

**AN ANALYSIS OF EMERGING TECHNOLOGIES IN FLEXIBLE ELECTRONICS**

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*Abstract*

*Flexible electronics have emerged as a ground-breaking technology, revolutionizing industries with their adaptability, lightweight structure, and multifunctional capabilities. This study explores the applications and advancements of flexible electronics in domains such as healthcare, IoT, energy harvesting, aerospace, and soft robotics. By integrating advanced materials like graphene and carbon nanotubes, these systems enable innovations in wearable devices, smart textiles, and sustainable energy solutions. Flexible electronics are driving the development of adaptive technologies, enhancing operational efficiency and enabling real-time data collection. With ongoing advancements in materials and fabrication techniques, flexible electronics are set to transform industries, providing sustainable, high-performance, and scalable solutions for the future.*

*Keywords: Flexible Electronics, Advanced Materials, Smart Textiles, Energy Harvesting, Soft Robotics.*

**I. INTRODUCTION**

Flexible electronics represent a transformative advancement in the field of technology, enabling the creation of devices that are lightweight, stretchable, and adaptable to a variety of surfaces. [1] Describe these technologies as the next generation of electronic devices, offering unprecedented opportunities for applications in healthcare, wearable technology, and consumer electronics. Their ability to conform to non-traditional shapes while maintaining electronic functionality marks a significant shift from rigid systems to adaptable ones. The fabrication processes for flexible and stretchable electronics have undergone significant development, as highlighted by [2]. Innovations in materials and manufacturing techniques have allowed for the production of durable, high-performance flexible devices, paving the way for their integration into everyday use. One of the most promising applications of flexible electronics lies in health monitoring systems. [3] Emphasize the potential of printed and flexible electronics to interface directly with human skin, providing continuous and non-invasive monitoring of physiological signals. This breakthrough has opened new frontiers in personalized healthcare and wearable diagnostics. Moreover, the integration of flexible electronics with soft robotics has introduced new possibilities for creating soft machines and adaptable systems, as discussed by [4]. These systems combine the mechanical properties of soft materials with the functional capabilities of

electronics, enabling innovations in fields ranging from automation to prosthetics. [5] Further elaborate on the advancements in flexible and stretchable electronics, focusing on their enhanced functional properties such as conductivity and resilience. These features make flexible electronics a critical enabler for emerging applications, including foldable displays, smart textiles, and electronic skins. This analysis aims to explore the emerging technologies in flexible electronics, focusing on their fabrication techniques, applications, and future potential across various industries.

## **II. ADVANCED MATERIALS FOR FLEXIBLE ELECTRONICS: INNOVATIONS AND APPLICATIONS**

Flexible electronics rely on advanced materials that combine mechanical flexibility with superior electronic properties, enabling applications across diverse fields. Recent research highlights innovations in materials and their integration into functional devices.

**Emerging Materials for Flexible Electronics:** [6] discuss the development of new materials such as organic semiconductors, metallic nanowires, and graphene. These materials exhibit exceptional conductivity, stretchability, and durability, making them ideal for flexible electronics. Their ability to retain functionality under mechanical strain has broadened the scope of applications, including wearable devices and healthcare technologies.

**Material-Device Integration:** [7] emphasize the role of hybrid materials, combining polymers with conductive fillers like carbon nanotubes and silver nanowires. These composites enhance the mechanical robustness and electrical conductivity of flexible devices, enabling innovations in areas like foldable displays and energy storage systems.

**Stretchable and Biocompatible Materials:** [8] focus on materials designed for stretchability and biocompatibility, such as hydrogels and elastomers. These materials allow for the development of flexible bioelectronics, including sensors and devices for real-time health monitoring. Advances in this area are critical for applications in soft robotics and prosthetics.

**Flexible Electronics for Bioelectronics:** [9] highlight the application of flexible materials in bioelectronics, such as implantable devices and skin-mounted sensors. Materials like stretchable electrodes and bio-compatible polymers enable seamless integration with biological tissues, paving the way for innovations in diagnostics and therapy.

### **2.1 Applications**

**2.1.1 Wearable Electronics:** Integration of graphene and organic materials enables high-performance, lightweight wearables for fitness and health monitoring.

