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An Overview on Advanced Materials Used in Health Care Applications

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ABSTRACT

Wearable devices possess immense potential that could bring about a revolutionary, nonclinical approach to health monitoring and disease diagnosis. Through ongoing innovation and dedicated focus on materials and fabrication technologies, the development of these healthcare devices is being actively encouraged. The integration of wearable devices capable of collecting diverse physiological data is gradually becoming a part of people's daily lives. Monitoring physiological indicators is crucial for assessing health, enabling early detection of diseases, and reducing the occurrence of more severe health issues. This proactive approach to disease prevention can also contribute to lowering overall public sector healthcare costs. This review emphasizes the importance of fabrication technologies and the properties of materials utilized in wearable healthcare devices.

Keywords: Health care device; Fabrication technologies; Nanomaterials; Sensors; Wearable device; Polymers.

1. Introduction

Humankind has benefited greatly from the manipulation of materials' properties. Inherent qualities of materials include electrical conductivity, toughness, toughness, magnetization, dielectric constant, and optical transmittance [1]–[5]. The internal structures of the materials—including the kinds of atoms, their local configurations, and the arrangements of these configurations into microstructures—are the source of these properties. To quickly review the emerging literature and determine the applications of different materials, extensive research has been conducted to identify the most important characteristics required for protection and ease of use.

When discussing materials in healthcare applications, they are often grouped according to their use in wearable healthcare devices. A noteworthy area of wearable technology development has been the emergence of wearable medical devices [6]–[8]. These gadgets gather several physiological data of the human body using wireless connection, multimedia, and sensor technology, allowing for the monitoring of bodily indicators [9],[10]. The wearability, portability, and sustainability of wearable technology help them to overcome the drawbacks of conventional medical equipment [11],[12].

The next generation of portable gadgets for remote medical practices is predicted to include wearable or attachable health monitoring smart systems [13],[14]. Integration of wearable electronics is a relatively new, big breakthrough that is spreading widely over time. Wearable technology is used in the medical field to track several physiological characteristics such as skin conductance, heart rate (HR), respiration rate, humidity, body temperature, and blood pressure [15],[16].

Flexible sensing electronics, which offer wearability, mobility, remote capabilities, and real-time data, have the potential to completely transform medical equipment and traditional diagnosis techniques [17]. Nowadays, medical facilities are able to get health signals in real-time, which helps with illness diagnosis and intervention selection. However, because central hospitals house the majority of healthcare services, getting care for a large number of patients can be time-consuming and arduous. Patients may experience inadequate or delayed treatment, which might worsen their agony or possibly cause them to pass away, especially if they live in impoverished nations. Further impeding disease diagnosis and treatment is the expensive expense of buying, utilizing, and maintaining medical equipment, which places a heavy financial strain on hospitals and patients. There are many obstacles to overcome in the development of wearable sensors for healthcare applications, such as choosing appropriate substrates, biocompatible materials, manufacturing processes, and guaranteeing continuous monitoring, washability, and uninterrupted signal display circuits [18]–[20].

Three basic parts make up flexible and stretchable sensors: the substrate, the active element, and the electrode/interconnect. Although organic materials are very stable chemically and mechanically, very few of them have desired active properties. However, because of their fragility and stiffness, conventional inorganic electronic materials lack mechanical compliance despite being responsive to a wide range of stimuli. Thus, integrating various materials can provide a way to attain mechanical robustness, flexibility/stretchability, and high-performance measurements in a single device. Developments in material preparation, such composite synthesis and dimensional scaling, can aid in the creation of these gadgets. The upcoming sections will delve into commonly used materials and their roles in substrates, active elements, and electrodes [21],[22].

2. Materials Used in Wearable health care devices

In recent years, wearable systems incorporating unique sensing materials and device structures have demonstrated high sensitivity in simulating human somatosensory systems. These systems have demonstrated the ability to easily and noninvasively track biophysical and biochemical signals, such as blood pressure, metabolites, functional proteins, body movements, body temperature, and oligonucleotides [1],[23]. Furthermore, by gathering thorough data on human health and producing sizable datasets, these wearable healthcare systems not only help to improve health status but also significantly advance medical technology [24]. But despite the market for wearable devices expanding quickly, there are a number of obstacles that have made the actual implementation of wearable healthcare systems comparatively sluggish.

First and foremost, materials with strength, abrasion resistance, and compatibility are needed for these systems to be wearable and compatible with the skin or other surfaces of the human body [25]. This means eschewing the semiconductor industry's standard use of integrated circuit technology and brittle materials. Second, the human body demonstrates intricate characteristics [26],[27]. In the development of wearable sensors for healthcare applications, the choice of appropriate substrates, biocompatible materials, and manufacturing processes is critical to addressing these issues. Other difficulties include the requirement for continuous signal readout circuits, washability, and the simultaneous monitoring of multiple analysts.

It is expected that wearables of the future will have more sophisticated features, like more precise recording. In order to do this, a variety of cutting-edge materials will be crucial to the creation of wearable technology with distinctive uses. Using the right materials and assembly techniques is essential to getting wearable sensors with high sensitivity, great stability, and a broad strain range. Because of their exceptional mechanical and electrical properties, a variety of materials, involving carbon-based materials, metal nanoparticles (MNPs), nanowires

(NWs), and conductive polymers (CPs), have been widely used in the creation of wearable healthcare devices in recent years [28]–[36]. Among the different material options, advanced carbon-based materials like graphene, carbon nanotubes (CNTs), carbon black nanoparticles (CBNPs), and carbon-based nanofibers offer unique advantages. These materials possess excellent electrical conductivity, high chemical and thermal stability, and ease of functionalization, making them highly suitable for wearable electronic products and applications [37]–[42]. Graphene is an essential carbon-based material for the development of wearable medical devices. Graphene's small size, exceptional mechanical properties, and superior electrical conductivity make it a good material to use as an active sensing element in flexible sensors [43].

