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An overview of materials, processing, and applications for wearable electronics

Mohammad Yusuf [a], Sara Eskandarinezhad [b]*

[a] Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610, Malaysia

[b] Department of Mining and Metallurgy, Yazd University, Yazd, Iran

A B S T R A C T

Wearable electronics are gaining widespread attention because of the potential applications of them in systems of wearable human care and health monitoring. These new devices are probably a collection of different applications like batteries, sensors, displays, and so on. In these respects, conductive fibers, inks, and fabrics were examined. On the field, three materials categories including carbon, metal, and polymer-based materials were investigated. Materials of carbon have advantages like good electrical conductivity, structural and inherent flexibility, high thermal and chemical stability, light weight, ease of chemical operation, and potential production of mass, enabling them to be a good candidate for wearable and flexible electronics. Conducting polymers have a number of drawbacks in their natural state; however, by combining them with other materials, these drawbacks can be solved. Conducting polymer composites have a wide range of applications in optoelectronic, electronic, and electrical sectors due to their synergetic effects. Liquid metal was bestowed with new-emerging characteristics and multifunctional applications. Due to the high surface tension and limited adherence on many surfaces, the manufacturing approach of patterning liquid metals on flexible substrates has received a lot of attention up to now. The current state of wearable materials as actuators and fabrication processes are discussed in this review paper.

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* Corresponding author: Sara Eskandarinezhad; E-mail: s.eskandari.nezhad@gmail.com
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1. Introduction

In the past two decades, the evolution in electronic devices has been made by devoting efforts to obtain desirable accomplishments. Electronic devices have many features to mention like their appearance, being wearable, and intelligent data collection for improving device interaction with the environment [1]. A wide range of wearable electronic applications can be mentioned like; storage devices, energy harvesting, flexible piezoelectric devices, soft actuators, transistors, flexible touch screens, artificial skins, and strain sensors.

Varied materials with flexible behavior, conductive polymers, metal nanomaterials, and advanced carbon materials are employed as wearable electronics [2-4]. Advanced carbon materials are carbon-based honeycomb-like; structures in the crystal lattice, like naturally-derived carbons, carbon black, graphite, graphene (e.g., reduced graphene oxide (rGO) and graphene oxide (GO), and carbon nanotubes (CNTs)), that contain sp^2-bonded carbon atoms. Ran et al. [5] contributed to a novel development strategy for multifunctional electronic nanocomposite fibers that were found to be thermochromic able to change color. They introduced a core-sheath nanocomposite fiber-based in CNT/polyurethane that was useful for wearable electro-thermochromic textiles electronic applications, and strain sensors to monitor movements and human health conditions [6, 7].

The combination of two different materials each shows supplementary characteristics with composites monolithic entity is of high interest for material engineerings. Among variable PMCs (polymer matrix composites), which are potential candidates for wearable and flexible electronics, fiber-reinforced polymers (FRPs) can be readily manufactured in flexible sheets and/or films, and their high aspect ratio of fiber makes them an efficient mechanical reinforcement and making them as the most proper form of PMCs [8-10]. A self-powered wearable electronic was fabricated by Zhou et al. [11] from fibrous mats of conductive polymeric composite for pressure sensing, harvesting, and supplying energy in microelectronic devices.

Moreover, by incorporating electronic components into popular fabrics, the result can be recognized as the novel generation for personalized systems in healthcare platform uses in a range of monitoring to disease therapy. Gallium-based liquid metals are representative of premiere flexible electronics, and potential candidates for creative printing technologies. As an instance, Guo et al. [12] fabricated modern wearable electronics by roller printing technology with semiliquid metal (Cu-EGaIn, eutectic gallium indium mixed with copper microparticles) adhered on cotton fabrics with a glue containing polyvinyl acetate (PVAC). Their study revealed that the chemical interaction and surface topography of PVAC glue and fabrics distinguish the influence of adhesion with the mixture of Cu-EGaIn. The analysis of electric properties illustrates the electromechanical stability of glue on the fabrics. Various smart fabrics, such as thermal management devices (showing benefits of large-area manufacture, low cost, and easy operation), as well as stretchable light-emitting diode array, and an interactive circuit were tailored for representing feasible applications in this method [13-16].

Due to the high surface tension and adherence limitation on many surfaces, the manufacturing approach of patterning liquid metals on flexible substrates has received much attention up to now. The current state of wearable materials as actuators and fabrication processes are discussed in this review paper. Since there is no comprehensive review article in the last five years in this field, this review is required for filling the gaps in this field.

2. Wearable electronic materials

Manufacturing and machinery of novel materials supply physical properties to microfluidic and high-performance electronic technologies to match completely with human tissue. Various procedures for electronic devices manufacturing combined with metal nanowires, conductive hydrogels, and organic electronic materials have been developed [17].

2.1. Conductive fibers

Fast progress in nanotechnology and nanoscience have paced the electronic materials miniaturization process. This subject is a key parameter for fiber-based wearable electronics to develop conductive or semi-conductive materials (soft and flexible) due to their unique mechanical, chemical, and electronic characteristics. Many materials like carbon-based micro/nanomaterials (graphene, carbon fiber, carbon nanotubes, and carbon particles (CP)), as well as metal oxide nanoparticles/nanowires, metals, and conductive polymers have been employed and surveyed [18, 19].

Flexible strain sensors sensing units consist of advanced carbon materials such as carbon-derived materials from natural biomaterials, carbon black (CB), CNTs, graphite, and graphene due to their superior mechanical and conductive properties. Zhao et al. studied the electrical conductivity of iodine-doped CNT fibers and observed 6.7 × S/cm conductivity represented a new value for fibers based on CNT [20]. Based on these promising features, CNT fibers can be considered as potential candidates for many applications, like; solar cell, microelectrodes, transmission lines, and fiber-based sensors, as well as flexible energy-storage

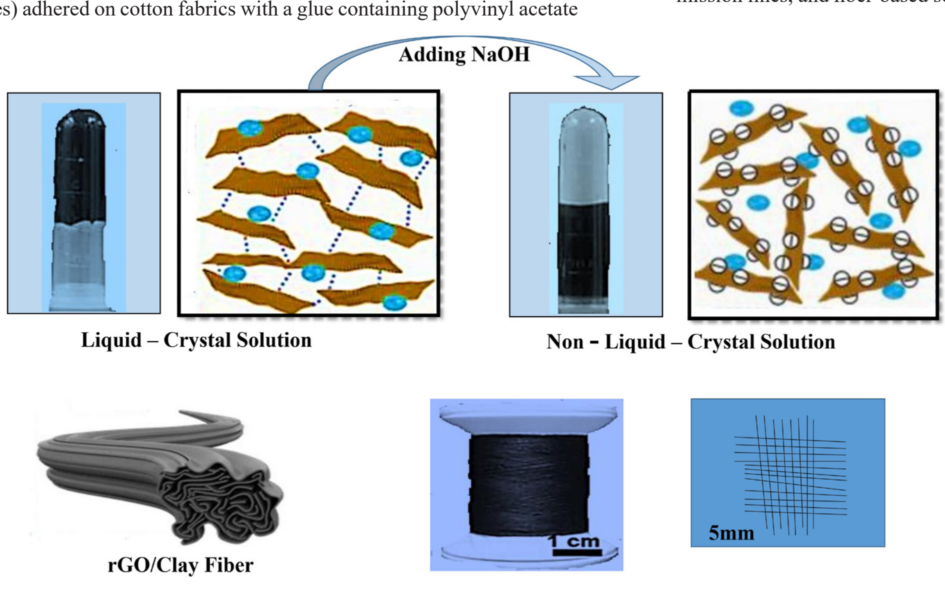

Fig. 1. Schematic diagram of the rGO/Clay hybrid fibers fabrication process
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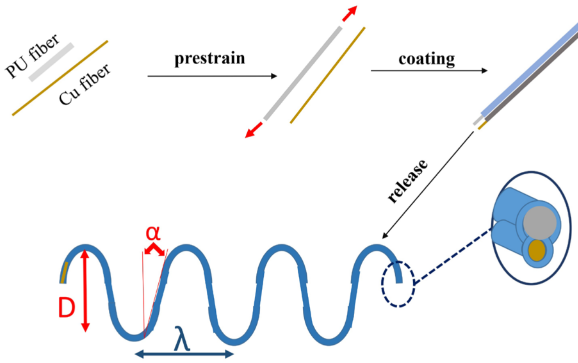

Fig. 2. 3D helical fiber fabrication method.

electrode materials due to their considerable properties such as proper chemical stability, excellent electrical conductivity, and greatly-exposed surface areas [21]. Carbon-based fibers can be formed in different woven cloths. They are significant substrates that are being commonly used in the combination of pseudocapacitive materials to improve the wearable capacitor's energy density. Chen et al. [22] synthesized hybrid inorganic high-performance graphene fibers containing nano clay and graphene oxide (GO) through non-liquid-crystal spinning, followed by chemical reduction. Besides, Jin et al. [23] manufactured washable and durable fibers based on carbon nanotubes for the fabrication of wearable high-performance thermoelectric CNTFs through the electrostatic spray manufacturing method, which is a low-cost and easy technique. Their mechanical and thermoelectric properties could be modified optimally by altering spray time and voltage. The schematic illustration of the rGO/Clay hybrid fibers fabrication process is depicted in Fig.1 [22].