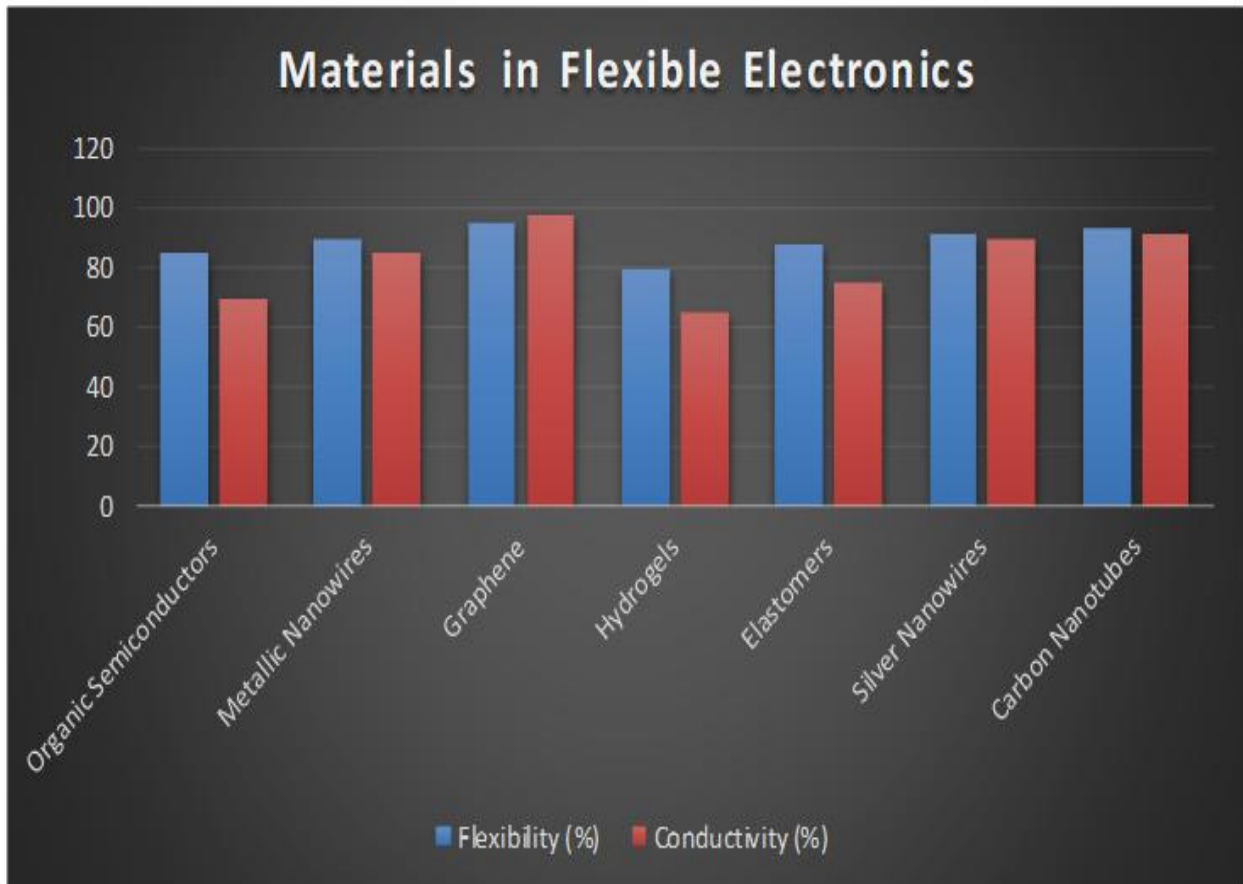
**2.1.2 Flexible Displays:** Materials like silver nanowires and transparent conductive polymers are key to foldable screens and bendable devices.

**2.1.3 Energy Storage:** Hybrid materials enhance the flexibility and efficiency of energy harvesting and storage systems like flexible batteries and solar panels.

**2.1.4 Biomedical Devices:** Biocompatible materials support the development of implantable devices and bio-sensors for continuous health tracking.