Furthermore, because of their excellent sensing capabilities, large surface area, strong adaptability, and compatibility with low-cost manufacturing processes, a variety of inorganic nanomaterials are used as building blocks for wearable sensors [44]–[47]. These materials offer the advantage of being broadly applicable, and they could significantly progress wearable technology. All things considered, the use of cutting-edge materials, such as carbon-based materials and inorganic nanomaterials, is essential for propelling wearable device innovation in a fast, steady, and predictable manner and allowing the devices to carry out a variety of tasks with greater accuracy. Because of its superior electrical conductivity, metal is a material that is frequently used in wearable sensors. Metals can be used as active materials in a variety of ways, such as liquid at room temperature, as flexible or stretchable configurations, or even as nanowires or nanoparticles. Piezoresistive composites and conductive inks are commonly made with fillers like nanowires (NWs) and nanoparticles (NPs).

Many different types of nanomaterials have been used in the development of wearable temperature sensors. In particular, conductive polymers, graphene, carbon nanotubes (CNTs), graphene, and nanoparticles of copper and nickel metal have all been employed as thermal sensing elements [48]–[52]. In order to give the active materials in flexible wearable sensors stability, it is imperative to use a flexible substrate. The flexible substrates polyurethane, polydimethylsiloxane (PDMS), polyethylene terephthalate, Ecoflex, and polyethylene naphthalate are among the most often used ones in wearable sensors for health monitoring [53]–[56].

The creation of flexible sensors that can adapt to the body and continue to function while moving and engaging in different activities is made possible by these materials. The utilization of biocompatible materials is crucial for wearable health sensors, as they come into contact with human skin. In this regard, both inorganic and organic materials exhibit biocompatibility. Piezoelectric sensors have been made using both organic and inorganic materials, including poly-L-lactic acid, polyvinylidene fluoride, and poly-D-lactic acid, as well as inorganic materials like zinc oxide, lead zirconate titanate, and lithium niobate [57]–[59]. Notably, because of their affordability and usability, piezoelectric polymers have drawn a lot of interest.

The most popular flexible piezoelectric material for wearable electromechanical sensors is polyvinylidene fluoride. The material's unique physical characteristics and semi-crystalline features are caused by its compact linear molecular structure. Apart from the inorganic and organic piezoelectric materials that were previously discussed, silk is a naturally occurring, flexible material that holds great potential for use in textile-based wearable sensors.

Due to its piezoelectric properties, silk can be applied to many different types of wearable sensors. In [60]. It is a good option for incorporation into wearable technology due to its biocompatibility and flexibility.

3. Manufacturing of wearable devices

The advancement of wearable devices is driving progress in materials science and manufacturing methods. Depending on the intended use, wearable sensors can have different fabrication techniques and materials. Many production methods have been documented over time, with printing technologies becoming more and more common for creating high-performance electronic components and related sensor devices on flexible substrates at the necessary processing temperatures [61]–[65]. Printing technology's additivity—the ability to create structures and patterns by layering on materials—is a key benefit. Traditional manufacturing methods, on the other hand, depend on material subtraction, which frequently increases waste production and causes environmental problems. Because printing processes are additive, there are fewer manufacturing steps needed on the assembly line, which leads to much faster production routes. This not only improves efficiency but also helps address environmental concerns associated with waste generation.

Screen-printing is a widely utilized technique due to its advantageous characteristics, including low cost, suitability for large-scale manufacturing, and robustness [66]. This process is widely used to produce sensing elements for electromechanical sensors and functional electrodes for electrochemical sensors [67]–[69].