Furthermore, the magnificent characteristics of conducting polymers such as great stability with the environment, effortless and convenient synthesis, excellent tunable mechanical, optical, and electrical properties compared to common inorganic materials have led them to be vastly studied [24]. To overcome the conducting polymer's limitations when used in their pristine form, hybridization along with other materials can be conducted. An outstanding electrical conductivity of ~ 1000 S cm^{-1} [25], as well as a relatively lower thermal conductivity of ~ 0.1-1 W $m^{-1}K^{-1}$ than common inorganic semiconductors (~1-100 W $m^{-1}K^{-1}$), have been exhibited by semiconducting polymers. Printability, flexibility, moldability, and convenient scalability are other main advantages of polymers that cannot be ignored [3]. On the other hand, the Seebeck coefficient of these polymers is not inherently high, so fewer thermoelectric efficiencies compared to their inorganic counterparts are demonstrated. [26]. UV-VIS spectra for the PVDFTrFE/P3HT composite fibers exhibited the uniform incorporation of P3HT blend solution that was not impacted chemically by the ferroelectric polymer. Reduction in fiber beads with low PVDF-TrFE concentrations formation in tetrahydrofuran (THF) solution was enabled by P3HT due to an increase in solution charge. This enhances the charge transferability from the needle tip to the solution drop, improving the Taylor cone configuration through the formation of a jet towards the collector. The overall capability of PVDF-TrFE/P3HT fibers fabrication improves the aim for devices based on quasi-1D ferroelectric manufacturing [27]. It is assumed that the highest desirable materials for composites fabrication can be organic small molecules compounds or polymers regarding their intrinsic flexibility or the ability to be mixed in fibers. Conducting polymers are to be technologically and scientifically important due to their unique optical, magnetic, electrical, and electronic properties. For instance, the synthesis of nanofibers containing polypyrrole with diameters in the range of 60–100 nm was carried out with a functional dopant like p-hydroxy-azobenzene sulfonic acid possessing high room-temperature conductivity (120–130 S/cm). A photo-isomerization function is caused by azobenzene moiety and proton doping. Particularly, the most accomplished conducting polymer, poly-(3,4-ethylene dioxythiophene) (PEDOT), is found to be used as wearable and flexible photodiodes capacitors electrodes, owing to their solution processability, and excellent conductivity. However, PEDOT or other conducting polymer films are limited to be used in displays due to their bluish tint [3]. Yang et al. [28] claimed a technique to fabricate greatly solderable, washable, conductive, and stretchable fibers tailored from conductive fibers of Cu and elastic fibers of polyurethane (PU). They are applied as wearable electronics interconnects. The pre-stretched PU fiber stress-relaxation and the Cu fiber plasticity result in the 3D helical shape, preparing a method for the 3D fibers morphology manipulation (Fig.2).

Moreover, metal oxide and metallic nanowires exhibit catalytic properties. Moreover, chemical sensing and metal-semiconductor junctions can be employed for electronic devices. Metal nanowires are potential materials to be considered as nanoelectronics device interconnects. The semiconducting and metallic nanowires in the range of 1 -100 nm are in high interest due to their wonderful quantum properties. The nanowire's quantum confinement has affected the inelastic light scattering, two-photon optical absorption, luminescence, and various processing manufacture [29, 30]. Compared with quantum dots (zero-dimensional structures), nanostructured wires contribute to a more desirable model system preparation for evaluating the dependence of magnetic, mechanical, optical, and electronic transport properties on dimensionality and size confinement [31]. Shi et al. [32] surveyed research on silver nanowires and braided-like stretchable fiber sensors manufactured through an easy and low-cost dip-coating process.

When the dimensions of the electronic device are decreased to the scale of nano, an issue of wiring these devices arises. Particularly, nanowires play a key role in photonic and electronic devices as active components and interconnect. Nanometals with low dimensions such as nanoparticles or nanowires (NWs) are attractive for wearable and flexible electronics based on fiber due to their excellent conductivities. Kevlar fibers of Ni- and Au-plated exhibit 6 S/cm electric conductivity [21]. This amount for Ag flakes-filled silicone fibers reach 470 S/cm, while for this amount for Ag coated- mats of nylon fibers by commercial electrodeless plating solution, trespass ~1800 S/cm when loaded with ~17 wt% Ag. A manufactured stretchable conductor by simple printing or coating liquid metal on an electrospun elastomeric fiber mat was reported by Ma et al. (Fig. 3) [33]. The hung-liquid metal among the elastomeric fibers is self-organized into a mesh-like lateral and buckled vertical structure, providing simultaneous properties of high electrical stability, conductivity, stretchability, and permeability [34].

2.2 Conductive fabrics

Novel applications and properties of the developed textiles have attracted notable interest, recently. Electrically conductive fabric composites are widely used in recent years. Compared to common conductive materials, the conductive polymers show 10−5 to S/cm conductivity. Textile polymerization provides a broad range of characteristics such as electromagnetic, mechanical, structural, and conductive properties attributed to the produced flexible conductive materials. Intricate patterns assist wearable sensors and intelligent textiles fabrication [35, 36]. The special design of the conductive polymer layers used as fabrics coating would obtain great insertion loss of microwave frequencies; making them promising materials for absorbers of electromagnetic radiation for wireless applications. Other conductive polymers based on conducting fabrics can be mentioned as follows: microwave attenuation, heating devices, electrotherapy, biomechanical sensors, gas sensors, and antistatic materials. As an example, conductive textiles by dip-coated Mxene sheets-modified-polypyrrole on the textiles of poly(ethylene terephthal-

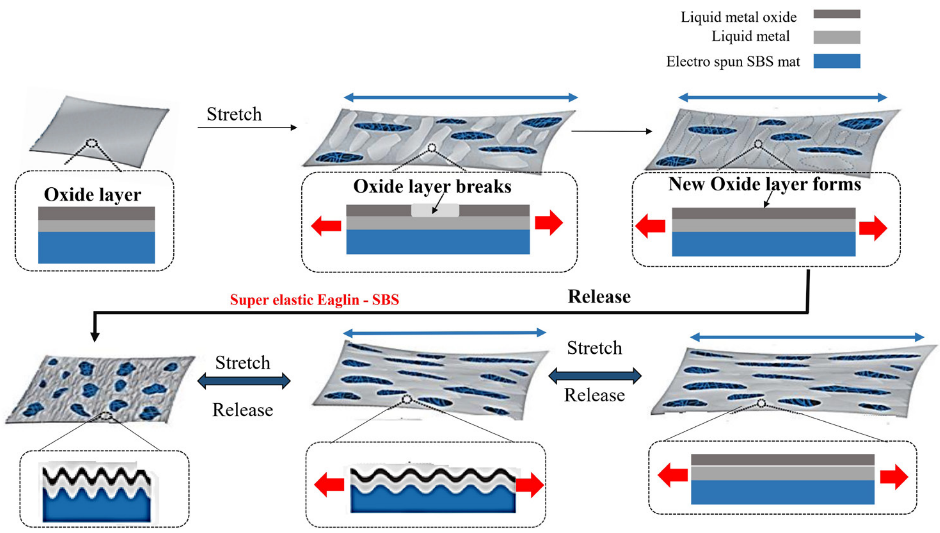

Fig. 3. Schematic diagrams of the pre-stretch activation method to prepare a permeable mat of EGaIn-SBS.

ate) were tailored by Wang et al. to be used in Joule heating and EMI shielding.8 Nonetheless, further chemical modifications for the textile substrates have to be performed for the textile surface activation by depositing conductive materials on the substrates of polymeric textile [37, 38].

In addition, the controllable manufacture of carbon-based rational-designed structured materials is contributed for the next-generation applications. Advanced carbon materials display fantastic unprecedented properties like easy functionalization, low toxicity, high thermal and chemical stability, and desirable electrical conductivity that make them promising candidates for wearable electronic devices in comparison with other materials [39]. Moreover, To coat three kinds of textile fabrics, nylon, polyester, and meta-aramid, Sadanandan et al. [40] introduced the ultrasonic spray coating method with water suspension of graphene nanoplatelets, which is highly scalable, efficient, low-cost, and simple. The sheet resistance of the textile electrodes was as low as 4.5 kΩ/sq without any necessary additives or intentional doping to improve adhesion [41].

In recent years, metal oxide nanostructures (MONSTRs) are employed in sensing, optical, and electronic devices; thus, to overcome the limitations of the commonly-used fabrication techniques, a novel method to fabricate MONSTRs is in high desire, with promising properties like being environment-friendly, low-cost equipment, low-synthesis temperature, catalyst-free growth, high-throughput fabrication, and applicability to a wide range of materials. Lately, an asymmetric supercapacitor consisting of coated metal based on fabric was reported by Pullanchiyodan et al. [42] to supply power for different wearable devices. This supercapacitor was fabricated from the printed paste of graphite on Berlin fabric, maintained as the electrode of the negative and conductive fabric of Cu/Ni/Ag plated i.e., Nora Dell, as the positive electrode. This prepared asymmetric supercapacitor exploits the electrolyte of the biocompatible PVA-KCl gel as the sustainable and safe substitute. The evaluation of the electrode materials microstructure reveals nanoscaled particles of metal oxides with high porosity structure attributing to the great behavior of manufactured device capacity (Fig.4) [37, 43].

Copper and silver nanoparticles deposition, followed by electroless plating coating of the copper thin layer was surface fabricated by Ali et al. [44]. The coated fabrics' performance with another conventional electroless plating coated sample was compared from the aspects of antibacterial properties, Joule heating, electromagnetic interference (EMI) shielding, and electrical conductivity (Fig.5).