Material Type	Flexibility (%)	Conductivity (%)
Organic Semiconductors	85	70
Metallic Nanowires	90	85
Graphene	95	98
Hydrogels	80	65
Elastomers	88	75
Silver Nanowires	92	90
Carbon Nanotubes	93	92

**Table 1:** Materials in Flexible Electronics [7], [8]



**Graph 1:** Materials in Flexible Electronics

This provides flexibility and conductivity percentages for various materials in flexible electronics.

### III. ENERGY HARVESTING WITH FLEXIBLE ELECTRONICS: FUTURE OF SUSTAINABLE TECHNOLOGY

Flexible electronics have emerged as a game-changing technology in energy harvesting, offering sustainable solutions for powering devices in a variety of applications. This field leverages advanced materials and designs to create efficient, lightweight, and adaptable systems.

**3.1 Advancements in Flexible Energy Harvesting:** [10] highlight the progress in flexible electronics for energy harvesting, focusing on materials like piezoelectric polymers and triboelectric Nano generators (TEGs). These technologies convert mechanical energy from movements, vibrations, or ambient forces into electricity, paving the way for self-powered systems.

**3.2 Materials and Technologies:** [11] discuss the integration of stretchable and flexible materials such as graphene, organic semiconductors, and nanowires in energy harvesting devices. These materials enhance the adaptability and durability of systems, making them suitable for wearable and portable applications.

**3.3 Flexible Sensors and Energy Harvesting:** [12] emphasize the role of flexible sensors in energy harvesting systems, which collect energy from environmental stimuli like temperature gradients, light, and pressure. These sensors, when combined with flexible energy storage devices, enable continuous operation of IoT and wearable devices.

**3.4 Devices and Systems:** [13] explore innovative systems such as flexible solar panels and thermoelectric generators, which are being integrated into textiles, building materials, and autonomous devices. These advancements make flexible electronics a cornerstone for sustainable energy solutions.

**3.5 Applications in Wearable Healthcare:** [14] highlight wearable healthcare systems powered by flexible energy harvesting devices. These systems support real-time monitoring and diagnostics without relying on bulky batteries, providing sustainable and user-friendly solutions for healthcare.

Flexible electronics for energy harvesting are set to revolutionize sustainable technology. Their ability to integrate into everyday objects and systems ensures widespread adoption in applications ranging from smart cities and IoT to renewable energy solutions. As the field evolves, innovations in materials and designs will further enhance efficiency, scalability, and affordability.

### 3.6 Pseudocode for Flexible Energy Harvesting System

```
Initialize system:  
    Configure energy harvester (piezoelectric, solar, or triboelectric) and storage device  
  
Start harvesting loop:  
    While active:  
        Detect stimuli (motion, light, temperature):  
            Activate corresponding energy harvester.  
            Convert environmental energy to electricity.  
  
        Optimize energy:  
            Adjust parameters for maximum efficiency.  
  
        Store energy:  
            Charge flexible battery or supercapacitor.  
  
        Power devices:  
            Supply energy to connected systems.  
            Enable power-saving mode if demand exceeds supply.  
  
        Monitor system:  
            Track performance and log data.  
  
Handle errors:  
    Switch to backup storage or notify user on failure.  
  
Shutdown:  
    Safely discharge storage and report metrics.
```

**3.7 Summary:** This simplified pseudocode focuses on key steps: initializing the system, harvesting and storing energy, powering devices, optimizing performance, and handling errors. It ensures efficient and sustainable energy harvesting for flexible electronics.

## IV. FLEXIBLE AND STRETCHABLE ELECTRONICS FOR SMART TEXTILES

Smart textiles integrated with flexible and stretchable electronics are revolutionizing wearable technology by combining comfort, adaptability, and advanced functionality. These textiles seamlessly incorporate sensors, circuits, and energy storage into fabrics, enabling a wide range of applications.

**Health Monitoring Applications:** [15] highlight wearable sensors embedded in smart textiles for real-time health monitoring. These sensors measure physiological parameters like heart rate, body temperature, and movement, providing continuous, non-invasive health data for personalized medicine.

**Materials and Adaptability:** [16] discuss the use of flexible materials such as conductive

polymers, graphene, and metallic nanowires in stretchable electronics. These materials enable smart textiles to maintain electrical functionality under mechanical deformation, such as bending, stretching, or compression.