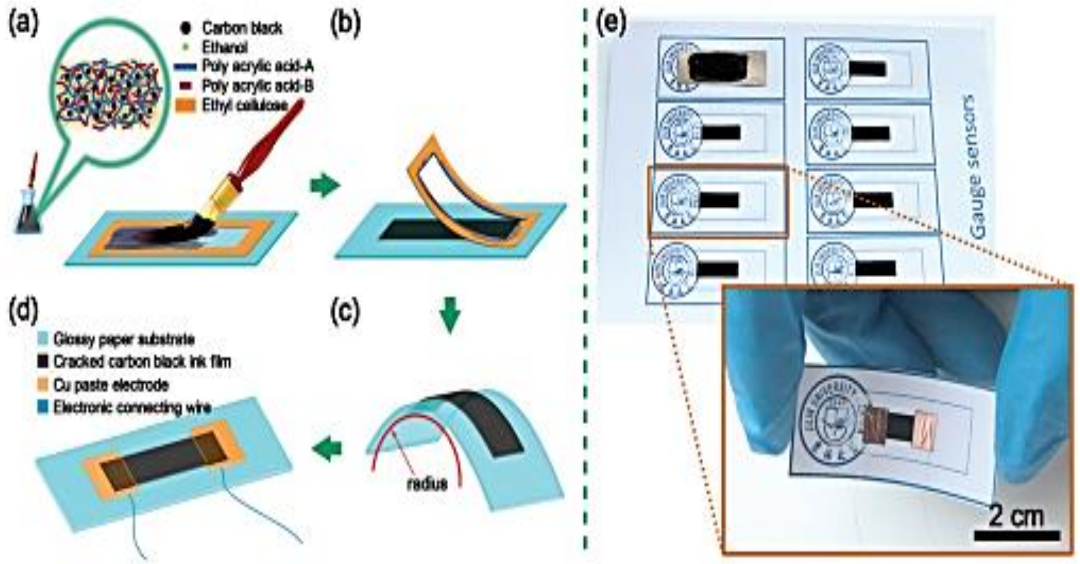

Figure 1. The PMSCSS (Printable Micron-Scale Cracked Strain Sensor) fabrication steps; (a) A paintbrush was used to apply carbon black (CB)-based ink to glossy paper during the screen-printing process. (b) A uniformly solidified ink film was produced by removing the mask used during printing once the ink had dried. (c) After that, the samples were bent to a radius of 1 mm, which caused a cracked morphology. After that, they were clamped between two glass slides in order to restore their flattened shape. (d) The layers and components of the PMSCSS are highlighted in the schematic structure. (e) A picture shows eight semi-finished PMSCSSs arranged on a glossy paper sheet the size of an A6. The image inset showcases the sensor's versatility. Each sensor has lateral dimensions of 21 × 50 mm and is printed on glossy paper that is 286 µm thick [70]

Figure 1 illustrates the fabrication steps for a printable micron-scale cracked strain sensor (PMSCSS) created using screen-printing [70]. Another printing technique, known as roll-to-roll gravure printing, offers a robust approach for various electrochemical sensing applications in wearable sensors. This manufacturing technique enables fast production on an industrial scale [71],[72]. Figure 2 presents a schematic diagram depicting gravure printing on a flexible substrate [73].

Inkjet printing is an advanced technique that involves precise deposition of functional ink droplets onto various substrates such as paper, plastic, or others, using a nozzle. This technique has gained significant importance in sensor development due to its accuracy, speed, and reproducibility [74]. An alternative to templates is inkjet printing, which has the following benefits:

(a) It uses less materials, which minimizes waste.

(b) It makes precise nanomaterial deposition possible, guaranteeing precise sensor fabrication.

(c) It provides flexibility in sensor design by making it simple to alter digital patterns [75].

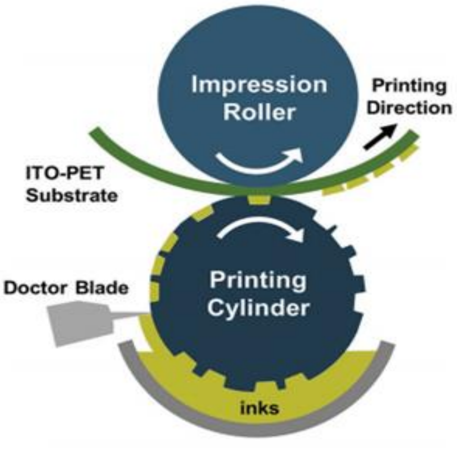

Figure 2. Gravure printing on a flexible substrate as shown in the schematic diagram [73]

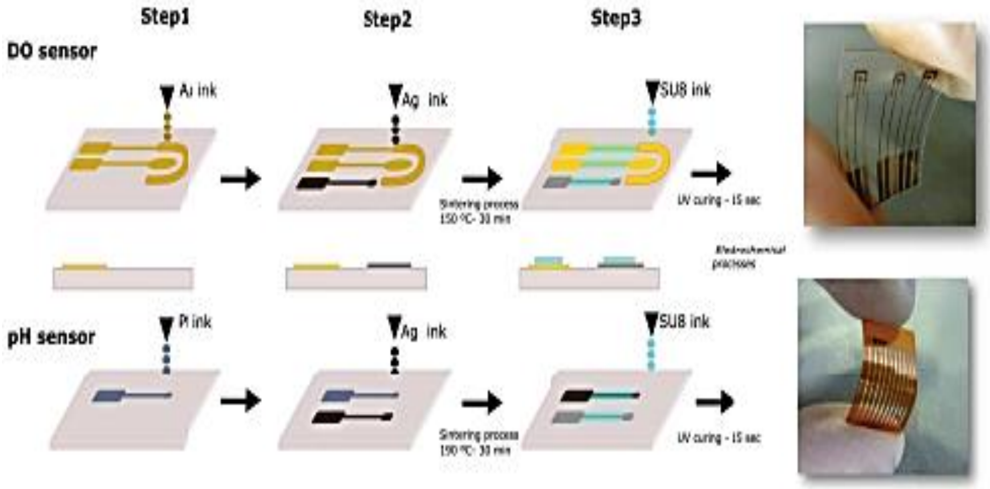

Figure 3. Schematic of the fabrication of the DO and pH sensors by inkjet printing on plastic substrates. At the right side can be observed pictures of the final printed sensors on PEN and Kapton substrates [76]

Currently, printing techniques, particularly screen printing, can produce thick membranes using a range of materials. However, their pattern resolution may not meet the demands of complex geometries. This has led to the development of a hybrid fabrication process that combines lithography and printing as a potentially effective method for producing highly patterned and sensitive devices [77]–[83]. This hybrid fabrication strategy enables the creation of diverse and adaptable wearable devices and can be further enhanced with custom-made inks and tools for screen printing. Another technique that demonstrates excellent performance in sensor manufacturing is laser scribing (LS) [1].