2.3. Conductive inks

An ink that conducts electricity via inoculation of conductive elements is taken as a thermoplastic viscous paste [45]. The typical role of conductive ink is fabricating conducive ways for using it as interconnects [46]. Conductive inks are nanomaterial suspensions in water or a solution by adding a stabilizing surfactant or polymer. Although these solutions have to evaporate fast after deposition, they do not rapidly dry out at the print head nozzles while being inappropriate for a short duration of time. Conductive nanoparticles are commonly used to provide high electrical conductivity in conductive inks. The diameter of these nanomaterials should be fewer than hundreds of nozzle sizes for the prevention of clogging the print head [47].

A good conductive ink dries in a desirable formation at a surface of the substrate without a coffee ring influence, suggest great conductivity of electricity post-printing performance, favorable adhesion to the substrate, desirable stability, low viscosity, acceptable printability, and should be easy to make and cost-effective [39]. Roll-to-roll printing, flexographic printing, gravure printing, screen printing, and inkjet printing are significant processes that conductive inks turn into a remarkable part of their industry. Antennas, memory ingredients, batteries, smart textiles, sensors, solar cells, thin-film transistors, healthcare devices, radio-frequency identification (RFID), flexible displays, inorganic and organic photovoltaics, and organic light-emitting diodes (OLEDs) are all examples of printed electronic applications that conductive inks are applied in them [48]. Up to 2026, the market value share of conductive inks is predicted to expand progressively [49].

Various kinds of frequently utilized conductive materials, in addition to graphene, have been documented in the literature. The most stable metal nanoparticles as gold nanoparticles (AuNPs) have extremely been utilized to print conductive materials. AuNPs are beneficial in a variety of applications, including chemical catalysis, optics, electronics, metal coatings, and colorants [50]. On the other hand, the expensive expense of mass manufacturing of AuNPs has eclipsed their benefits in electronic applications. They also necessitate an extended sintering time and a high sintering temperature. Cui et al. fabricated an AuNP ink using two acrylic resin (AR) and overlapping layers of poly (N-vinylpyrrolidone) (PVP) displayed conductivity. Moreover, Schoner et al. found that gold structures printed on a glass substrate sintered at 280C for 10 min had a conductivity of 1.9 ×S/m [51].

Square lines and structures with parallel edges and an average width of 260 mm were shown to be printable. Another desirable nanomaterial applied for flexible electronics is silver nanoparticles (AgNPs). AgNP-based inks except graphene have mostly been investigated and have been the most significant commercial nanotechnology-derived yield [52]. The fundamental challenge with AgNPs is that superior conductivity is achieved by sintering at increased temperatures for getting the printed layer. The prior scientists have reported that owing to the low glass-transition temperatures of flexible polymer substrates like PET and

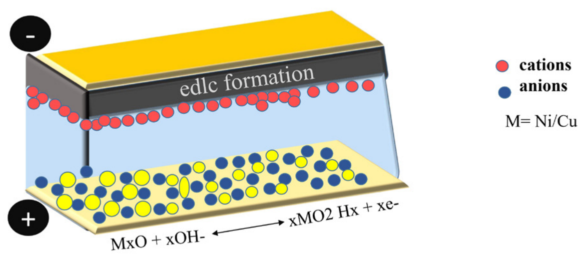

Fig. 4. Schematic representation of fabric ASC with different capacitance mechanism, the microstructure of electrode/current collector materials.

PEN, sintering temperatures up to 200°C are not suitable for them [53]. Nie et al. [13] synthesized a silver conductive film via inkjet printing silver citrate conductive ink on a PET substrate. After curing at 150°C for 50 minutes, the film had a low resistivity of 17 lX cm, and after curing at 230°C for 50 minutes, it achieved a resistivity of 3.1 lX cm [54].

Rfid et al. [46] described their study on dodecyl amine-protected AgNPs improved by a little quantity of dodecanethiol as a co-protective factor, demonstrating that the curing conditions impact the Ag film. After curing at 130 °C for 10 minutes, a stable polymer-free conductive ink containing AgNP patterns was formed via inkjet printing and demonstrated resistance of 7.2 cm. Zhang and Zhu [47] succeeded in fabricating AgNPs sintered at room temperature using a dipping procedure for inkjet-printed flexible electronics in 2015. These discoveries revealed a novel method for sintering the printed pattern at room temperature via dip processing and now obtain superior electrical conductivity. Kastner et al. optimized and evaluated the printing of a reactive silver ink fabricated of silver acetate and dissolved in an ammonium hydroxide solution. According to the results, after annealing at 120 °C for diverse minutes, the conductivity value of the printed film on glass was 4.42 10^6 S/m, with the thickness of the pattern varying from 150 to 133 nm. With a pattern thickness of 150 nm, the conductivity of printed silver films on coatings of acrylate was 2.9 10^5 S/m [55, 56].

Unquestionably, AgNPs and AuNPs have great printability and high electrical conductivity. However, more study is needed due to the long sintering time required, high sintering temperature, and expensive cost which make them unsuitable for large-scale usage, particularly in industrial applications. Due to the inexpensive price and excellent electrical conductivity of copper nanoparticles (CuNPs), they become promising alternative materials to silver and gold nanoparticles. Kang et al. [15] described a CuNP ink sintered at 200°C in a nitrogen-filled furnace and printed on a flexible glass epoxy substrate. They obtain a low resistance of 36.7 n m and a consistent grain structure in a 10-layer printed electrode as a result of the research. Tsai et al. devised a technique for making antioxidant conductive copper ink, which yielded a low sheet resistance of 47.6 m/sq after 30 minutes of calcination at 250°C in nitrogen. These conductive Cu coatings were stable for more than six months in an air setting, demonstrating long-term stability [57, 58].

Kwon et al. recently presented a new hydrogen plasma sintering technique (150 °C for 10– 20 min) that accomplished complete densification and decrease inkjet-printed patterns via ion ink of Cu complex. Water has two impacts on the performance of copper complex conductive inks using amines as ligands, according to the investigation of Xu et al. Water's dual effect on copper-complex conductive inks might be balanced by adding the blend of 2-ethylhexylamine and 2-amino-2-methyl1-propanol as ligands to copper. The printed films were discovered to have low resistivity, ranging from 9.70 cm to 14.42 cm, and could be preserved for two months, meeting the typical criteria of printed electronics. CuNPs have high electrical conductivity and are inexpensive compared to AuNPs and AgNPs, but their primary disadvantage is that they are quickly oxidized in heat and humidity, which restricts their application [59, 60].

Table 1.

Various types of fibers and fabrication techniques

Material	Fabrication method
Thermosets	
Polydimethylsiloxane	Modeling, coating
Epoxy	Printing
Hydrogel	
Poly(ethylene glycol) diacrylate(PEGDA)/alginate	Modeling, coating
PEGDA-poly acrylamide (PAAm)/alginate	Modeling, coating
TPE	
Styrene-ethylene-butylene-styrene (SEBS)	Molding, coating, thermal drawing, extrusion
Cyclic olefin copolymer elastomer (COCE)	Molding, coating, thermal drawing, extrusion
Biodegradable	
Agarose/Gelatin	Thermal drawing, molding, coating, extrusion
Poly(octamethylene maleate citrate) (POMC)/ poly(octamethylene citrate) (POC)	Thermal drawing, molding, coating, extrusion
Polylactic acid (PLA)/poly (lactic-co-glycolic) (PLGA)	Thermal drawing, molding, coating, extrusion
Silk	Thermal drawing, molding, coating, extrusion

3. The fabrication process of wearable electronic materials

Synthesis procedures are crucial in the specification of stability, cost, and properties of wearable electronics. Fabrication of conductive fibers via carbon, metal, polymer, and other materials is explained in the first section, followed by the synthesis technique of fabric material in the second section, and finally describing the fabrication process of conductive ink in the third section [61].

3.1. Fabrication of Fibers

In general, there are two ways for fabricating wearable electronics and fiber-based flexible. Electronic devices are created with conducting fibers composed of traditional fibers surface modified with different functional components, or piezoelectric materials, carbon, metal, and conductive polymer in the first group. X–Y grids of copper wires were combined into woven textiles to produce interconnecting lines according to the study of Zeng et al. Locher et al. suggested a conducting band interconnection method between electronics and textiles. The second class is based on the electronic ingredient of thin-film like transducers or embedding off-the-shelf miniature which is supplementary to the first, onto traditional dielectric fabrics as an imparting electronic function or motherboard on the surface of fabrics through lamination, printing, or coating. The combination of thin-film flexible electronic devices, such as commercial integrated circuits with plastic fibers, interconnect lines, transistors, and sensors that can be woven into textiles via a commercial fabrication technique has been documented at the fiber level. Electronic fibers are woven in the weft direction of a woven fabric through a commercial band weaving machine to create wearable and flexible electronics [62, 63]. Before solidification and crosslinking, thermoset elastomers should be formed to fiber. It would be hard to soften and dissolve thermosets after crosslinking. Thermoplastic elastomers (TPEs), on the other hand, may simply dissolve in melted or solvents. They might also be thermally treated using a variety of techniques, such as thermal drawing and thermal injection. Hydrogels are made up of a cross-linked hydrophilic polymer chain. They are sometimes seen distributed in water as colloidal gel. [64] (Table.1)

Many methods for fabricating graphene fibers from graphene oxide dispersions have been documented, including chemical reduction-induced self-assembly, drawing-twisting, dry film scrolling, chemical vapor deposition, and shape constrained hydrothermal methods. Additionally, the shear-thinning behavior of GO dispersion is similar to the most spinnable polymers. As a result, both dry and wet spinning may be employed to make graphene fibers [65, 66].