**Bio-Sensing Capabilities:** [17] emphasize the role of flexible and stretchable bio-sensors in detecting biochemical markers. These sensors, integrated into fabrics, can monitor sweat composition, glucose levels, and other bio-signals, advancing applications in health diagnostics and fitness tracking.

**Wearable Personal Health Monitoring:** [18] explore wearable electronics embedded in smart textiles for personalized health monitoring. These systems are lightweight and unobtrusive, providing users with actionable insights into their health while ensuring comfort and durability.

**Advanced Materials and Integration:** [19] focus on advanced materials like hydrogels, elastomers, and textile-compatible conductive inks. These materials enhance the integration of electronic components into fabrics, creating textiles that are washable, durable, and highly functional.

#### **4.1 Applications of Smart Textiles**

**4.1.1 Sports and Fitness:** Wearable textiles that monitor movement and physiological data for performance optimization.

**4.1.2 Healthcare:** Continuous monitoring of patients' vital signs for remote diagnostics and treatment.

**4.1.3 Fashion and Entertainment:** Interactive clothing with embedded LEDs and sensors for aesthetic and functional purposes.

**4.1.4 Military and Defence:** Smart uniforms that monitor soldiers' health and environmental conditions.

Smart textiles integrated with flexible and stretchable electronics are poised to redefine industries ranging from healthcare and fitness to entertainment and defence. As materials and fabrication techniques advance, these textiles will become even more versatile, durable, and accessible, driving innovation in wearable technology

## **V. THE ROLE OF FLEXIBLE ELECTRONICS IN THE DEVELOPMENT OF SOFT ROBOTICS**

Flexible electronics play a pivotal role in advancing soft robotics, offering materials and designs that integrate seamlessly with the soft, adaptive, and compliant structures characteristic of these robotic systems. By enabling real-time sensing, actuation, and energy management, flexible electronics are transforming how soft robots interact with their environments.



**5.1 Materials for Flexible and Soft Electronics:** [20] highlight nanomaterials like graphene, carbon nanotubes, and metallic nanowires as essential components in flexible electronics for soft robotics. These materials offer high conductivity, stretchability, and durability, making them ideal for integrating sensors and actuators into soft robotic systems.

**5.2 Stretchable and Adaptable Devices:** [21] discuss how stretchable electronics, such as flexible circuits and elastic sensors, are enabling soft robots to mimic biological systems. These devices maintain functionality under extreme deformation, supporting applications like robotic limbs and wearable exoskeletons.

**5.3 Applications in Wearable Robotics:** [22] emphasize the role of wearable electronics in creating soft robotic devices for human assistance and augmentation. These devices incorporate flexible sensors and actuators that adapt to the body's movements, enabling applications in healthcare, rehabilitation, and assistive technologies.

**5.4 Mechanics of Stretchable Systems:** [23] explore the mechanics of stretchable electronics, focusing on their integration into soft robots for tasks like environmental sensing and adaptive manipulation. These systems enable robots to perform complex movements and interactions with greater precision and sensitivity.

Focus Area	Key Contributions	Primary Applications
Materials for Flexible and Soft Electronics	Use of nanomaterials like graphene and carbon nanotubes for high conductivity and stretchability.	Soft sensors and actuators in robotic limbs.
Stretchable and Adaptable Devices	Integration of flexible circuits and elastic sensors for deformation-tolerant devices.	Biomimetic systems like wearable exoskeletons.
Applications in Wearable Robotics	Development of wearable robotic devices for healthcare and assistive technologies.	Healthcare rehabilitation devices and robotic assistance.
Mechanics of Stretchable Systems	Enhancement of adaptive manipulation and precision through stretchable mechanics.	Environmental sensing and adaptive grippers.