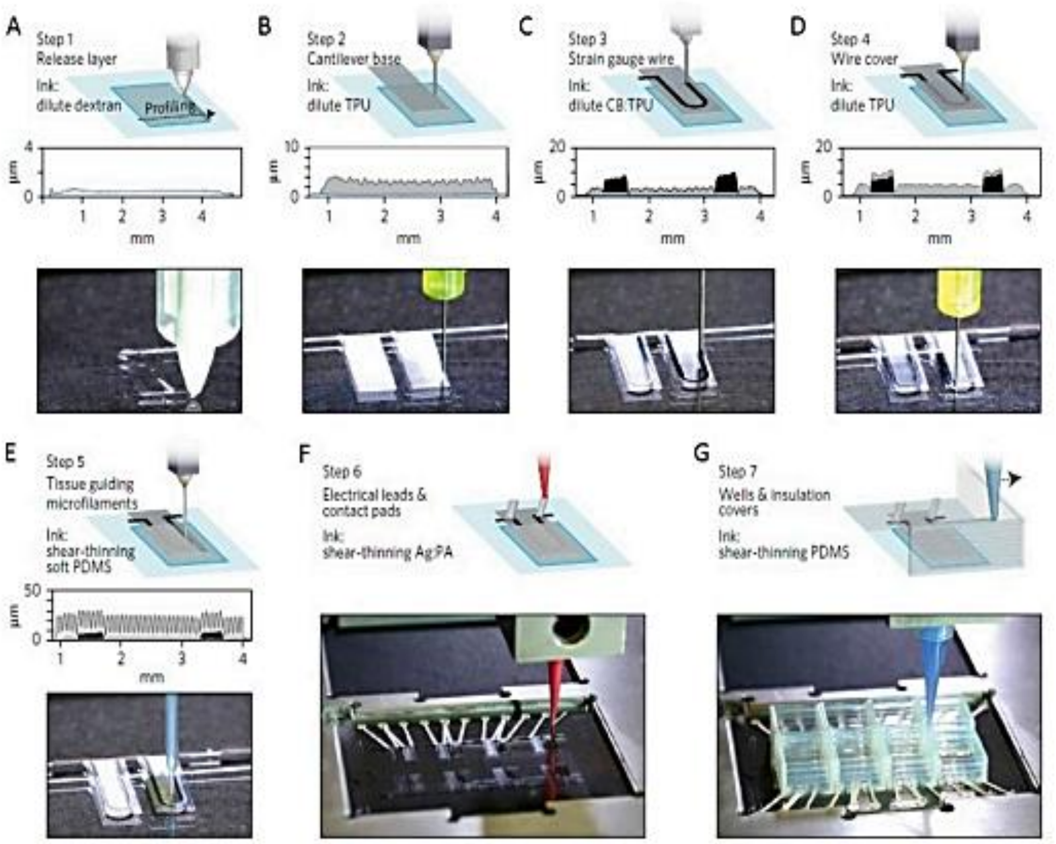

Figure 4. The device principle and the microscale 3D-printing procedure [82]

Figure 4 illustrates the device principle and the microscale 3D-printing procedure for the sensor fabrication.

(A) Print step 1 involves the printing of a 0.5-µm dextranthin-film sacrificial layer.

(B) A 3 µm TPU thin-film cantilever base is printed in print step 2.

(C) Print step 3 modifies the cantilever base by adding a 6.5-µm-thick CB:TPU strain sensor loop.

(D) A 1.5-µm TPU wire cover is added in print step 4.

(E) Print step 5 entails printing PDMS microfilaments in lines that slightly overlap, measuring 20 µm in height and 60 µm in width. These filaments direct cardiomyocytes to form anisotropic laminar tissues and function as the cantilever's upper portion.

(F) High-conductivity Ag: PA ink is used to add electrical leads and contacts in print step 6.

(G) Lastly, in print step 7, covers consisting of PLA, ABS, or PDMS are printed to form wells for holding cells and media and to insulate exposed wires [82].

4. Summary

The development of portable and wearable electronics is essential for many industries, including point-of-care medical applications and environmental monitoring. For the purpose of monitoring physiological parameters such as skin conductance, heart rate (HR), respiratory rate, body temperature, physical pressure, blood pressure, and humidity, wearable technologies are critical to the healthcare sector. Nonetheless, there are several barriers standing in the way of the advancement of wearable sensors for use in medicine. These difficulties include choosing appropriate substrates, biocompatible materials, and fabrication methods in addition to the requirement for continuous signal readout circuits, washability, and the simultaneous monitoring of multiple analytes. The use of biocompatible materials becomes essential because the majority of wearable health sensors come into contact with human skin. In this regard, both organic and inorganic piezoelectric materials, such as poly-L-lactic acid, polyvinylidene fluoride, and poly-D-lactic acid, provide biocompatibility. Examples of the former include zinc oxide, lithium niobate, and lead zirconate titanate. Notably, because of their affordability and usability, piezoelectric polymers have drawn a lot of interest. The creation of wearable technology is driving advances in manufacturing processes and materials science. The materials and fabrication techniques used to create wearable sensors vary depending on the uses for which they are designed. Printing technologies have become increasingly popular in the past few years as a means of manufacturing high-performance electronic components and sensors on flexible substrates, while adhering to the necessary processing temperatures.

