties measured with a source meter in conjunction with the KickStart Software to obtain resistance, resistivity, and conductivity, thermal conductivity was measured using Transient Hot Bridge

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Lund, A. 2018 [59]	Materials Science and Engineering R: Reports	Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials	Fibres and yarns treated to be conductive using conjugated polymers and carbon materials	Reviewing possible technologies, methods and properties of conductive textiles treated with conjugated polymers and carbon materials including areas of application
Hughes-Riley, T. 2018 [60]	Fibers	A historical review of the development of electronic textiles	Electronic textiles, smart textiles	Chronological review of e-textiles and their applications, mainly sensors and technological approaches
Chatterjee, K. 2019 [61]	Fibres	Electrically conductive coatings for fibre-based E-Textiles	Conductive polymers	Fabrication process of electrically conductive textiles
Mohamed, A. A. 2019 [62]	Journal of Textile and Apparel, Technology and Management	Suitability of conductive knit fabric for sensing human breathing	Silver coated Polyamide (Nylon) Fibre (Ag/ Nylon); yarn count 70 denier ratio of silver to Nylon is 20%–80 %	Electrical resistance measurement, human breathing simulator design
Shabani, A. 2019 [63]	Textile & leather review	Resistivity behavior of leather after electro-conductive treatment	White sheep crust leather coated pyrrole, ferric chloride, anthraquinone –2-sulfonic acid sodium salt monohydrate	Volume resistance measurement, relation of resistivity and air humidity
Shabani, A. 2019 [64]	Textile & leather review	The anisotropic structure of electro conductive leather studied by Van Der Pauw method	White sheep crust leather coated pyrrole, ferric chloride, anthraquinone – 2-sulfonic acid sodium salt monohydrate	Surface resistance measurement, Van Der Pauw, anisotropy
Akbarpour, H. 2019 [65]	Journal of Nanostructure in Chemistry	Comparison of the conductive properties of polyester/viscose fabric treated with Cu nanoparticle and MWCNTs	Polyester/viscose fabric treated with nanoparticles MWCNT and Cu	Treated fabrics using nanoparticles, conductivity test, electrical resistance, strength and voltametric charts
Hardianto, H. 2019 [66]	Journal of Engineered Fibres and Fabrics	Textile yarn thermocouples for use in fabrics	Nickel-coated carbon fibre adding stainless steel yarn, polypyrrole-coated carbon fibre, or carbon fibre	Different conductive textile yarns were tested to use as thermocouple and thermopile
Kamyshny, A. 2019 [67]	Chemical Society Reviews	Conductive nanomaterials for 2D and 3D printed flexible electronics	Printed nanomaterials, ink-based metal nanoparticles	Reviewing materials and methods used to incorporate into 2D and 3D printed electronic textiles
Nuramdhani, I. 2019 [68]	Polymers	Charge-discharge characteristics of textile energy storage devices having different PEDOT:PSS ratios and conductive yarns configuration	Twill woven polyester-cotton fabric treated with PEDOT:PSS, two types of conductive yarn, firs is pure stainless steel and silver-coated polybenzoxazole (Ag-PBO) used as electrodes	Electrical characterisation charge and discharge measured using microcontroller
Lund, A. 2020 [69]	Journal of Power Sources	A polymer-based textile thermoelectric generator for wearable energy harvesting	Wool fabrics treated with conducting polymer: polyelectrolyte complex poly(3,4ethylenedioxy-thiophene): poly(styrene sulfonate) (PEDOT: PSS)	Electrical conductivity measurements, thermal resistance, design thermoelectric generators