**Table 2:** Role of flexible electronics in soft robotics [21], [22]

## VI. IOT AND FLEXIBLE ELECTRONICS: ENABLING SMART CONNECTED DEVICES

The convergence of IoT (Internet of Things) and flexible electronics is creating a new era of smart connected devices, offering innovative solutions for various applications, including healthcare, wearables, and automation. Flexible electronics provide the adaptability and

functionality needed to seamlessly integrate electronic systems into diverse IoT environments. [24] Emphasize graphene-based materials as a cornerstone for flexible and stretchable electronics in IoT devices. These materials offer superior conductivity, mechanical flexibility, and durability, enabling lightweight, high-performance sensors and circuits critical for IoT applications. [25] Highlight the development of flexible and wearable electronics for IoT, focusing on their role in real-time data collection and communication. These systems are designed to be energy-efficient and compatible with wireless connectivity, supporting seamless integration into IoT ecosystems. [26] Discuss wearable systems powered by flexible electronics, specifically designed for biomedical IoT applications. These devices monitor physiological parameters such as heart rate, glucose levels, and body temperature, enabling personalized healthcare and remote monitoring. [27] Explore the use of carbon nanotube-based flexible electronics in IoT devices. Their lightweight, stretchable nature and high electrical conductivity make them ideal for creating IoT sensors, energy harvesters, and smart textiles.

### 6.1 Applications of Flexible Electronics in IoT

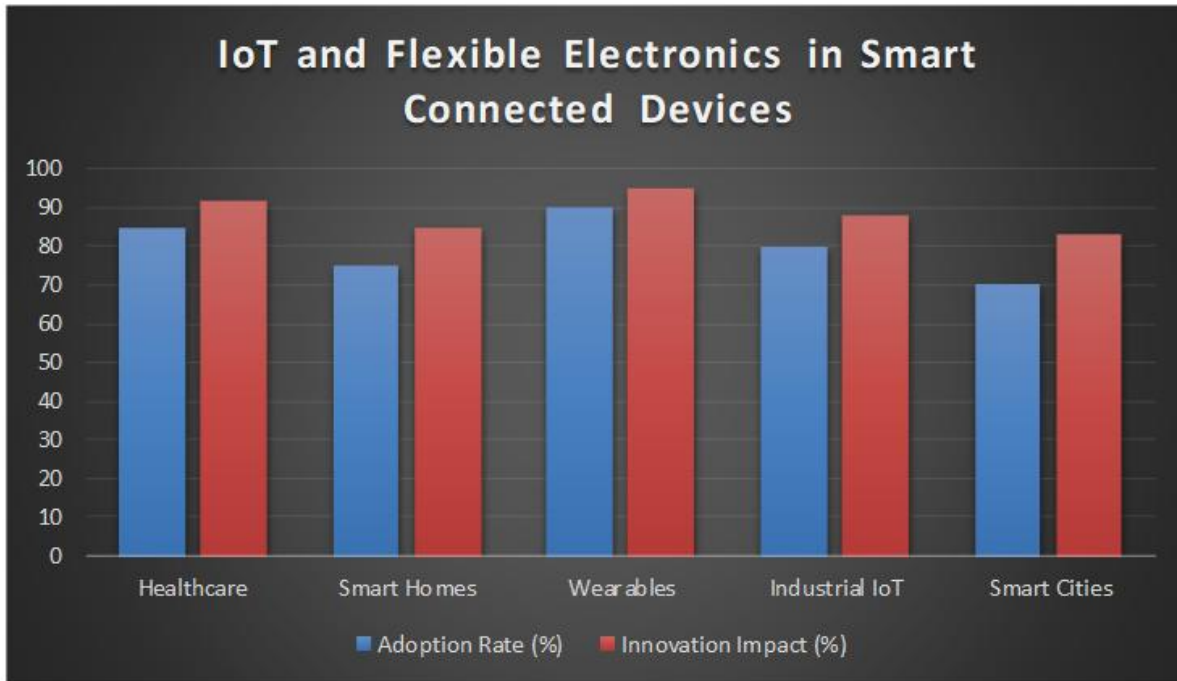
- 6.1.1 **Healthcare:** Smart sensors for continuous monitoring of vital signs and remote diagnostics.
- 6.1.2 **Smart Homes:** Flexible electronic sensors for temperature, humidity, and energy management.
- 6.1.3 **Wearables:** Fitness trackers, smart watches, and clothing integrated with IoT for data-driven insights.
- 6.1.4 **Industrial IoT:** Flexible sensors for equipment monitoring and predictive maintenance.
- 6.1.5 **Smart Cities:** IoT-enabled streetlights, traffic systems, and environmental monitoring.

The integration of IoT and flexible electronics is driving innovations in connected devices, transforming how data is collected, analysed, and utilized. As material science and fabrication technologies advance, flexible electronics will play a pivotal role in creating sustainable, efficient, and intelligent IoT systems, making the vision of smart connected environments a reality.