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The author has declared no competing interests.

Consent for Publication

The author declares that he consented to the publication of this study.

Author’s Contribution

Author’s independent contribution.

References

[1] Yan Liu, Hai Wang, Wei Zhao, Min Zhang, Hongbo Qin & Yongqiang Xie (2018). Flexible, Stretchable Sensors for Wearable Health Monitoring: Sensing Mechanisms, Materials, Fabrication Strategies and Features. Sensors, 18: 645. doi: 10.3390/s18020645.

[2] D. Saber, Ibrahim B.M. Taha & Kh. Abd El-Aziz (2023). Wear Behavior Prediction for Cu/TiO_2 Nanocomposite Based on Optimal Regression Methods. Materials Research, 26: e20220263.

[3] Kh. Abd El-Aziz, D. Saber & H.E.M. Sallam (2015). Wear and Corrosion Behavior of Al–Si matrix composite reinforced with Alumina. Journal of Bio- and Tribo-Corrosion, 1: 5.

[4] Kh. Abd El-Aziz, Kh. Zohdy, D. Saber, & H.E.M. Sallam (2015). Wear and Corrosion Behavior of High-Cr white Cast Iron Alloys in Different Corrosive Media. Journal of Bio- and Tribo-Corrosion, 1: 25.

[5] D. Saber, A. Fathy & Kh. Abdel-Aziz (2016). A study of corrosion behavior of copper-alumina nano composites in different corrosive media. International Journal of Mechanical Engineering (IJME), 5(6): 1−10.

[6] Abhinav Saxena, Deepak Khare, Swati Agrawal, Angaraj Singh & Ashutosh Kumar Dubey (2021). Recent advances in materials science: a reinforced approach toward challenges against COVID-19. Emergent Materials, 4: 57−73

[7] D. Saber & A.H. Abdelnaby (2022). Recent Developments in Natural Fiber as Reinforcement in Polymeric Composites: A Review. Asian Journal of Applied Science and Technology, 6(3): 56−75.

[8] Megahed, M., El-Aziz, K.A., & Saber, D. (2022). Characterization of steel lined with multilayer micro/nano-polymeric composites. Sci Rep., 12: 19194. https://doi.org/10.1038/s41598-022-22084-5.

[9] Al-qaness, M.A., Ewees, A.A., Fan, H., & Abd El Aziz, M. (2020). Optimization Method for Forecasting Confirmed Cases of COVID-19 in China. Journal of Clinical Medicine, 9: 674.

[10] Dalia Saber & Khaled Abd El-Aziz (2022). Advanced materials used in wearable health care devices and medical textiles in the battle against coronavirus (COVID-19): A review. Journal of Industrial Textiles.

[11] Fuminori Tanabe, Yukiko Uchida, Soichi Arakawa & Michiko Morimoto (2020). Increased adhesion of methicillin-resistant Staphylococcus aureus to the surface of personal protective clothing damaged by friction during nursing action. American Journal of Infection Control, 48: 416−419

[12] Mohamed A. EL-meniawy, Ayman M. Abdelhaleim, Asmaa H. Abdelnaby & Dalia Saber (2021). Mechanical properties and corrosion behavior of sugarcane Bagasse fiber reinforced Low Density Polyethylene composites. Egyptian Journal for Engineering Sciences and Technology, 36: 63−71.

[13] Lei, K.-F., Hsieh, Y.-Z., Chiu, Y.-Y., & Wu, M.-H. (2015). The structure design of piezoelectric poly (vinylidene fluoride) (PVDF) polymer-based sensor patch for the respiration monitoring under dynamic walking conditions. Sensors, 15: 18801–18812.

[14] Kh Abd ElAziz, Emad M. Ahmed, Abdulaziz H. Alghtani, Bassem F. Felemban, Hafiz T. Ali, M. Megahed & D. Saber (2021). Development of Al-Mg-Si alloy performance by addition of grain refiner Al–5Ti–1B alloy. Science Progress.

[15] Y.Y. Yu, F. Bu, H. Zhou, Y. Wang, J. Cui, X. Wang, G. Nie & H. Xiao (2020). Biosafety materials: an emerging new research direction of materials science from the COVID-19 outbreak. Mater. Chem. Front., 4: 1930.

[16] Sithara P. Sreenilayam, Inam Ul Ahad, Valeria Nicolosi, Victor Acinas Garzon & Dermot Brabazon (2020). Advanced materials of printed wearables for physiological parameter monitoring. Materials Today, Volume 32.

[17] Xuewen Wang, Zheng Liu & Ting Zhang (2017). Flexible Sensing Electronics for Wearable/Attachable Health Monitoring. Small, 13: 1602790

[18] Saleem Khan, Shawkat Ali & Amine Berma (2019). Recent Developments in Printing Flexible and Wearable Sensing Electronics for Healthcare Applications. Sensors, 19: 1230. doi: 10.3390/s19051230.

[19] D. Saber, Kh., Abd El-Aziza, R. Abdel-Karim & A.A. Kandel (2020). Corrosive Wear of Alumina Particles Reinforced Al–Si Alloy Composites. Physics of Metals and Metallography, 121(2): 197–203.