Using this approach Yang et al. created a stretchable fiber-shaped dye-sensitized solar cell (DSSC). Therefore, a continuous multi-walled carbon nanotubes (MWCNT) sheet was drawn onto the elastic fiber with an angle, stabilized on an exactly motorized translation stage. Via tuning the moving speed of the translation stage and the rotary speeds of the two motors, the MWCNT sheet as-fabricated was bundled desirably onto the elastic fiber. Van der Waals forces acted as a binding force between the MWCNTs and the fiber surface. Spin and dip-coating were used to coat the cladding layer on the fiber core. After that, the cladding layer was heated to cure it. The stretchy biofuel cell fiber's active enzyme layer-coated electrode was also made using other coating processes, such as dry-coating. Other elastic fiber manufacturing procedures are shown as one-step co-extrusion manufacturing of a stretchy fiber, which was advanced from a simple extrusion approach suitable with thermoplastic materials. Leber et al. prepared a core-cladding optical fiber made by co-extrusion using the fluorinated polymer Daikin T-530 (RI: 1.36) as the cladding and the polystyrene-based polymer Star Clear 1044 (RI: 1.52) as the core. It was able to withstand 300 percent of reversible tensile loads. Molding is one of the popular processes for producing elastic fibers. Yetisen et al. developed a hydrogel optical fiber using post-coating processes and molding [52, 67].

3.2. Fabrication of conductive fabrics

For possible applications in wearable electronics and gadgets, conductive fabrics with stability, long-term durability, and mechanical flexibility under rough circumstances are required. The manufacturing technique, which must be environmentally friendly, scalable, and inexpensive, is an issue related to the fabrication of such materials. Using bio-mass-derived glucaric acid/chitosan (GA-chitosan) organic salt aqueous solution and single-walled carbon nanotubes (SWNTs), we developed a fully "green" way for manufacturing machine-washable conductive textiles by spray coating or dip-coating textiles with a novel conductive polymer and crosslinked composite coating [68]. Direct coating of electrically conductive thin film materials, including carbon nanotubes (CNTs), reduced graphene oxide, MXenes, silver nanowires, and metallic particles on the textiles via layer-by-layer, inkjet printing, or dip-coating that are common strategies for fabricating highly conductive textiles. For example, Jia et al. created desired conductive textiles for EMI shielding via drop-casting 3% wt silver nanowires on pre-strained textiles. Additionally, Wang et al. prepared conductive textiles for Joule heating and EMI shielding via dip-coating polypyrrole modified MXene sheets on poly (ethylene terephthalate) textiles. Although to activate the textile surface and deposit the conductive elements onto the polymeric textile substrates, further chemical processes on the textile substrates are usually necessary [66, 69].

3.3. Fabrication of conductive inks

Paper substrates are the most commonly used substrate used to construct electrochemical sensors, and there are several extensive and up-to-date studies in the literature that describe the key breakthroughs in the manufacturing and application of electrochemical paper-based analytical devices (e-PADs) [70-72]. Paper substrates provide several appealing characteristics, including biodegradability, biocompatibility, flexibility, lightweight, superb availability, and inexpensive cost [73]. In terms of physicochemical features, paper is a porous, flexible, and hydrophilic substance with variable features from various paper kinds. As a result, choosing the right paper substrate is crucial for creating desirable electroanalytical tools. Filter and chromatographic papers are commonly utilized to make e-PADs due to their good wicking capabilities, steady distribution of fiber size, and qualified porosity [72].

The wicking paper ability is an important feature because it promotes conductive ink adhesion and allows the solution to flow through microfluidic tools without additional pumping [73, 74]. The wicking capacity of paper, on the other hand, aids in the infiltration of the supporting electrolyte solution into the electroanalytical tool. During electrochemical measurements, it destroys the electrical connections and affects the active electrochemical region of the working electrode, resulting in irreproducibility difficulties. It is not an important issue by using plastic substrates. Furthermore, these substrates are biocompatible, flexible, plentiful, and low-cost. As a result, several electrochemical sensors manufactured on plastic substrates, including polyethylene terephthalate (PET) and polyester are also provided in the literature [75-77].

The conductive ink adhesion to plastic substrates is less compared to

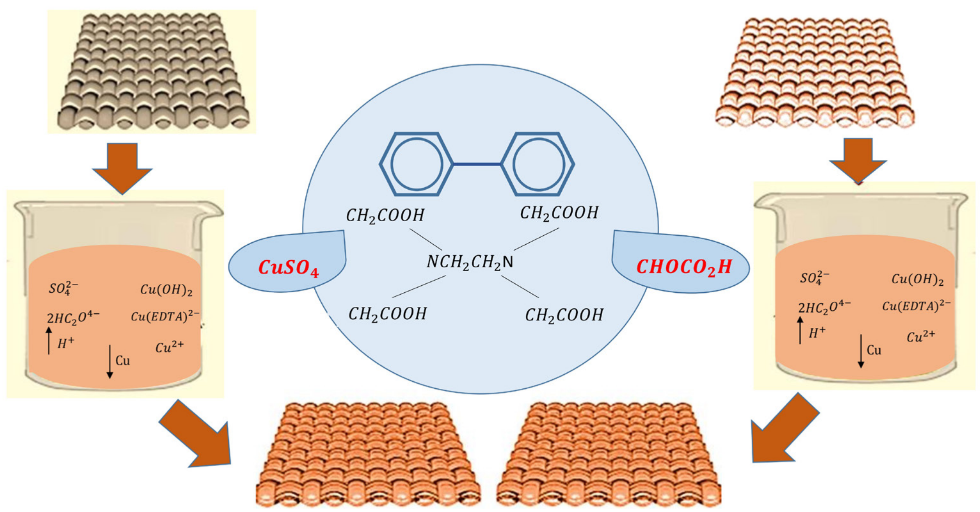

Fig. 5. Schematic of Cu- and Ag-particle fabrics coated by Cu electroless plating.

paper substrates, which is the major challenge in working with plastic substrates. To solve this challenge, the plastic substrates are normally sanded before applying conductive ink [75, 76]. Several processes for ink application can be utilized depending on the substrate and ink composition. Pen drawing, inkjet printing, stencil printing, and screen-printing are the most common techniques for immobilizing conductive inks onto the substrate surface. These approaches are thoroughly described in the literature, and there are numerous instances of applications. The discussions offered here will be limited to a summary of each approach and their necessities related to ink features [70-72, 78]. Screen printing is a stencil process that involves utilizing a mesh screen, commonly composed of nylon or, silk to transfer a stenciled fabrication to a flat surface [71]. The scalability and cost-effectiveness are the main benefits of this process, whereas the time-consuming cure phase and a relatively large waste generation are its essential drawbacks [70]. In addition, because screen-printing has slight requirements for the physical-chemical characteristics of the conductive ink [79], it is suitable for the majority of manufactured inks. Another benefit of screen-printing is its adaptability since it can be used on a wide range of surfaces and patterns [70]. Stencil-printing is a more inexpensive and simpler kind of screen-printing that does not need the apparatus and the screen essential for screen-printing equipment. The ink is immediately used to the substrate in stencil printing through an open mask constructed of plastic stickiest [70]. Although stencil printing is one of the most cost-effective ways for immobilizing conductive inks on flexible substrates, its disadvantages include lack of repeatability and significant waste output [71]. To eliminate ink adhesion to the mask and achieve steady substrate coverage, stencil printing needs more viscous conductive inks than screen printing [70, 71].

4. Applications of wearable materials as actuators and sensors

It is common knowledge that sensor transducers can transform one form of energy into another form for more processing. This supplies us with data about our physical, environment of biological, and chemical [80]. The sensor's introduction into our daily lives has altered human living standards. For instance, a contemporary smartphone, which can accurately fix, display location, orientation, and aggregate for users by combining a large number of sensors such as gyroscopes, accelerometers, magnetometers, and barometers. Wearable devices are electronic gadgets that incorporate sensors into clothes, decorations, tattoos, and implants internal to enable in-vivo sensing, data storage, and mobile calculation [81].

The majority of consumer electronic companies around the world have launched wearable products like the Apple Watch, Band of Microsoft, and Huawei watch due to the increasing innovation of wearable technologies of sensing, and also wireless technologies of communication, and microelectronics development. These wearable sensors with a variety of functionalities are useful instruments for tackling the measurement of sensor issues in the health, sports, medical, industrial, and military zones. Wearable sensors are divided into three categories based on measurement parameters: motion sensors of state, biomedical sensors, and biophysical sensors. Wearable sensors, on the other hand, are predicted to be the most executable and most promising programs soon [82].

Wearable devices with a variety of simple sensors like temperature, pressure sensors for body posture and movement, disease monitoring of biosensors, and sensors of multifunction for voice and expressions of facial, can provide valuable feedback on real-time offer to a central system[83]. Wearable sensors with light weights, outstanding thermal and mechanical capabilities, flexibility, and it is more ideal to avoid low cost any discomfort and safeguard sensors from damage. Wearable sensors have been employed in a variety of disciplines including rehabilitation, health care, and communication. Wearable sensors collect physiological and movement data like respiration rate and leg motion, which is subsequently relayed through a wireless connection to a distant center. Various items, such as smartwatches, smart clothes, fitness trackers, and even medical smart attachments, have been introduced to the market by a different number of firms from all over the world. The market has progressed above human fitness, health, and wellbeing to include entertainment, commercial, and industrial applications. The potential for revolutionary wearable technology concepts is obvious, as the market is predicted to rise from its present worth 40 billion USD to an astounding worth 160 billion USD by 2026. The research and development stage has grown in tandem with the increase of market demand over the last several years. Most of this progress may be attributed to the rise of digital medicine, which necessitates constant and, in certain circumstances, remote monitoring of patients [84, 85].