Application Area	Adoption Rate (%)	Innovation Impact (%)
Healthcare	85	92
Smart Homes	75	85
Wearables	90	95
Industrial IoT	80	88
Smart Cities	70	83

**Table 3:** IoT and Flexible Electronics in Smart Connected Devices [26], [27]





**Graph 2: IoT and Flexible Electronics in Smart Connected Devices**

This represents adoption rates and innovation impact percentages for IoT and flexible electronics applications.

## VII. FLEXIBLE ELECTRONICS IN AEROSPACE AND DEFENCE APPLICATIONS

Flexible electronics are revolutionizing the aerospace and defence sectors by providing lightweight, durable, and high-performance solutions tailored to the unique demands of these industries. These technologies enhance functionality while reducing weight and energy consumption, making them ideal for critical aerospace and defence applications.

[28] Highlight the development of flexible, printable, and lightweight sensors for aerospace applications. These sensors are designed to operate in extreme conditions, such as high temperatures and pressures, making them ideal for monitoring structural health and environmental conditions in aircraft and spacecraft.

[29] Emphasize the use of advanced materials like conductive polymers, graphene, and nanomaterials in flexible electronics for defence applications. These materials offer high mechanical resilience and electrical conductivity, ensuring reliability in demanding environments such as military drones and autonomous systems.

[30] Discuss wearable sensors integrated into flexible electronics for defence personnel. These systems enable real-time health monitoring, communication, and environmental sensing, enhancing the safety and efficiency of soldiers in the field.

**7.1 Applications in Aerospace and Defence**

- 7.1.1 Structural Health Monitoring:** Flexible sensors embedded in aircraft and spacecraft to detect stress, fatigue, and damage in real time.
- 7.1.2 Wearable Devices for Soldiers:** Flexible electronics for health tracking, navigation, and situational awareness.
- 7.1.3 Flexible Antennas:** Lightweight and adaptable antennas for communication and surveillance systems.
- 7.1.4 Energy Harvesting Systems:** Flexible solar panels and energy storage solutions for powering autonomous systems and drones.
- 7.1.5 Stealth and Adaptive Camouflage:** Flexible displays and coatings for adaptive camouflage and low-visibility operations.

The integration of flexible electronics into aerospace and defence systems is driving innovation in lightweight, efficient, and multifunctional technologies. As materials and fabrication techniques continue to evolve, flexible electronics will play a critical role in enhancing operational capabilities, improving safety, and reducing costs in these industries.

<b>Application Area</b>	<b>Key Features</b>
Structural Health Monitoring	Real-time detection of stress, fatigue, and damage in aircraft and spacecraft.
Wearable Devices for Soldiers	Health tracking, navigation, and situational awareness for defence personnel.
Flexible Antennas	Lightweight, adaptable antennas for communication and surveillance.
Energy Harvesting Systems	Flexible solar panels and energy storage for autonomous systems and drones.
Stealth and Adaptive Camouflage	Flexible displays and coatings for adaptive camouflage and low-visibility operations.

**Table 4:** Flexible Electronics in Aerospace and Defence Applications [28]

This table summarizes key applications and features of flexible electronics in aerospace and defence.

**VIII. CONCLUSION**

Flexible electronics have also played a transformative role in soft robotics, enabling the creation of adaptive, biomimetic systems that combine stretchable sensors and actuators for precision and complex interactions. These innovations are redefining robotics, automation, and wearable assistance technologies.

Furthermore, the integration of flexible electronics with IoT is driving the evolution of smart

connected devices, revolutionizing healthcare, industrial systems, and urban infrastructure. The ability to combine flexibility with high-performance sensing, energy harvesting, and data processing underscores their potential for future applications in smart cities, renewable energy, and advanced communication systems.

As material science and fabrication techniques continue to evolve, flexible electronics are set to expand their impact across new industries. The ongoing advancements will likely address existing challenges like scalability, durability, and cost-effectiveness, ensuring their widespread adoption. Ultimately, flexible electronics represent a key enabler for innovative, sustainable, and intelligent technologies, shaping the future of human interaction with devices and systems across a variety of sectors.

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