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Afroj, S. 2020 [70]	Advanced Functional Materials	Highly Conductive, Scalable, and Machine Washable Graphene-Based E-Textiles for Multifunctional Wearable Electronic Applications	Graphene-based e-textiles	Analysation for electronic applications
Tseghai, G. B. 2020 [71]	Sensors	PEDOT:PSS-based conductive textiles and their applications	PEDOT:PSS and composites	Analysing possible applications of PEDOT:PSS conductive textiles, methods of treatment for producing conductive textiles
Hylli, M. 2020 [72]	IOP Conference Series: Materials Science and Engineering	The color fastness properties of conductive leather improved by the use of mordants	Leather samples using mordant FeSO4, Na2SO4 × 10 H2O	Colour fastness, Surface resistance, dry rubbing
Krifa, M. 2021 [73]	Textiles	Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas	In situ polymerisation of aniline on nylon, Electrospun doped PANi, PPy/PPTA fibres	Electrical conductivity, application-based textiles antennas
Angelucci, A. 2021 [74]	Sensors	Smart textiles and sensorized garments for physiological monitoring: A review of available solutions and techniques	Conductive fibres and filaments	Reviewing applications of smart textiles to different wearable sensor applications
Jin, I. S. 2021 [75]	Polymers	A facile solution engineering of PEDOT: PSS-Coated conductive textiles for wearable heater applications	Microfibre fabric (Welcron, nylon/polyester splitting yarn) was treated using PEDOT:PSS	Electrical sheet resistance was measured using four probe method, temperature distribution was measured using the thermal camera, crystalline properties were measured by an X-ray diffraction instrument
Shakeri V. 2021 [76]	Journal of Industrial Textiles	Highly stretchable conductive fabric using knitted cotton/lycra treated with polypyrrole / silverNPs composites post-treated with PEDOT:PSS	Cotton/lycra stretchable fabric is treated polypyrrole (PPy), silver nanoparticles (SNPs) composites, and post-treating PEDOT:PSS	Linear four probe method was used to measure electrical resistance, morphology of fabrics and fibres cross-section observed with a field emission scanning electron microscopy
Rogale, S. 2021 [77]	Materials	Measurement method for the simultaneous determination of thermal resistance and temperature gradients in the determination of thermal properties of textile material layers	M3 Fabric upper-side: 100% polyester; membrane: polytetrafluoroethylene; fabric inner-side: 100% polyester fleece M4 (100% polyester) M5 (lining: 100% polyester; membrane: 100% polypropylene; padding: 100% polypropylene) M6 (100% polyester micro-fleece)	Thermal proprieties, electrical resistance, temperature gradients

First author, published year, ref.	Journal/ Conf.	Title	Conductive type	Methodology
Kaynak, A. 2021 [78]	Materials	Electrothermal modeling and analysis of polypyrrole-coated wearable e-textiles	Polypyrrole coated fabric	Thermal modelling, surface resistivity
Adak, B. 2021 [79]	Journal of Textile Science & Fashion Technology	Utilization of Nanomaterials in Conductive Smart-Textiles: A Review	Conductive textiles, Graphene, MXene, Polymer nanocomposite	Review of nanomaterials used in conductive textiles
Wang, P. 2022 [80]		Fabrication of durable and conductive cotton fabric using silver nanoparticles and PEDOT:PSS through mist polymerization	Cotton fabrics are coated using silver nanoparticles and PEDOT:PSS	Surface electrical resistance measured according to the AATCC-76–2005
Luo, Y. 2022 [81]	Journal of the Korean Society of Clothing Industry	Fabrication of Electro-conductive Textiles Based Polyamide/ Polyurethan Knitted Fabric Coated with PEDOT:PSS/Non-oxidized Graphene	Knitted fabric treated with PEDOT:PSS/Non-oxidised Graphene	Four probe method was used to measure sheet electrical resistance, tensile properties were evaluated
Penava, Ž. 2022 [82]	Materials	Heat as a Conductivity Factor of Electrically Conductive Yarns Woven into Fabric	Silver-coated conductive yarns were weaved in woven fabric using different techniques	Sample heat dissipation was investigated as function of applied voltage and also it was investigated the change of electrical resistance influenced by temperature change
Repon, R. 2022 [83]	Polymers	Effect of Stretching on Thermal Behaviour of Electro-Conductive Weft-Knitted Composite Fabrics	Weft-knitted composite fabrics with silver coated polyamide multifilament yarns	Temperature measures as function of stretching, applied voltage as function of time
Alamer, F. 2022 [84]	Nanomaterials	Overview of the Influence of Silver, Gold, and Titanium Nanoparticles on the Physical Properties of PEDOT:PSS-Coated Cotton Fabrics	Cotton fabrics coated with PEDOT:PSS	Reviewing applications and technologies used in e-textiles formed by PEDOT:PSS coatings of cotton
Kalaoglu-Altan, O. 2022 [85]	iScience	Improving thermal conductivities of textile materials by nanohybrid approaches	Passive conductive textiles	Reviewing methods for producing passive conductive textiles to improve thermal conductivity
Tokarska, M. 2022 [86]	Materials	A Mixing Model for Describing Electrical Conductivity of a Woven Structure	Polyamide woven fabric; nickel and copper metalized, polyester woven fabric; nickel metalized and polyester woven fabric; nickel metalized	Investigating Archie's law as it can be used to describe electrical conductivity of woven textiles
Abou Taleb, M. 2022 [87]	Journal of Industrial Textiles	Facile development of electrically conductive comfortable fabrics using metal ions	Wool, polyester, and wool/ polyester fabrics were treated with two metal salt solutions, 0.005 M $CuSO_4$5H2O and 0.005 M AgNO3 and 0.01 M nano-ZnO	Scanning electron microscopy, energy dispersive X-ray, Fourier transform infrared and atomic absorption spectroscopy, AC electrical conductivity, air and water permeability