The number of publications on this subject is widely raising. Textile-embedded sensors, actuators, and treatments are now on the market, and one of the biggest hurdles is material technology, which is necessary to provide varied features including flexibility, user comfort, and miniaturization, and fashionability. Wearable electronics are divided into two broad categories: wearable actuators and wearable sensors. Current uses of nanomaterials in sensors and actuators will be described in each part, along with a discussion of distinct categories [86, 87].

4.1. Actuators and Artificial Muscles

Actuators respond to a signal or electrical stimulus generated by the processing unit or a signal received directly from a sensor. whereas nanomaterial sensors sense a stimulus external and convert it into a measurable signal that can then be transmitted to a monitoring device or processing unit. Mechanical, thermal, chemical, or magnetic stimuli can be used to create these responses, which can include deformations of structural, noise, heating, or even release of material. Such a response strategy is important in wearable technologies because it may turn passive wearables into "smart" or "active" wearables. However, the use of nanocomposites or nanoparticles in wearable actuators is still in its infancy [88].

Due to the current trend on smart wearables, performance-enhancing, and smart clothing, materials' position in the future market is accelerating. The e-textiles development and smart fabrics in the textile industry have broadened uses of wearable stimuli, while heating elements are embedded in the wearables, nanocomposite-based devices of therapies, muscle stimuli and muscles of artificial, devices of rehabilitation, and wearable drug systems of delivery have all performed to the actuators of wearable development. The next section will provide a full discussion of applications in various sectors. Material selection is critical for incorporation into wearable and flexible electronics. They must have appropriate strength, flexibility, and structural rigidity, as well as the ability to deliver sufficient actuation force, depending on their uses [57, 89].

They should also be comfortable and biocompatible, which is very important for medication delivery and treatment systems. Due to their limited flexibility, classic transducer materials such as magnetostrictive, piezoelectric materials, quantum dots, and tunneling composites are difficult to incorporate into flexible materials. Researchers have researched several groups of materials and produced innovative other materials and nanocomposites for actuators of the wearable since Lewis proposed the use of dielectric materials as artificial muscle in 1994. Scientists have become more interested in electroactive polymers (EAPs), as well as a variety of EAPs and macromolecular materials such as Poly3,4-Ethene Dioxy Thiophene (Poly Styrene Sulfonate) (PEDT: PSS), CNTs, Poly

Vinyl Dene Fluoride (PVDF), graphene, and shape-memory alloys. With a wide range of materials and uses, researchers have looked at a multitude of manufacturing methods. Electrospinning, spray coating, knitting, solution casting, and weaving, are among the most interesting manufacturing techniques [90, 91].

Actuators are classified as transducers since they turn any electrical signal into a quantifiable mechanical output. Actuators are a type of device that produces mechanical movement, noise, or material release in textiles and other wearable applications in response to an electrical signal. Although nanomaterials in wearable actuators are not as important as in wearable sensors, they are currently being employed in several fascinating applications. The spectrum of uses for novel composites is expanding, and this might have an intriguing influence on wearable electronics. Wearable heaters, therapeutic devices, artificial muscles, and wearable drug delivery devices are among the novel uses for wearable actuators made possible by the development of smart textiles [92].

Since Lewis first recognized the idea of incorporating nanomaterials in wearable actuators, others have been exploring ways to minimize such stimuli to wearables. Dielectric elastomers, fabric-based materials, and electroactive polymers are some of the material classes that researchers have sought to create for use as flexible and wearable actuators. Conducting polymers was prepared by Maziz et al. into the fabric and yarns, knitted them into a "texactuator" (textile + actuator). When these threads are knitted together, the strain augmentation is 53 times greater than yarn-based of woven materials. When woven into a suit to be worn like an exoskeleton, this fabric can be used as an auxiliary dress or artificial muscle [45].

4.2. Wearable heating elements

One of the key issues explored under wearable electronics is applying temperature and heating in wearable devices. Wearable heating element applications can be divided into two categories: personal thermal comfort and applications of thermotherapy. Heating and cooling jackets are key actors in people's thermal management applications and are even converted trends of fashion among teenagers. These human types' thermal systems of management are critical in nations with harsh winter seasons, as well as for a variety of leisure and sports activities such as camping and hiking, where the climate might be harsh. The loss of energy used for heating space is one of the key problems of traditional heating of building-based thermal comfort. Personal thermal comfort must be addressed directly to the person, and wearable gadgets [46].

Hsu et al. proposed a way for improving thermal comfort by dip-coating cotton textiles with metal nanowires (NWs). When compared to the usual building heating strategy, the offered permeable and washable fabric claimed to save more than 30 times per person of energy. Liu et al. developed a multifunctional and hydrophobic cloth in which they created a thermal polymer of conductive fiber and integrated it with a fabric to improve the thermal conductivity. 3D-printed fibers were woven into a fabric with improved thermal conductivity characteristics, allowing body heat to be discharged more effectively. They claimed a 55 percent improvement in cooling impact when compared to cotton cloth. The majority of the flexibility and breathability concerns of synthetic functional materials have been overcome by converting commercial fabrics into wearable heating devices. Ilanchezhiyan et al. created wearable heating cloth yarns and fabric mats by coating cotton fibers with functionalized CNT [93, 94].

Yang et al. used nanofibers to improve the heat reflective characteristics of the facemask. This will reduce any radiant thermal losses /absorptions from the face and improve thermal convenience. In the medical world, wearables with thermotherapeutic applications are quite useful. Thermotherapy, or targeted skin heating, can extend the vascular system, increase blood flow in that area. This is an essential therapy strategy that physiotherapists are already employing to alleviate pain and muscular weakness. A flexible fabric-like mesh structure based on silver nanowires has been created to give joint thermotherapy points of care. The stretchy architecture of the device improved heat transfer yield and allowed for curvilinear lamination junctions. Because of its kerygma construction, the rapid heating element of the response has exhibited great stretchability and form restoration. Aside from this collection, many ways using various materials were employed as wearable tools to warm the skin [47, 95].

4.3. Drug delivery

Wearable drug delivery devices based on nanomaterials are among hot issues lately due to their capacity to enable localized noninvasive medication administration. Incorporating a therapeutic career with functional materials can improve the patient's comfort. Fabric-based drug delivery systems, wearable patch-based drug delivery systems, and small-scale-based device drug delivery systems are all gaining traction as viable alternatives to traditional drug administration techniques. Mechanical, light, electrical, bio and thermal stimulations are the four common triggering methods employed in drug delivery applications. We shall not look at bio-stimulated drug delivery systems because they are beyond the scope of this paper. Di et al.'s stretch-triggered drug delivery patch is made up of drug-loaded nanoparticle depots placed in the stretchy elastomer [96].

Every finger in bent motion releases a predefined medication amount via a sequence of microneedles when attached to a stretchy skin part such as finger joints. A thermally induced medication module of delivery for blood sugar management has also been designed and experimented on mice with great effectiveness. Hydrogels are entered into medicine and covered by phase-shifting substances for regulated drug release. Electro-resistive heaters are used in the majority of thermal triggering drug delivery systems to supply and manage the required temperature of the nanoparticles loaded with the drug. By activating medication-carrying nanoparticles; it can be an electric field that allows painless drug delivery. With the introduction of an electric field, graphene electrodes containing the drug can release therapeutic agents onto the skin. The number of electrical impulses can readily alter the medication delivery depth. Thermally-activated drug-loaded reservoirs suggest an alternative way for needles or drug-loaded particles [55, 97].

Wearable actuators were chosen from a larger group of materials by the researchers. The group's highlights include metal nanoparticles, electroactive polymers, conductive polymers, liquids of ionic (ILs), and carbon-based materials. The stretchy heating characteristics of silver nanowire deposited onto a Poly-dimethyl Siloxane (PDMS) film have been demonstrated. They have been excellently positioned as a wearable heater regard to their fast thermal reactions (60 ° C and 60% elongation). Vacuum filtration of AgNW onto a PDMS film revealed high conformal coverage. Before vacuum drying, Hsu et al. soaked the commercial cotton fabric in an AgNW solution. Conductive polymers have long been a popular choice for actuators among polymeric materials. Most research organizations have taken use of PEDOT: electroactive PSS's characteristics [43, 98].

For improved mechanical properties, Zhou et al. used a PEDOT with wet rotation: PSS fiber mattress doped with ethylene glycol (EG). The actuator respond quickly and had actuation stress of 22 MPa. On the contrary, the pure polymer and carbon composite fiber and PEDOT: PSS of IL have demonstrated substantial actuation characteristics. Lin et al. indeed soaked the tissue paper in a polyionic solution before inserting it with an actuator [46].

4.4. Strain/motion sensors

Joint flexion, wrist pulse, breathing movements, heart rate, eye blinking, and voice recognition are among the human motions that use pressure and strain sensors to track. Sensors for gross movements should be very stretchy. Sensors for tiny movements, on the other hand, must have high sensitivity, high reaction alternation, and close contact with the experimental area. however, they do not have to be very stretchy, since undesirable noises may produce [99]. As a result, sensors for effective motion detection should be individually constructed. This section covers capacitive sensors and electrical resistive to detect tensile strain and pressure. The resistance change, as with resistive sensors, is primarily caused by changes in the materials' intrinsic resistance as well as geometrical changes. Buckling structures can assist sensors in both ways. Buckles prevent irreversible and inhomogeneous connection casualties, leading to improved wearable sensor mechanical tolerance, particularly for tensile strain sensors [100].