[20] Kh. Abd El-Aziz & D. Saber (2020). Mechanical and microstructure characteristics of heat-treated of high-Cr WI and AISI4140 steel bimetal beams. J. Mater. Res. Technol., 9: 7926–7936.

[21] Adarsh Sandhu, Roland Hany, Atsufumi Hirohata, Shunichi Hishita, et al. (2020). Global snapshot of the effects of the COVID-19 pandemic on the research activities of materials scientists between Spring and Autumn 2020. Science and Technology of Advanced Materials, 22(1): 173–184

[22] Yan Liu, Hai Wang, Wei Zhao, Min Zhang, Hongbo Qin & Yongqiang Xie (2018). Flexible, Stretchable Sensors for Wearable Health Monitoring: Sensing Mechanisms, Materials, Fabrication Strategies and Features. Sensors, 18: 645. doi: 10.3390/s18020645.

[23] M.H. Chua et al. (2020). Face masks in the new COVID-19 normal: materials, testing, and perspectives. Research, 728673.

[24] Yanfei Chen, Yun-Soung Kim, Bryan W. Tillman, Woon-Hong Yeo & Youngjae Chun (2018). Advances in Materials for Recent Low-Profile Implantable Bioelectronics Materials, 11: 522.

[25] A.R. Horrocks & J.A. D'souza (1992). Degradation of polymers in geomembranes and geotextiles. Handbook of Polymer Degradation, S.H. Hamid, M.B. Amin & A.G. Maadhah (eds), Marcel Dekker, New York.

[26] Kh. Abd El-Aziz, M. Megahed & D. Saber (2023). Mechanical properties and corrosion protection performance of micro/nano alumina fillers coated steel. Polymer Composites.

[27] Zheng Loua, D., Lili Wangb, Kai Jiang, Zhongming Weia & Guozhen Shena (2020). Reviews of wearable healthcare systems: Materials, devices and system integration. Materials Science & Engineering R., 140: 100523.

[28] B.C.K. Tee, C. Wang, R. Allen & Z. Bao (2012). An electrically and mechanically self-healing composite with pressure- and flexion-sensitive properties for electronic skin applications. Nat. Nanotech., 7: 825–832.

[29] Z. Liu, J. Xu, D. Chen & G. Shen (2015). Flexible electronics based on inorganic nanowires. Chem. Soc. Rev., 44: 161–192.

[30] Li, -T.-T., Chen, A.-P., Hwang, P.-W., Hsing, W.-H., Lou, C.-W., Chen, Y.-S., & Lin, J.-H. (2017). Synergistic Effects of Micro-/Nano-Fillers on Conductive and Electromagnetic Shielding Properties of Polypropylene Nanocomposites. Mater. Manuf. Process., 33: 149–155.

[31] Z. Lou & G. Shen (2016). Flexible Electronics: Flexible Photodetectors Based on 1D Inorganic Nanostructures. Adv. Sci., Volume 3.

[32] Yang, X., He, W., Wang, S., Zhou, G., & Tang, Y. (2012). Preparation of High-Performance Conductive Ink with Silver Nanoparticles and Nanoplates for Fabricating Conductive Films. Mater. Manuf. Process., 28(1): 1–4.

[33] X. Hu, G. Li, P. Zhu, J. Tang, R. Sun & C.-P. Wong (2019). Facile and scalable fabrication of self-assembled Cu architecture with superior antioxidative properties and improved sinterability as a conductive ink for flexible electronics. Nanotechnology, Volume 30.

[34] K.-Y. Chun, Y. Oh, J. Rho, J.-H. Ahn, Y.-J. Kim, H.R. Choi & S. Baik (2010). Highly conductive, printable and stretchable composite films of carbon nanotubes and silver. Nat. Nanotech., 5: 853–857.

[35] D. Saber, Hamed M. Almalki & Kh. Abdel Aziz (2020). Design and building of an automated heat-treatment system for industrial applications. Alexandria Engineering Journal.

[36] Kh. Abdel Aziz, D. Saber & A.A. Megahed (2021). Investigation and Prediction of Abrasive Wear Rate of Heat-treated HCCIs with different Cr/C ratios Using Artificial Neural Networks. American Foundry Society (AFS), International Journal of Metal casting, 15(4): 1149–1163.

[37] E. Singh, M. Meyyappan & H.S. Nalwa (2017). Flexible Graphene-Based Wearable Gas and Chemical Sensors. ACS Appl. Mater. Interfaces, 9: 34544–34586.

[38] M.A. Zhilyaeva, E.V. Shulga, S.D. Shandakov, I.V. Sergeichev, E.P. Gilshteyn, A.S. Anisimov & A.G. Nasibulin (2019). A novel straightforward wet pulling technique to fabricate carbon nanotube fibers. Carbon, 150: 69–75.

[39] Hoseong Song & Sooman Lim (2020). Screen-printing process of electromagnetic interference (EMI) shielding materials on mulberry paper. Materials And Manufacturing Processes, 35(15): 1701–1706.

[40] Z. Wang, Z. Wang & Z.-J. Pan (2018). Recent progress of $NiCo_2O_4$-based anodes for high-performance lithium-ion batteries. Mater. Sci., 22: 213–228.

[41] Islam S. Emam, D. Saber & A. Waheed (2019). High temperature cyclic oxidation of 800H superalloy at 750-950 ºC in air. Journal of Testing and Evaluation (Accepted: January 2019).