2 Electro-conductive textiles

Conductive textiles can be made by using conductive fibres, yarns, coatings, polymers or by applying inks to textiles. All smart textile components require to some extent electro-conductive materials, which can be conductive yarns or fabrics. These conductive yarns serve as a functional material forming the basis for the functionality of the whole smart textile system.

Electro-conductive fibres/yarns can be divided into two main groups:

a) Fibres/yarns which are applied in forms such as conductive wires

These can be pure metals, mainly silver, copper and stainless steel, produced with methods such as wire drawing, bundled wire drawing, cutting production, melt spinning and melt extraction [88].

Metal fibres have several advantages, including their strength, composition, biological inertness and immediate availability in textile form at low production costs. They are unaffected by washing or sweating due to its inertness. However, they are unable to deliver homogeneous heating and their brittle nature can cause long-term damage to the spinning machinery [44].

b) Fibres/yarns chemically treated to be conductive

Metal-based fibres, as mentioned above, have highest conductivity, but are not stretchable enough and by using more elastic interconnects, conductivity decreases. The second group of fibres/yarns is coated using conventional conductive polymers, galvanic substances or metallic salts. The most commonly used coating processes are electroless plating, evaporative deposition, sputtering and coating with conductive polymers. Although conductive textiles can be obtained also by treating the surface of traditional textiles, which can be achieved by coating them with polymers such as polypyrrole [4], deposited onto the surface of textile substrates or by printing with conductive inks and forming a conductive layer. Polypyrrole (PPy) is an organic conductive polymer formed with a chemical or electrochemical polymerisation of pyrrole. The polymerisation solution contains a monomer, dopant and oxidising agent to start the polymerisation of monomers. Different textile materials have been used to produce polypyrrole-coated textiles obtained with chemical reaction, e.g. polyester [89], polyamide [20, 90] cotton [91] and wool [92]. Different methods follow in chemical polymerisation. While often a two-step polymerisation has been the method of choice [23, 90, 91, 93], in situ polymerisation [73, 94] and emulsion polymerisation [95] are applied as well. Polyaniline has been applied as a coating on polyester and polyamide fabrics via in situ polymerisation [96]. Moreover, a two-step polymerisation of aniline on fabrics is commonly used [97]. Possible techniques are also a chemical coating with conducting polymers [98] or a reinforcement of polymeric materials with conductive compounds via spinning [99].

Furthermore, one of the most explored conventional conductive polymers is also polystyrene sulfonate (PEDOT:PSS). This polymer was used by Ding et al. [33] to treat stretchable fabrics by soaking them into a conductive polymer, resulting in the concentrate being homogeneously dispersed on the fabrics. Stretchable cotton textiles post-treated with PEDOT:PSS were investigated in [76]. Moreover, Ryan et al. [55] tested PEDOT:PSS to produce high conductive silk yarns, which were good for e-textile used in different applications, retaining conductive properties also after several washing cycles. In addition, the washing durability of conductive textiles treated with PEDOT:PSS was investigated in [100]. Furthermore, cotton fabrics have been treated using PEDOT:PSS to produce electrically conductive textiles by various authors [56, 69, 80, 84]. The applications of commercially available PEDOT:PSS as a potential to produce energy storage and capacitors from electro-conductive textiles were studied [43]. The energy storage devices gained from textiles treated with PEDOT:PSS were the subject of research in [57, 68], where the obtained devices acted as capacitors and their electrical characteristics in charging and discharging were studied.