Buckles also exaggerate the area change of geometrical contact, which improves the pressure sensor's sensing capability. Primary capacity (of a capacitive sensor with the surface area of the primary electrode () and the dielectric thickness of (is equal to = r/, where 0 and r are vacuum dielectric constant and permeability of relative of the dielectric medium, respectively. If the Poisson ratio of the dielectric layer and the electrode is the same, the capacitance after stretching with strain may be expressed as $C = (1 + C_0)$. Two layers of AgNW electrodes were uniaxial buckling built for resistive strain sensors, with the buckling directions perpendicular to one other, allowing for multidirectional strain sensing [101].

In other words, multidirectional sensing may be accomplished by combining anisotropic sensing units with certain angles. For the practical usage of sensors, the linear response of tensile strain resistance is important. When conductive composites are stretched, their resistance often increases exponentially. The contact area should be carefully adjusted to conductors to solve this problem by geometrical engineering. Shi's team employed a fish-scale-like morphology, or buckles into cracks to achieve a broad range of sensing and high reliability (albeit the range of linear responses is limited). Liu's group devised a sheath buckled construction to increase the buckle contact area. The interbuckle contact area reduced as the tensile strain increased, leading to a linear-responsive range of strain up to 100 percent [102].

Buckles may be produced on many unique surfaces using patterns such as laser checkers, columns, spheres, or pyramids to enhance sensibility, stretchability, and range of linear answers for resistive tactile sensors. To boost sensitivity, additional spacers are like electrified mattresses that were sometimes used to split buckling electrodes of pressure sensors. Capacitive pressure sensors, which employ metal nanowires as flexible electrodes, are more extensively used for touch panels and positioning than resistive pressure sensors. The key to making sensors stretchable is buckling geometry; comprehensive reviews on the subject are available. Despite significant progress, the pressure sensors and strain development for wearable electronics face significant obstacles [103, 104]. Notwithstanding the manufacturing prototypes of sensor arrays for monitoring multidimensional stresses or positions, large sensory array applications that can endure multidirectional and different deformations have yet to be reported. Furthermore, integrating units of measurement with other devices such as antennas and energy harvesters is also a problem [105]. After conducting materials undergo mechanical deformation in response to an applied strain, piezoresistive strain sensors produce a change in the resistance. The most popular method for making nanomaterial-based strain sensors are depositing or synthesizing nanomaterials on the surface or doping them in a substrate of elastomeric (such as PolyUrethane (PU), PDMS, or PolyEster (PE)) to form a continuous formation of the conductive network. The factor of gauge (GF) is defined as (R/), where is the applied strain, and is the relative resistance slope fluctuation of the sensor under pressure. The GFs are primarily caused by transduction processes such as material piezoresistivity disconnect between overlapping nanomaterials, tunneling effect, crack propagation, and design of strain sensor structure [106].

Strain applied to a strain sensor can cause slipping or interruption among nanomaterials, reducing the contact surface among them and therefore increasing electrical resistance. Many high-sensitivity pressure sensors have been created based on the disconnect principle. Nanowire and graphene strain grid sensors with high GFs and tunable sensitivity have been widely researched among them. This microstructure (consists of a strain/release membrane of composite with RGO film and an elastic bed) based on disconnection mechanism improves the strain sensor's sensitivity (GF 16.2–150) and traction capability (up to 82 percent strain). The FSG sensor's properties allowed it to be attached to human skin and track human actions including phonation recognition and wrist pulse. A capacitive strain sensor is another typical form of flexible electronics sensor. The capacitance fluctuation in strain capacitive sensors responds to the strain is used. A typical capacitive sensor consists of a layer of a dielectric sandwiched among two electrodes, the dielectric layer thickness varying as the sensor is stretched. Parallel page layout is the most often used architecture in the original design of capacitive sensors because it is simple to model and build. The sensor electrodes must fulfill the condition of being stretchy in order to accomplish conformal skin adhesion. As a result, flexible conductors made of nanomaterials are often utilized as electrodes. The applied strain generally causes the elastic material to flex, causing the thickness of the dielectric layer and the surface of the overlap to vary among the two electrodes and the capacitance to change in response to the strain [106]. C l 0 0 = r 0w d0 0 / (1) is the initial of a capacitive strain sensor is of the parallel plate type, where 0 and r are the vacuum dielectric constant and the relative permeability of the dielectric layer, respectively, and l0, w0, d0 are the initial length, width, and thickness. The dielectric layer, respectively, the GF of the capacitive strain sensor may be calculated as GF = C / .). In addition, a multidimensional strain sensor based on Ag NW diffusion network films with a uniformly sandwich structure showed an extraordinary capacitive response in axial and vertical strain. With a high GF (>20), the gadget can detect a wider range of strains (up to 35 percent). The distribution of strain on the joint for the hand grasp action may be distinguished and mapped by the sensor implanted in a glove [107]. Capacitive strain sensors with tangled structural electrodes had higher linear sensitivities and lower residuals than capacitive strain sensors with the parallel plate, according to another method. Because of their lesser sensitivity, capacitive sensors of strain are more suited for big strain supervision than resistive strain sensors. A particular piezoelectric effect of solid type material is used in piezoelectric-type strain sensors to help transmit mechanical energy into output power. Wearable strain sensors have been developed using a range of piezoelectric nanomaterials such as polylactic acid, nanowires of zinc oxide (ZnO), PVDF nanofibers, and PVDF-TrFE. Piezoelectric strain sensors have a wider detecting range, a faster reaction time, and are very sensitive to dynamic mechanical stimuli. They are also often self-powered [108].

4.5. Pressure sensors

The wearable pressure sensors with high sensitivity could mimic the human skin features by producing electrical impulses to understand the applied pressure, and has a wide range of potential applications in artificial intelligence systems and physiological human signal monitoring. Pressure sensors, like strain sensors, use physical transduction principles such as piezo-resistive, capacitance, piezoelectric, and triboelectric. For the most part, the resistive (resistance changes pressure) and capacitive effects (varies of capacitance with pressure) have been used in the manufacturing of pressure sensors. To respond to the applied pressure, the resistance type measuring device primarily relies on variations in geometrical Structure, call resistance, or tunneling resistance. Due to the simple preparation technique and device structure, the easy reading signal, and the wide measuring range piezo-resistive pressure sensors have been widely used recently [34, 109, 110].

Various developing nanocomposites and nanomaterials with innovative geometric microstructures have been investigated for the development of high-performance resistive pressure sensors. Although, most conventional resistance sensors with flat composite structures have poor sensor performance, so highly sensitive networks for pressure measurement can be formed using new microstructures of geometric, like interlocking structures, penetrating networks of nanomaterial (e.g., CNTs, NWs, and rGO), patented microstructures, porous structures (e.g., hollow spheres, sponges, and foams), conductive As a pressure sensing device, monolayer graphene was placed over a hierarchical structure of PDMS bio-inspired. The gadget was found to be more stable and reliable after a 10,000-cycle durability test [111]. These sensors, which were made from electrospun nanofiber fabric and films, have an outstanding piezo-resistive reply. The sensitivity of a pressure sensor made of PVDF- rGO nanofiber sheets was up to 15.6 kPa, with a detection limit of less than 1.2 pa and operating voltage 1v. High sensitivity to detect static pressure and decreased hysteresis are two advantages of capacitive pressure sensors. Recently, capacitive pressure sensors have been given the capacity to use wearable sensor devices with high sensitivity and high contact. Stretchable graphene-based transparent electrodes were used to create a capacitive touch sensing system. Under increasing deformation, the multi-contact and 3D sensing characteristics of the sensor were emphasized. Furthermore, it achieved excellent sensor results in both noncontact and contact surface sensing modes at the same time [111].

Kernel-shell PDMS/PVDFHFP mattresses made of elastic nanofibers were used as the sensor's dielectric layer. The gadget accurately sensed dynamic and static pressure by using capacitance shifts and triboelectric phenomena. On the other hand, piezoelectric sensing has been proposed as a viable option for developing a new self-powered generation pressure sensor with the performance of exceptional. Piezoelectric nanomaterials having remarkable piezoelectric and mechanical characteristics, like ZnO nanowires and flexible electrospun nanofibers of PVDF-TrFE, have been employed to make piezoelectric pressure sensors at various periods [112, 113].

Human motion detection, health care supervision, the skin of electronic (e-skin), soft robotics, and interface of human-machine, monitoring human health, the artificial intelligence, electronic skin, and so on have all piqued interest in flexible wearable pressure sensors. However, achieving more sensitivity and a wide detecting range that as well as performing good in reaction time provide wearing comfortability, remains stability and dependability is a major difficulty for pressure sensors. For a flexible wearable piezo-resistive pressure sensor, the conductive fabric of MXene/cotton was manufactured using a simple cover dip-coating approach and sandwiched among an interdigitated electrode and a polydimethylsiloxane film. Cotton fabric's abundant hydroxyl groups and MXene's functional groups aided in the adhesion of MXene conductive nanosheets to tangled fiber networks, leading to a conductive network that is effective [51].