[42] Megahed M., Saber D., & Agwa M.A. (2019). Modeling of wear behavior of Al-Si/Al_2O_3 metal matrix composites. Physics of Metals and Metallography, 120(10): 981–988.

[43] C. Wang, K. Xia, H. Wang, X. Liang, Z. Yin & Y. Zhang (2019). Advanced Carbon for Flexible and Wearable Electronics. Adv. Mater., Volume 31.

[44] M. Gai, L.LI, & Y. Song (2017). Inkjet printing wearable electronic devices. J. Mater. Chem. C., 5: 2971–2993.

[45] S. Nasei, Y. Song, Y. Wang, X. Ruan, D. Du, A. Gozen & Y. Lin (2018). Micro additive manufacturing of glucose biosensors: A feasibility study. Anal. Chim. Acta, 1043: 142–149.

[46] Kh. Abdel-Aziz, Abo El-Nasr A.A, A. Elfasakhany, D. Saber & M. Helal (2018). Influence of casting mould wall thickness on the properties and microstructure of A356 alloy reinforced with micro/nanoalumina particles. ARCTIC Journal.

[47] Z.S. El-Kinani, D. Saber & A.M. Hassan (2018). Characterization of Wood Plastic Composites by using Positron Annihilation System. The Egyptian International Journal of Engineering Sciences and Technology.

[48] Z. Lou, S. Chen, L. Wang, R. Shi, L. Li, K. Jiang, D. Chen & G. Shen (2017). Ultrasensitive and ultraflexible e-skins with dual functionalities for wearable electronics. Nano Energy, 38: 28–35.

[49] Z. Tang, D. Yao, S. Hu, D. Du, W. Shao, B. Tang, J.M. Fan, X.G. Tang & J. Gao (2020). Highly conductive, washable and super-hydrophobic wearable carbon nanotubes e-textile for vacuum pressure sensors. Sen Act A, 303.

[50] Y. Jin, E.P. Boon, L.T. Le & W. Lee (2018). Fabric-infused array of reduced graphene oxide sensors for mapping of skin temperatures. Sens. Actuators A., 280: 92–98.

[51] Emad M. Ahmed, D. Saber, Kh. Abd ElAziz, Abdulaziz H. Alghtani, Bassem F. Felemban, Hafiz T. Ali & M. Megahed (2021). Chitosan-based nanocomposites: preparation and characterization for food packing industry. Mater. Res. Express, 8: 025017.

[52] D. Saber, Ibrahim B.M. Taha & Kh. Abd El-Aziz (2021). Prediction of the Corrosion Rate of Al–Si Alloys Using Optimal Regression Methods. Intelligent Automation & Soft Computing.

[53] X. Li, N. Wu, Y. Rojanasakul & Y. Liu (2013). Selective stamp bonding of PDMS microfluidic devices to polymer substrates for biological applications. Sens. Actuators A., 193: 186–192.

[54] S. Kim, X. Zhang, R. Daugherty, E. Lee, G. Kunnen, D.R. Allee, E. Forsythe & J. Chae (2013). Design and implementation of electrostatic micro-actuators in ultrasonic frequency on a flexible substrate, PEN (polyethylenenaphthalate). Sens. Actuators A., 195: 198–205.

[55] D. Saber, Abdulaziz H. Alghtani, Emad M. Ahmed, Bassem F. Felemban, Hafiz T. Alib, M. Megahed & Kh. Abd El-Aziz (2022). Enhancement of Barrier and Mechanical Performance of Steel Coated with Epoxy Filled with Micron and Nano Alumina Fillers. Materials Research, 25: e20210413.

[56] Mohamed A. EL-meniawy, Ayman M. Abdelhaleim, Asmaa H. Abdelnaby & Dalia Saber (2021). The Influence of Alkali Treatment and Coupling Agent on Mechanical and Chemical Resistance Properties of Polymeric Material Reinforced Via Natural Fiber. Design Engineering.

[57] X. Ma, X. Zhang & P. Fang (2017). Flexible film-transducers based on Polypropylene piezo electrets: fabrication, properties, and applications in wearable devices. Sens. Actuators A., 256: 35–42.

[58] H.M.A. Hamid & Z.C. Elik Butler (2018). Characterization and performance analysis of Li-doped ZnO nanowire as a nano-sensor and nano-energy harvesting element. Nano Energy, 50: 159–168.

[59] Hafiz T. Ali, Abdulaziz H. Alghtani, Bassem F. Felemban, Kh. Abd El-Aziz, D. Saber, Emad M. Ahmed, M. Megahed & Mohamad Fotouhi (2021). Multivariable analysis for selection of natural fibers as fillers for a sustainable food packaging industry. Mater. Res. Express, Volume 8.

[60] Sara Nasiri, Mohammad Reza & Khosravani (2020). Progress and challenges in fabrication of wearable sensors for health monitoring. Sensors and Actuators A., 312: 112105.

[61] Hao-Chih Yuana, Vernon E. Yost, Matthew R. Page, Paul Stradins & Daniel L. Meier (2009). Efficient black silicon solar cell with a density-graded nanoporous surface: Optical properties, performance limitations, and design rules. Appl. Phys. Lett., Volume 94.

[62] S. Khan, S. Tinku, L. Lorenzelli & R.S. Dahiya (2015). Flexible Tactile Sensors Using Screen-Printed P(VDF-TrFE) and MWCNT/PDMS Composites. IEEE Sensors J., 15(6).