Tseghai et al. [71] offered a comprehensive overview of most state-of-the-art applications, of electro-conductive textiles, which are treated with PEDOT:PSS and their composites, and also an overview of treatment methods.

– *Carbon-based conductive materials*

Traditional conductive fabrics like metallic filaments and conducting polymers have several drawbacks. Different research groups have combined carbon-based conductive materials with textile materials, as it will be described below.

Due to its high electrical conductivity, enhanced mechanical qualities, environmental stability and potential for low-cost manufacture, the most widely used carbon-based material for electro-conductive textiles is graphene. Graphene was used in [101], where the authors investigated graphene-coated cotton fabrics to obtain low-cost and high conductive cotton-based homogenous nano sheets for further use in smart textile applications. Furthermore, cotton-based fabrics were analysed in [102], where they were treated with graphene oxide (GO) and reduced graphene oxide (rGO) to produce antibacterial electro-conductive textiles. This resulted in Ag^0/rGO-coated samples not developing bacterial growth.

Recently, there has been a surge of interest in producing conductive smart textiles by incorporating active conductive nanoparticles into textiles. Due to their high electrical and thermal conductivity, particular emphasis has been placed on carbon-based nanomaterials, i.e. carbon nanotubes (CNTs). These are found in a variety of diverse and critical applications, including nano-electronic devices, nano-scale structural materials, actuators and sensors, functional fabric and e-textiles etc., which is due to their exceptional properties, i.e. mechanical, thermal and electrical behaviours. In the textile industry, CNTs are used in the production of conductive fibres and yarns with different techniques [30], e.g. electro-spun fibre [103, 104], electrophoretic spun fibre [105], recondensed fibre [106], solution spun fibre [107], melt spun fibre [108].

Another common conductive material is also carbon black, which is a low-cost material easy to fabricate [109]. Gültekin et al. [110] investigated the electrical and thermal properties of carbon black coated cotton fabric by achieving conductivity increase. Besides, carbon black and PPy were used together to coat cotton fabrics by Chaves et al. [58], where they investigated mechanical and electrical properties focusing on the production of durable samples for use in real world applications.

An outstanding review of fabrication procedures of common carbon-based electronic materials and relevant applications was presented in [109]. Moreover, carbon-based nanomaterials applied in e-textiles were reviewed in [59, 79, 111, 112].

– *Conductive inks printed on textile surface*

Printing using conductive inks is another method, which has found usage in a variety of applications in the electronics area – not only at the beginning of smart/intelligent textiles, but this technique was also used to produce conductive fabrics. There are different textile printing methods that can be used, e.g. rotogravure, offset lithography, flexography, screen and inkjet printing technologies [18, 73]. Printing electrical traces directly on a fabric is a versatile method that occasionally displays its shortcomings, e.g. the thickness of the silver paste during the printing is one of its limits. Most of the applications, especially on textiles, are limited to screen and inkjet printing as they are very good for low volume and high-precision work. Although inkjet printing offers greater design versatility and production flexibility, screen printing is more economic and covers a huge range of products.

3 Resistance measurement methods

The electrical resistance of materials is related to other electrical properties like voltage and current, while the surface resistivity is the resistance to current leakage along the surface of an insulating material. The most common method to measure the resistance is the two probe method as shown in Figure 3a, where the voltage drop between two electrodes is measured as an effect of the applied known current. However, this method has drawbacks due to neglecting the contact resistance of electrodes. Consequently, four probe techniques come into play. There are two types of these techniques, i.e. linear placement and peripheral placement. Wenner [129] found and resolved the issue of neglecting contact resistance by proposing an inline four probe geometry technique to decrease the electrode contact resistance, as it can be seen in Figure 3b. The method using four probes circumferentially along the sample was proposed by Van Der Pauw [114]. Initially, this method was devoted to any arbitrary shape surface resistance measurement, while later, this method was adopted by many authors in order to measure electrical resistance of conductive textiles, as given in Figure 3c. An improvement of the measurement accuracy can be achieved by applying a correction factor to asymmetrical samples.