The MXene/cotton (MCF) fabric high sensitivity pressure sensor (5.30 kpa in the pressure range 0-1.30 kpa), wide sensing range (0-160 kpa), and fast response/recovery time (50 ms / 20 ms), excellent and long-lasting stability shows durability by combining good flexibility and the porous three-dimensional structure of cotton fabric with the sensor-specific sandwich architecture. Furthermore, the MCF of the pressure sensor can detect a variety of human health symptoms like finger movement, wrist pulse, and Parkinson's static tremor of early-stage. This is an important point, an MCF-based pressure sensor created E-skin to detect different touch inputs, indicating high potential for the next generation of wearable electronics [114, 115].

4.6. Electrochemical sensors

We have seen great progress in electrochemical sensor development for continuous non-invasive monitoring of chemical markers over the last five years. Special attention is paid to skin-covered electrochemical measurement platforms that are significantly different from conventional laboratory-based systems of electro-analytical. Traditional bulky electrochemical equipment and large electroanalytical cells must be transferred to the person's arms or wrists, presenting several key operational and design issues. Besides these obstacles, electrochemical sensors are presently the most used wearable chemical sensors. Wearable electrochemical sensors provide non-invasive continuous molecular information about dynamically changing chemical components of various bioenergy for a variety of biomedical, wellness, and security applications [58].

Traditional blood-centered invasive diagnostics, which are typically used in hospital settings, are being phased out in favor of tailored, remote diagnostic and care points in biomedical diagnosis. Wearable electrochemical sensors have come into play a key role in these fast advances, and now they are causing a major paradigm shift in analytical chemistry. Epidermal electrochemical sensors are a substantial departure from standard centralized laboratory-based electroanalytical systems, and they're only getting started. Wearable electrochemical sensors have recently become popular over the last three decades, owing to significant advances in a variety of fields, lab-on-chip detection microsystems, including chemically modified electrodes, miniaturized instrumentation, printed planar electrodes, and flexible materials [116]. Wearable electrochemical measurement systems are now the most popular wearable sensor systems, owing to the truth that miniaturization does not affect their appealing parsing performance. Many of the latter breakthroughs are based on lessons learned by engineers and scientists during the mobile evolution and wearable glucose monitoring systems for management of diabetes over the past four decades of miniaturizing analyzers of glucose that benefited from significant investments of financial. Wearable electrochemical sensors are becoming increasingly complex, including new designs, materials, and sensing algorithms to attain excellent performance analytically [117, 118].

The potential for electrochemical sensors to be integrated into fluidic systems has long been recognized in electrochemistry studies. Given the growing importance of sensor devices and integrated separation, this trend is likely to continue. Many experts believe that there is no longer a clear distinction between a chemical sensor and an integrated device separation. They are built on diverse concepts and have the same goal in mind. Kennedy's group has produced several excellent instances of highly effective pseudo-chemical sensor systems [119]. Due to their excellent sensitivity and selectivity, enzyme-based amperometric sensors have been extensively studied. These sensors can be functionalized with small volume samples of complicated matrices. However, one of the most difficult aspects of enzymatic electrochemical sensing is maintaining stability, which can be hampered by enzyme denaturant or fouling from species present in the sample matrix or produced during the sensing process. To recapitulate, fully realizing the potential of the created electrochemical sensors and biosensors, particular electrochemical procedures that are suited for the sensor and analyte must be used [120, 121].

4.7. Temperature sensors

Temperature is the most physical characteristic that represents the condition from the measured item and its surroundings [1, 3, 12], varies in times and geographically, allowing for object's monitoring and environment's changes. Temperature control is critical in daily living, temperature and production of industrial sensing have received more attention in recent years. Temperature sensors are likely to have more practical uses in the rapid development of intelligent wearable devices and temperature control systems. Sensor components, in particular, are frequently needed to be directly connected to curved surfaces or human skin for continuous and consistent data reading. As a result, flexible temperature sensors which can bend or even stretch are in high demand. In practical applications, metals, inorganic semiconductors, and metal oxides are often utilized as heat-sensitive materials in rigid temperature sensors. These materials have some flexibility at the micro/nanoscale, but they are prone to breakage when bent repeatedly or at a considerable corner. Simultaneously, the preparation techniques for these substances are rather complicated, requiring high temperatures in many cases [26-28]. Non-toxic, high precision, rapid response, high sensitivity, and high repeatability are other desirable qualities in flexible temperature sensors for wearable applications. Flexible temperature sensors based on carbon nanotubes have lately gained a lot of interest due to their unrivaled benefits in meeting the above requirements. Carbon nanoparticles, a type of sophisticated conductive material, have been extensively used in wearable electronics [60].

Flexible temperature sensors based on carbon nanomaterials have been extensively explored. Better mechanical stability and advanced carbon nanomaterials have higher electrical conductivity, higher thermal conductivity, and higher chemical stability compared to other substances used in temperature sensors, and are easy to manufacture and give them a competitive advantage in flexible temperature sensors use, and utilized in domains like electronic skin (e-skin) and wearable electronics, demonstrating outstanding sensitivity, high precision, improved repeatability, and quick response. In addition, the range of temperature detection is broad (normally 20–120 °C), and the maximum sensitivity is often achieved among 20 and 50 °C that meets the requirements of wearable temperature sensors which must be sensitive to temperatures between 25 and 40 °C. Flexible carbon nanomaterial-based temperature sensors have shown considerable promise in a variety of fields, such as wearable electronics, robotics, care of medical, and sports [43].

Flexible temperature sensors based on carbon nanoparticles are also beneficial for implantation in health monitoring electronics in vivo, since carbon nanomaterials are non-toxic and biocompatible. They do not generate pollution when mixed with biodegradable substances and hence do not environmental damage after decomposition, making them the potential for outdoor throwaway devices. For temperature sensors, abstaining from the influence of mechanical stress on sensors function remains a difficulty. Temperature sensors should always have a construction that allows them to adapt to curved surfaces. Wearable sensors must be accurate and dependable without interfering with users' natural movements or comfort. Flexible sensors' skin-like stretchability and conformability are thus important features. The resistance of a flexible temperature sensor can be influenced by induced-human strain/stress, lowering its dependability [37].

The use of highly malleable thermoplastic polymers, like polyethylene terephthalate (PET) and polyurethane (PU), as well as silicon elastomers (PDMS, EcoFlex), is one way to achieve this. Kim et al. demonstrated a flexible organic temperature sensor made of polyvinyl alcohol which was extremely stable after 50 flexural cycles. Dinh et al. investigated different folding angles for a CNT-based thermal flow sensor. The greatest resistance change in the folding studies was around 0.2 percent, indicating the remarkable CNT-based sensor stability. A fiber-shaped of graphene/nickel-based temperature sensor was demonstrated by Hilal et al. After the bending test, the new sensor preserved 75% of its sensitivity. The flexibility and mechanical properties were investigated by Rajan et al showed the potential of graphene-coated polypropylene textile fiber-based temperature sensors. Multiple bending did not result in a substantial change in resistance [122]. PEDOT: PSS Kapton-based flexible and printed cotton sensors were shown to have great stability and no noticeable alterations after being bent up to 300 times in another investigation. Temperature sensors must also contend with humidity stability. Ambient humidity inevitably affects flexible and wearable sensors. As a result, developing a flexible temperature sensor that is humidity insensitive could be extremely important. Kim et al. showed the use of ion channels to create a flexible temperature sensor. Wang et al. created a crosslinked PEDOT: PSS-based flexible temperature sensor that has excellent stability among 30% and 80% relative humidity. Liu et al. demonstrated a humidity-resistant polyethyleneimine/reduced oxide-based of graphene temperature sensor that can be attached to the skin [36].

4.8. Physiological biochemical sensors

Wearable biochemical sensors are gaining popularity because of their enormous potential in customized therapy and consecutive health monitoring. As a result, a lot of work has gone into developing sensors that can measure numerous components of chemicals in the human body in real-time and non-invasively, such as perspiration, saliva, tears, and so on. Wearable biochemical sensors have been designed to investigate many biomarkers, and are now regarded as wearable electronic devices for practical use, thanks to breakthroughs in the science of materials and engineering of mechanical. Wearable biophysical sensors can be pressed against the skin to monitor biophysical characteristics of the human body in real-time, like blood pressure, skin temperature, and heart rate that is important in medicine applications [39].

Wearable chemical sensors use lab-on-a-chip technology to cope with parallel processing and trace several samples on a single sensing device. Wearable biochemical sensors can precisely quantify biomarkers in urine, sweat, blood, saliva, tears, and breathing gases, allowing for monitoring human body metabolism and health. Furthermore, certain wearable biochemical sensors can detect dangerous compounds (like sulfide and phosphide) as well as a variety of environmental circumstances, improving the quality and safety of daily life. Motion-state sensors and biophysical sensors are two types of wearable sensors that have been on the market for a long time and are frequently utilized by customers. Besides, wearable biochemical sensors, are still not widely available since the components in human fluids are extremely complex, making biochemical parameters hard to distinguish compared to biophysical sensors [48].

The majority of wearable biochemical sensors are used for diagnostic biomarkers which are found in the body regularly. Some chemicals, on the other hand, are not generally available in healthy persons, however, they appear sick persons or have health problems. Antigens, for instance, are frequently found in body fluids and sick tissue cells, and unhealthy persons. Furthermore, several dangerous substances found in the environment, like phosphates, sulfides of toxic, nerve gas, and cocaine may be inhaled or eaten by individuals, causing health problems. Wearable biochemical sensors that detect such compounds could be used to track illness reconstruction and assess the environment's health for the human body. For example, to make a sensing electrode that can detect certain antigens, a combination of light-resistant and conductive polymer-modified into antibodies was utilized [123].