[63] A.S.G. Reddy, B.B. Narakathu, M.Z. Atashbar, M. Rebros, E. Rebrosova & M.K. Joyceb (2011). Fully Printed Flexible Humidity Sensor. Procedia Eng., 25: 120.

[64] Dalia Saber, Marwa Abd El-baky & Mohamed A. Attia (2021). Advanced Fiber Metal Laminates Filled with Silicon Dioxide Nanoparticles with Enhanced Mechanical Properties. Fibers and Polymers, 22(9): 1–17.

[65] D. Saber, Kh. Abd El-Aziz, Bassem F. Felemban, Abdulaziz H. Alghtani, et al. (2022). Characterization and performance evaluation of Cu‑based/TiO_2 nano composites. Scientific Reports, 12: 6669.

[66] L.J. Hubble & J. Wang (2019). Sensing at your fingertips: glove-based wearable chemical sensors. Electro analysis, 31: 428–436.

[67] Wang, Y., Shi, Y., Zhao, C.X., Wong, J.I., Sun, X.W., & Yang, H.Y. (2014). Printed all-solid flexible microsupercapacitors: Towards the general route for high energy storage devices. Nanotechnology, Volume 25.

[68] Kanoun, O., Muller, C., Benchirouf, A., Sanli, A., Dinh, T.N., Al-Hamry, A., Bu, L., Gerlach, C., & Bouhamed, A. (2014). Flexible carbon nanotube films for high performance strain sensors. Sensors, 14: 10042–10071.

[69] Zhao, Y., & Huang, X. (2017). Mechanisms and materials of flexible and stretchable skin sensors. Micromachines, 8: 69.

[70] Honglie Song, Junqiu Zhang, Daobing Chen, Kejun Wang, Shichao Niu, et al. (2016). Superfast and high-sensitivity printable strain sensors with bioinspired micron-scale cracks. Nanoscale.

[71] M. Bariya, Z. Shahpar, H. Park, J. Sun, Y. Jung, W. Gao, H.Y.Y. Nyein, T.S. Liaw, L.C. Tai, Q.P. Ngo, M. Chao, Y. Zhai, M. Hettick, G. Cho & A. Javey (2018). Roll-to-roll gravure printed electrochemical sensors for wearable and medical devices. ACS Nano, 12: 6978–6987.

[72] Atta, M., Megahed, M., & Saber, D. (2022). Using ANN and OA techniques to determine the specific wear rate effectors of A356 Al-Si/Al_2O_3 MMC. Neural Comput & Applic., 34: 14373–14386.

[73] Young Yun Kim, Tae-Youl Yang, Riikka Suhonen, Marja Välimäki, Tiina Maaninen, et al. (2019). Gravure-Printed Flexible Perovskite Solar Cells: Toward Roll-to-Roll Manufacturing. Adv. Sci., Volume 6.

[74] Zheng, Y., He, Z.Z., Yang, J., & Liu, J. (2014). Personal electronics printing via tapping mode composite liquid metal ink delivery and adhesion mechanism. Sci. Rep., Volume 4.

[75] Q. Li, S. Luo, Y. Wang & Q.M. Wang (2019). Carbon based polyimide nanocomposites thin film strain sensors fabricated by ink-jet printing method. Sens. Actuators A., 300.

[76] A. Moya, M. Zea, E. Sowad, R. Villa, E. Ramona, R.R. Baumann & G. Gabriel (2017). Inkjet-Printed Dissolved Oxygen and pH Sensors on Flexible Plastic Substrates. Smart Sensors, Actuators, and MEMS VIII, Edited by Luis Fonseca, Mika Prunnila, Erwin Peiner, Proc. of SPIE., Volume 10246.

[77] Leigh, S.J., Bradley, R.J., Purssell, C.P., Billson, D.R., & Hutchins, D.A. (2012). A simple, low-cost conductive composite material for 3D printing of electronic sensors. PLoS ONE, Volume 7.

[78] S. Nasei, Y. Song, Y. Wang, X. Ruan, D. Du, A. Gozen & Y. Lin (2018). Micro additive manufacturing of glucose biosensors: A feasibility study. Anal. Chim. Acta., 1043: 142–149.

[79] T. Han, S. Kundu, A. Nag & Y. Xu (2019). 3D printed sensors for biomedical applications: a review. Sensors, 19: 1–22.

[80] Saber D., Abdelnaby A.H., & Abdelhaleim A.M. (2023). Fabrication of ecofriendly composites using low-density polyethylene and sugarcane bagasse: Characteristics' degradation. Textile Research Journal. doi: 10. 1177/00405175231161281.

[81] J.R. Windmiller, A.J. Bandodkar, S. Parkhomosvsky & J. Wang (2012). Stamp transfer electrodes for electrochemical sensing on non-planar and oversized surfaces. Analyst, 137: 1570–1575.

[82] Yuanyuan Xu, Xiaoyue Wu, Xiao Guo, Bin Kong, Min Zhang, et al. (2017). The Boom in 3D-Printed Sensor Technology. Sensors, 17: 1166.

[83] Mohan, A.M.V., Kim, N., Gu, Y., Bandodkar, A.J., You, J.-M., Kumar, R., Kurniawan, J.F., Xu, S., & Wang, J. (2017). Merging of thin- and thick-film fabrication technologies: Toward soft stretchable "island-bridge" devices. Adv. Mater. Technol., 2: 1600284.