The problem of measuring electrical resistance of textiles began with issues caused mostly by the static electricity, this leading to many problems, even when the processed fibres were natural, e.g. cotton, wool, silk and flax, which are hydrophilic and have moderate conductivity. With the advent of poorly conducting hydrophobic synthetic fibres, e.g. nylon,

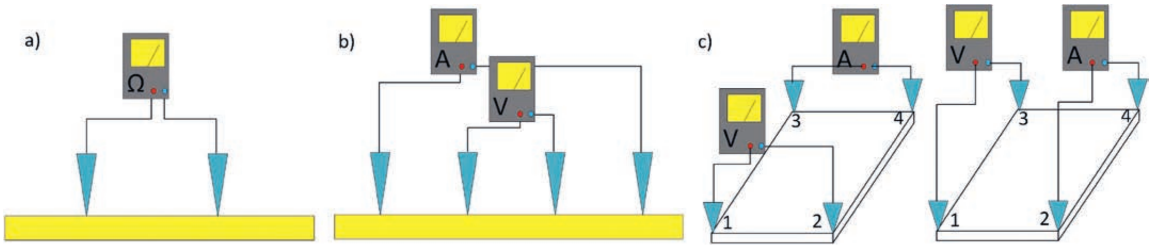

Figure 3: Surface resistance measurement methods: a) two probes, b) linear four probes, c) Van Der Pauw

Dynel and Dacron, the effects of static electricity changed from a minor to a major problem, as described by Hersh and Montgomery [15]. They used a novel apparatus to study the electrical resistance of a textile fibre and fibre assemblies to investigate the effects of static electricity in fibrous materials. Electrostatic properties of natural fibres were investigated under various environmental conditions, discovering that the electrical properties of those fibres are highly dependent on the moisture content of the material.

Volume resistivity is the resistance to the flowing current through the body of an insulating material, and in the case of textile materials with a very rich structure and highly developed surface, measurements of volume and surface resistances (measured in a two-electrode system) should correlate with each other. The basis for such a correlation may be the assumption that a conduction current (volume or surface), measured in a two-electrode system, flows through the bulk material [115]. Another novel method for evaluating the electrical properties of textile assemblies was proposed by Berberi [17], where the proposed idea was a novel multi-step method for assessing electrical resistance. He has developed a novel probe for measuring resistance that makes use of the material's volume fraction properties. Also, this novel probe was used to measure the electrical properties of electro-conductive leather and by applying this multi-step method, it was concluded that the electrical properties of conductive leather were not influenced by the sample form [63]. The measurement of surface and volume resistance of textile materials was discussed by Kacprzyk et al. [37], who compared various electrode placement systems in order to measure the resistance.

The methods mentioned above focused on the electrical properties of textile fibres; however, most of the existing researches measure surface resistance due to their application purposes. Furthermore, the conductivity of threads was studied by Dhawan et al. [22] and they developed efficient conductive threads by interconnecting them orthogonally. The aim of their research was to reduce the DC resistance associated with interconnections, which was achieved by trying different materials and a specific bonding/welding procedure. The interconnecting resistance was measured using a DC multimeter. They found that the welding procedure was the most effective in producing efficient and uniform interconnections.

On the other hand, determining the electrical resistance of textile samples with various forms and raw material compositions was challenging for Asanovic et al. [27], who developed a measuring device based on direct current measurement through textile samples. Dielectric loss tangents and relative dielectric permeability for textile samples were measured by using specially capacitance cells. Their study results showed that the resistance of textile materials was strongly dependent on their absorbed moisture.

On the other hand, the ageing of conductive fibres coated with electrically conducting doped polypyrrole (PPy) plays an important role in electrical and thermal characteristics, which was investigated by Varesano et al. [24], who used simulated ageing tests. They evaluated performance decay during the processing stages and final product used, and their findings indicated that the fabrics made of PPy coated wool fibres had acceptable conductivity decay.

Similarly, hybrid yarns were in focus of various publications, e.g. Šafářová et al. [115] tried to develop models that describe the dependence of electrical resistivity R on wire length L. They concluded that this behaviour was highly nonlinear and in contradiction with metals.