Lee and colleagues employed gold to create a three-dimensional sensing electrode. After connecting antibodies to the suggested wearable sensor, it may be utilized to identify tumor cells in patients. Similarly, sensors that detect sulfides, phosphates, etc compounds often utilize conductive carbon materials and conductive polymers as detecting electrodes in combination with molecules that can react with biomarkers. Hall et al. proposed a sensor based on wearable gloves made up from carbon electrodes that have been corrected using a multi-walled CNTs combination and 4-(3-butyl-1-imidazolio)-1-butanesulfonate. Using square-wave voltammetry, the sensor of glove-based can directly oxidize fentanyl in both powder and liquid forms into 10 m detection constraints [124].

Zhao et al. suggested a portable fully integrated nanosensing device graphene-based for detecting cytokine indicators in saliva that was smaller than a smartphone and could be carried around. The material or the micro-manufacturing method was used to create the three-dimensional structures. In general, using conductive porous materials rather than complicated production procedures is more cost-effective [125].

The manufacturing methods of the sensing electrodes have a tight association with the development of wearable biochemical sensors. The major methods of preparation sensor electrodes are wearable biochemical sensors, screen printing technologies, and a system of micro-electro-mechanical (MEMS). These two traditional production processes are applied to the field of wearable biochemical sensors, supporting sensor technology and application development. Using a screen print page, one of the most common ways for fabricating sensing electrodes is screen-print. The picture must be printed photographed and transferred to a very thin cloth (the screen) to block off the unprinted parts and function as a stencil. Various on the same sensing electrode can combine biosensors using screen-printing technology to provide simultaneous detection of various values. For wearable biochemical sensors, both on-screen MEMS technologies and printing have the mass-produced advantages of electrodes of the sensor. Screen-printing methods need fewer instruments and have simpler product lines, which makes them more suited for most labs. However, MEMS technologies allow for nanometre-level control of the film thickness on sensing electrodes. In general, these two technologies not only enable the mass production of electrodes of the sensor for wearable sensors of biochemical, but also make it easier to design the structure, integrate the electrode, and parameter the sensor electrodes [126].

4.9. Energy harvesting and portable power supply

The energy source for portable and wearable electronic devices is a fundamental impediment to their integrated and flexible deployment. Electronic gadgets increasingly use replaceable batteries as their primary source of power. The rigidity of these batteries, on the other hand, limits the general flexibility of electrical equipment. The short life of batteries, as well as the potential for contamination, are incompatible with the ideals of sustainable development. The human body temperature is constant, yet it is a temperature differential between it and the outside environment. As a result, thermoelectric generators can transform the human body heat with useable electric energy, making them a reliable energy source. Solar energy is another type of green, sustainable, and clean energy that may be used to power wearable electronic gadgets. In addition, hybrid energy pickers which combine the ability to collect diverse sources of energy boost energy harvesting efficiency and expand application scenarios[127].

Automated sensor devices which can perceive essential chemical, physical, and biochemical data without an external source of energy supply have increasingly emerged with people's awareness of the development of self-powered technology. A capable self-sensing system is projected to be the most common type of sensor node in the future of the internet of things age since there are no difficulties with battery replacement or pollution. Self-powered sensing can be accomplished in two ways. The self-output electrical signal can be used as a signal to the sensor in active sensing. A triboelectric signal, for example, could be utilized as a signal to the sensor for pressure sensing. Another technique to achieve self-powered sensing is to use energy picking technologies to deliver power to a module of the sensor. To power modules of sensors and enable active sensing, numerous self-powered systems based on wet electricity, thermoelectric, piezoelectric, and redox electricity have been researched [3].

With the advancement of self-powered technology, it is now feasible to perform a variety of actuation operations without the use of external energy. For example, to implement the tasks of automated control, medication administration, microfluidics and liberation, and adjuvant therapy, several researchers employ electric power converted from other energies kinds as excitation signal energy. Self-powered intelligent systems, such as portable and wearable computers, gradually, are replacing bulky computers as the interface for a new intelligent human-machine generation interaction, are playing an important key in the identification of intelligence, control of intelligence, and other areas. In the evolution of electronic gadgets, self-powered systems are progressively becoming a major trend. Some recent publications have detailed the most recent advancements in self-powered systems. Khalid et al., for example, reviewed the energy of human-powered harvesting technologies which may be used for smart electronic systems. Dong et al. began self-powered presented and sensors cutting-edge work based on the synergy effect of artificial intelligence technology and wearable sensors [21].

Gunawardhana et al. and Wang et al. concentrated on the triboelectric energy harvesting technology, describing the development and implementation of wearable triboelectric nanogenerators (TENGs) in self-powered systems in detail. The foundation of a self-powered system is energy collection. Furthermore, we require sustainable, renewable energy and clean to power wearable and portable gadgets for the sake of convenience and environmental preservation. There are many different types of environmental energy, including energy created by the human body as well as energy given by the environment. Mechanical human activities like finger movement, running, and walking may generate significant energy of mechanical in daily life. Although collecting the human body's mechanical energy, low-frequency and multimode-human mechanical properties movement are difficult. The two most frequent methods for collecting the mechanical energy produced by the motion of human is triboelectric and piezoelectric generators [128].

The well-known principle of frictional electricity underpins triboelectric energy harvesting. When two dissimilar items come into touch, static charges are generated on their surfaces. As a result of the relative motion among two potential differences, charged objects are created, which drives the charges flow. Flexible piezoelectric polymer materials have reached the public eye as a result of advances in materials research. Polymer piezoelectric materials have exceptional flexibility and may conformally bind to the human body's surface, considerably enhancing wearability and encouraging the development of piezoelectric energy pickers for mechanical energy harvesting of the human body. For a high-performance nanocomposite of hybrid site (HNCG) production machine, Jeong et al. produced a 1D–3D (1–3) completely piezoelectric nanocomposite utilizing perovskite BaTiO3 (BT) nanowire and pattern (P (VDF-TrFE)) (vinylidene fluoride-co-trifluoroethylene) [21, 129].

When employed for hand movement energy collecting, the flexible HNCG produced 14 V voltage and 4 A current. Even prior piezoceramic film-based flexible energy harvesters can't match this degree of output performance. A system of hybrid energy harvesting integrated with numerous modes, based on a single energy harvesting technology, makes use of diverse enhanced efficiency of energy and methods of energy harvesting. Lee et al. fabricated a hybrid nanogenerator of energy-scavenging based on a micropatterned polymer of piezoelectric P(VDF-TrFE), a highly stretchable, graphene nanosheets, and a micropatterned polydimethylsiloxane (PDMS)–carbon composite of the nanotube. The energy of biomechanical can alone be collected when the body of a human maintains a specific motion posture, whereas thermoelectric energy could be harvested constantly regardless of humans [20].

When linked to a human elbow, shoulder, hand, and other body parts, this hybrid energy harvester can gather biomechanical and thermal energy at the same time. Solar energy is essential in the subject of energy harvesting since it is a type of sustainable clean energy. The biomechanical and solar energy collection at the same time is also thought to be a good way to boost energy collecting efficiency. A solar-triboelectric hybrid system of energy harvesting was proposed by H. X. Zhang's group. The technology of energy harvesting is the foundation of self-powered systems, allowing them to perform some operations without the need for external energy. Sensors are the cornerstone of electronic devices' extensive functionalities since they are required to sense the external world. Wearable scene sensors can operate as a five human sense organs extension, allowing individuals to better perceive their surroundings [130].

As a result, self-powered systems offer a lot of potential in the realm of wearable sensing. Several portable and wearable self-powered sensors for measuring physiological, chemical, and physical information have been created using energy harvesting technologies. Self-powered sensing can be accomplished in two ways. The first one is active sensing, in which the electrical signal is used as the sensing signal and the output electrical signal is influenced by external stimuli. Liu et al. revealed self-powered epidermal electronics by a tactile sensing function. Active sensing has been extensively employed in temperature monitoring, pressure monitoring, and humidity monitoring. This type of epidermal electronics uses a triboelectric signal to reflect pressure on the skin and distribution of pressure, which has a lot of promise in wearable electronics. The deformation degree of a piezoelectric material affects its output, allowing these materials to perform active human body positions detection. A flexible wearable pressure sensor based on piezoelectric materials was shown by Yang et al [19].

5. Conclusion and future aspects

Wearable electronics parallel to digital health care expansion have developed rapidly in recent years and are likely to extend even more in the first few years of the new decade. Integrating Nanomaterials and Nanocomposites with wearable electronics is the next generation of these devices. Furthermore, converting existing attachment-based wearables and devices to integrated technologies need a substantial reduction in size that maintains their capabilities and function. Wearable sensors based on nanomaterials are already well-known, but actuators of nanomaterial-based wearable are still in their initial states. The contribution of nanoparticles and nanocomposites to wearable technology is examined in this paper, with an emphasis on wearable sensors and actuators. Wearable technology has established itself as one of the most interesting subjects in the industry over the last few years, fueled by market hype, youth trends, and vast sums of money. In this review, various organic, inorganic, polymeric, and hybrid materials are introduced for fabricating wearable electronics by different fabrication techniques. Important features in wearable technology include multifunctionality, being user-friendly, and being comfortable. Smart-textiles are among the most interesting materials for wearable electronics. Challenging issues in wearable electronics include continuous, stable, and prolonged energy supply. The wearable electronic market is also witnessing slow commercialization, primarily due to price sensitivity; acceptance from end-users; and concerns related to the quality, authenticity, and reliability of the products. These issues make large-scale exploitation challenging. More consideration and studies are required to overcome these challenges.

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