As already mentioned, the most commonly used resistance measurement methods are the two and four probe. Lipol et al. [52] investigated two and four terminal methods for the novel conducting threads, concluding that the two terminal method was more informative than the four terminal method, and that the latter had no advantage over the former.

Another method for measuring sheet resistance is the so-called Van Der Pauw method, which was used in the case of electro-conductive textiles by various researchers [34, 39, 47, 64, 116, 117]. Tokarska et al. [39] investigated the contact diameter of electrodes and their arrangement on sample edges, while their main focus was the proper placement of electrodes. This research was extended and exploited more by this group [42], as they conducted a multivariant research on electrical properties of woven fabrics.

Furthermore, the Van Der Pauw method was used to investigate the electrical properties of conductive woven fabrics, analysing the effect of electrode placement on resistance measurements, concluding that surface resistance was a function of electrode placement. During the investigation of surface resistance by applying the Van Der Pauw method, authors also investigated homogeneity and anisotropy. Anisotropy was also studied by Azoulay et al. [16], who focused on the electrical properties of textile fabrics and measured the surface resistivity in various directions, revealing an anisotropy effect attributed to the sample weave pattern. The anisotropy structure of screen printed textiles was studied by Kazani et al. [34], who measured the electrical surface resistance of screen printed textiles by using the Van Der Pauw's method, which showed the anisotropic behaviour of electro-conductive textiles.

Apart from the conductive textile materials mentioned above, Shabani et al. [64] recently focused on electro-conductive leather, where the Van Der Pauw method was used to measure the electro-conductive properties. It was concluded that a different electrode placement along the sample circumference revealed the anisotropic structure of samples.

The anisotropy behaviour of conductive textiles together with other properties, e.g. electrical or thermal, was studied by various groups [29, 37, 40, 51, 63, 104, 109, 118].

4 Electro-thermal proprieties

Conductive textiles are widely used to provide comfort to humans, from heating to life monitoring functions. Thus, investigating the electro-thermal properties of conductive textiles plays an important role in their applicability. Many research groups that have investigated conductive textiles have found a strong relation of thermal conductivity with electrical conductivity. Similarly, Wang et al. [26] evidenced that increasing electrical conductivity by coating a wool fabric with PPy led to an increase in thermal conductivity. The correlation between the heat conductivity and electrical conductivity of PPy-coated wool textiles was investigated, demonstrating that when these materials were coated with conductive PPy to create electro-conductive textiles, their thermal conductivity improved. Meanwhile, the heat dissipation caused by an electric current flow at certain voltages was studied by Penava et al. [82], observing how heat influences the changes in the electrical resistance of electro-conductive yarns. It was concluded that the temperature change in conductive yarns resulted due to the contribution of an external source or due to the passing electric current in a linear change in the resistance of conductive yarns. Moreover, the temperature distribution and heat generation for stretchable conductive textiles used for medical purposes was investigated in [83]. The research revealed that the required temperature of 40 °C was achieved within 2–3 minutes, but the increase of sample surface had a negative impact on heat generation.

The thermal properties of knitted structures, their manufacturing methods and the effect of contact pressure at structural binding points on the degree of heating were analysed by Hamdani et al. [41]. They were interested in analysing generated heat as a function of distance between the supply terminals and yarn decay properties due to the heating. By taking thermographic images, they discovered that knitted fabrics, with silver and elastomeric yarn, can generate enough heat to warm the body. Moreover, the thermography was used to analyse the woven conductive textiles for the non-homogeneity and anisotropy, using the modelling and infrared thermography to analyse the contact resistance [29].

Furthermore, the temperature distribution was investigated by Felczak et al. [51] for a double-layered fleece textile by studying the thermographic measurements. They developed a theoretical model and compared it to experimental data.

Designing technically comfortable electro-thermal textiles has been a challenging task due to the lack of adequate measurement devices and methods.

Consequently, Rogale et al. [77] developed a new measuring device and method for simultaneous measurements to determine the thermal resistance in one or more textile material layers, e.g. multilayer composite clothing, where the temperature gradients of textile material layers, as well as the theoretical principles of operation and practical results were presented. The analysis of electrical properties sensing behaviour and the mechanical analysis of polymer fibres coated with an intrinsically conductive polymer, and their electromechanical behaviour under tensile load was performed experimentally by Meoli et al. [18]. The investigated electromechanical behaviour of these conductive fibres showed a correlation of various mechanical and environmental factors with electrical resistance.

The heat transfer properties of anisotropic conductive textiles analysed by Yen et al. [40], revealed that by employing non-electric high effective thermal conductive yarns perpendicularly to the electro-conductive yarns increases temperature distribution uniformity. In order to analyse the heating fabric, a numerical program based on a spectral element method was used. The investigation of textiles does not focus only on electro-thermal properties. Reiners et al. [119] also considered cutting resistance. Meanwhile, for the textiles such as tarpaulin fabrics used to protect against vandalism, it was determined based on the analysis that in addition to cutting resistance, the tearing strength and the seam slippage should be tested.

Prior to experimentally analysing the thermal distribution of conductive textiles, the temperature distribution in textile materials was modelled as an effect of single laser pulse treatment using simulation software. The surface heat sources were modelled for different shapes in Comsol Multiphysics to verify experimental results [120]. Similarly, the modelling was used by Banaszczyk et al. [4] to analyse current distribution in conductive textiles. They used a large electrical resistor network to investigate contact resistance, surface resistance and also homogeneity of the structure. The research results showed that this method was able to measure current distribution using modelled prototype, as it was difficult for direct measurements. A similar methodology was used, again by Banaszczyk et al. [29], where the modelling method was compared with the four probe method to measure the contact resistance of conductive textiles. The results gained from both methods were complementary to each other. Moreover, Wai et al. [32] developed a resistive network to analyse the electrical resistance of knitting stitches, concluding in simulated results being comparable with experimental results. The modelling methods mentioned above were based on software or electrical modelling, while Bahadir et al. [54] applied Artificial Neural Networks to derive surface temperature distribution of conductive textiles. Based on this research, not only that the temperature distribution can be analysed, but also the sample temperature distribution can be predicted. Conductive fibres can cause problems due to the electrostatic charge. To analyse these behaviours, theoretical modelling was applied by Tappura et al. [19], showing that the induced charge was a strong correlation of base material conductivity and dielectric properties.

Passive electro-conductive textiles were investigated in [85], where an overview of most commonly used methods and materials used to improve the thermal conductivity of samples was presented.

5 Smart applications of electro-conductive textiles

Smart textiles, known as electronic textiles (e-textiles), incorporate electronic components in order to perform different functions. Thereby, using electrical, thermal, mechanical, chemical, magnetic, and other inputs and outputs, they can perform the following functions:

– *Passive smart textiles:* they can sense sensor outputs from user or environment.
– *Active smart textiles:* they can integrate a sensing device to control actuator behaviour.
– *Very smart textiles:* they can react and adapt behaviour to given circumstances.

In this section, we are going to highlight smart textile applications of electro-conductive textiles, which are used to produce resistive sensors, where different etching techniques revealed the possibility of obtaining customised wearable sensors [48]. The fabrication of resistive sensors was analysed by Capineri et al. [46], who applied conductive textiles to obtain pressure and temperature sensors for use in measuring human interaction parameters, e.g. step measurements. Moreover, conductive wires were used by Uzun et al. [88] to produce smart textiles for the purpose of protection, and also to be able to install various sensors for measuring life body parameters. In this way, by using different yarn production techniques, they analysed the effectiveness of smart textiles. The production of smart sensors, using textiles and screen printed technology, was studied by Khan et al. [121]. The used technology revealed the possibility of using screen printing to produce pressure sensors. A further investigation is to follow to improve this idea. Moreover, obtaining capacitive sensors from PET conductive fibres through printing on them was the focus of Vásquez Quintero et al. [49]. These sensors were integrated into industrial textiles, mainly used in the automotive industry. Moreover, Lee et al. [122] integrated a fibre-based pressure sensor into textiles to monitor human body parameters.

Recently, conductive textiles were integrated with temperature measurement technology, more specifically by using thermocouples, where Hardianto et al. [66] integrated the thermocouples for measuring body temperature and this temperature was then used to generate low power electricity used for portable electronic devices. The idea of energy harvesting by integrating thermocouples into wearable textiles was elaborated by Lund et al. [69]. Furthermore, Root et al. [123] analysed related work in order to observe human comfort when sensory technology and textiles are integrated together. It was observed that combining the conductivity of metal coatings with flexibility, low weight and stretch of a fabric may lead to significant advancements in miniaturised textile thermocouple fabrication.

Based on the literature review, it was established that until now, the used smart textile sensors were fabricated from incorporated metal-based technologies, whereas Afroj et al. [70]current reduced graphene oxide (rGO applied graphene-based textiles. They developed washable electronic textiles intended for ultraflexible supercapacitors.

Furthermore, smart textiles have been fabricated not only from fabrics, but also from leather. Conductive leather for smart applications was investigated by Wegene et al. [45], where it was proposed to use conductive leather for gloves to operate on touch-screen technologies. Moreover, a screen printed technology on conductive textiles was used in [124] to produce a piezoresistive sensor from graphene nanoplates.

Conductive textiles based on PEDOT:PSS that have been used in the development of sensors, actuators, energy harvesting and storage devices were reviewed in [71]. Similarly, conductive leather was investigated by Hylli et al. [72], revealing that after the treatments with mordants and polymerisation, the colourfastness of dyed leather increased and also, the ability to maintain their conductive properties remained. The authors were able to obtain coloured electro-conductive samples.

A wide variety of applications of smart textiles encouraged many researchers to devote the focus of their work on the areas of textile sensors. Krifa et al. [73] reviewed the application of smart fabrics in wearable technology with the focus on sensors and antennas. Another review, a review of applications of smart sensors for psychological monitoring, was described by Angelucci et al. [74]. The combination of electronics with textiles, and the possible techniques and their solutions was reviewed by Stoppa et al. [44].Cho et al. [125] reviewed wearable e-textiles used for sensing, their methods being construction, used materials and applications. Furthermore, the application of textile-based sensors was conducted in [126], where they had in focus the recent developments in the field of electrochemical sensors and biosensors. A historical overview of how electronic textiles have evolved, their areas of applications, especially sensors and wearable textiles, was elaborated in [127].

This paper discussed various strategies for making smart fabrics, a very interesting and promising area also being 3D printing approaches. Direct 3D printing of polymers into textile fibres with the purpose of developing wearable electronic textiles was studied in [127].

Mellin et al.[128] used the 3D printing technology to produce the metal-based nanosized metal powders for use in electro-conductive textiles.

6 Conclusion

The incorporation of conductive elements into textiles has produced the so-called electrically conductive textiles, which enable the production of interactive electronic textiles (smart textiles). As the wearable systems have become more feasible in the recent years due to the advancements in textile technologies, innovative materials, nanotechnology and miniaturised electronics, the most important factor for the user acceptance of wearable devices is the fit comfort. Moreover, we are convinced that certain requirements must be satisfied for their usage in these applications, including electrical characteristics, thermal characteristics, comfort, and durability to different environmental and mechanical influences. In this paper, we briefly described the most common processes and materials for obtaining conductive materials, beginning with conducting metals (most often silver, copper and stainless steel) integrated into textiles, continuing with carbon conductive nanotube utilised to generate conductive yarns, and techniques for processing textiles, e.g. chemical treatment with electrically conductive polymers employing in situ polymerisation. Based on the studies, polypyrrole was the most often employed, as well as the PEDOT:PSS applications. In addition to the use of nanoparticles, the printing of textiles employing ink was another form of textile processing.

All of these methods used to produce electro-conductive textiles served as the starting point in the development of smart wearable textiles, making the exploration of electrical characteristics the central focus of this article.

Moreover, the two probe, four probe and Van Der Pauw resistance measurement methods were explored, where the Van Der Pauw method was proven to be the most practical one, since it was dedicated to measuring the resistance of flat and arbitrary-shaped materials.

The primary purpose of electro-conductive fabrics is their use in wearable technology, where they must fulfil comfort standards necessary to provide the warmth for the body, or in a wide variety of other applications. Therefore, the thermal features, e.g. temperature distribution, were researched in order to bring many study results into the focus. Nonetheless, it should be highlighted that the usage of conductive materials is going to increase, as will their capacity to meet the comfort criteria.

To conclude, we believe that the development of smart textiles necessitates a multidisciplinary approach that fundamentally integrates the knowledge of circuit design, smart materials, microelectronics and chemistry with comprehensive understanding of textile manufacturing.

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