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Application of renewable energy based devices in healthcare sector

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Abstract: Global energy consumption is exceeding available generation capacity at an alarming rate. Energy security and reliability must be increased and vigorous research into alternative energy sources is required to efficiently fulfill future energy demands. The second most energy-intensive building type in the commercial sector is healthcare facilities, which use a lot of energy. This review provides a comprehensive overview of the current advancements and applications of renewable energy sources in healthcare systems. The study explores various innovative devices powered by renewable energy, including triboelectric nanogenerators, biofuel cells, solar-powered medical equipment, and wearable technologies. Key applications such as drug delivery systems, implantable medical devices, solar autoclaves, heart and respiratory monitoring systems, glucometers, and solar microscopes are discussed in detail. The review highlights the advantages of these innovations in reducing carbon footprint and improving medical efficiency.

Keywords: Renewable Devices; Biofuel Cells; Healthcare; Triboelectric Generators

1. Introduction

Biomedical and healthcare equipment's are extremely crucial to examine, assess and record physiological data. There has been a rapid expansion in the use of electrical devices such as cardiac sensors, cell stimulation devices, drug delivery systems, pacemakers and other medical devices through rapid advances in biodegradable and biocompatible materials, device simplifications and reduced power consumption [1-5]. These technologies enhance the quality of life for millions of people worldwide. [6]. However, healthcare facilities are regarded as important energy users due to their requirement for dependable power and thermal energy sources [7,8] for thermal treatment, ventilating, lighting, air - conditioners and the usage of medical and non-medical equipment [8]. Hospitals and health facilities require a lot of energy to run because they must be accessible 24 hours per day and 365 days a year [9]. As a result, access to energy is therefore essential for "equipment's" and "health center's" [10].

Fossil fuel resources cannot be a reliable energy source for meeting the need for energy due to the rise in global population, environmental issues and energy consumption [11]. Additionally, using fossil fuels results in the release of 21.3×10^9 tons of CO_2 every year into the ecosystem [12]. As a result of these significant CO_2 emissions, the earth's surface temperature is rising [13]. Between 1990 and 2016, the amount of global CO_2 emissions is depicted in Figure 1 [14]. The average worldwide temperature has increased by 1.1 degrees

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Celsius since pre-industrial times and by 0.2 degrees during 2011-2015, according to the World Meteorological Organization's (WMO) report on the global climate for 2015-2019 [15]. Glaciers and ice caps have melted due to rising global temperatures, which has caused sea levels to rise [16]. The high levels of greenhouse gases emitted as a result of human activity have a number of negative effects including ozone depletion, acid rain, air pollution, and global warming [17]. These issues led researchers to concentrate on alternative energy sources like renewable energies. In order to meet the need for energy while reducing greenhouse gas emissions, renewable energy sources have demonstrated their ability to make a significant contribution to global efforts to protect the environment [18]. In 2017, the International Renewable Energy Agency reported that renewable energy capacity worldwide reached 2179 GW [15]. There are many different types of renewable energy including geothermal, wind, and solar [19,20]. These energy forms can be utilized to create electricity or for other applications like heating systems and desalination units [21-23]. Table 1 summarizes a comparison between renewable energy sources and the other power generation techniques mentioned below.

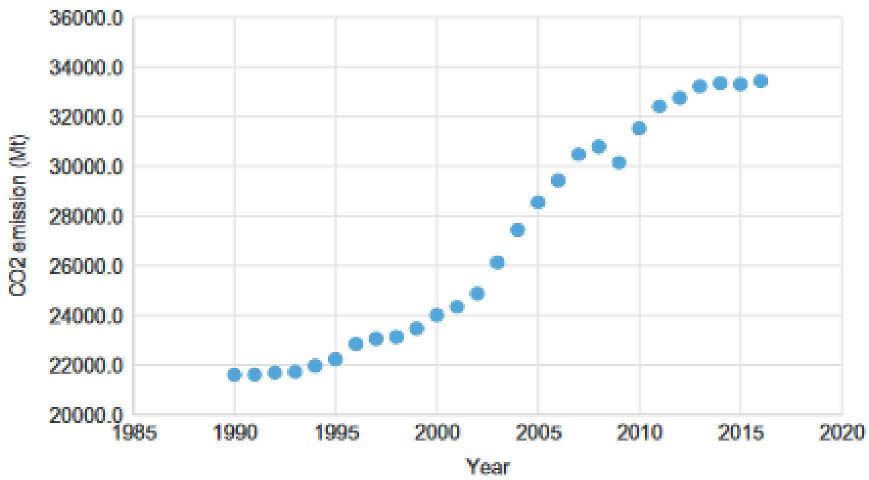

Figure 1: CO_2 emission of the world [14]

Table 1: Lists the benefits and drawbacks of energy generation methods for the medical industry [24]

Technology	Strengths	Weakness
Renewables	Sustainable and scalable	Variable output requires storage
Gas combustion	High energy efficiency	Polluting
Diesel Combustion	Well understood and easily refueled	Expensive and Polluting
Hydrogen fuel cell	Clean and can be refueled.	Expensive for conventional back up

Several industries and sectors use renewable energy technologies to become more environmentally-friendly. Recent technology advancements have made various renewable energy systems mature, dependable and cost-effective while being used in numerous homes, commercial and agricultural applications. As a result, its usage in hospitals is advantageous and desired since it helps the transition to a low-carbon economy by reducing carbon emissions caused by energy use [25]. This review presents a comprehensive overview of various renewable energy-based devices and their healthcare applications, offering a unified perspective that is rarely explored in previous studies.

2. Healthcare Devices based on Renewable energy

Introduction of renewable energy sources in the medical field would definitely be opportunity for future medical facility demands in terms of availability, cost effectiveness, efficiency. In figure 2 renewable energy based devices and its contribution in healthcare and biomedical field are discussed.

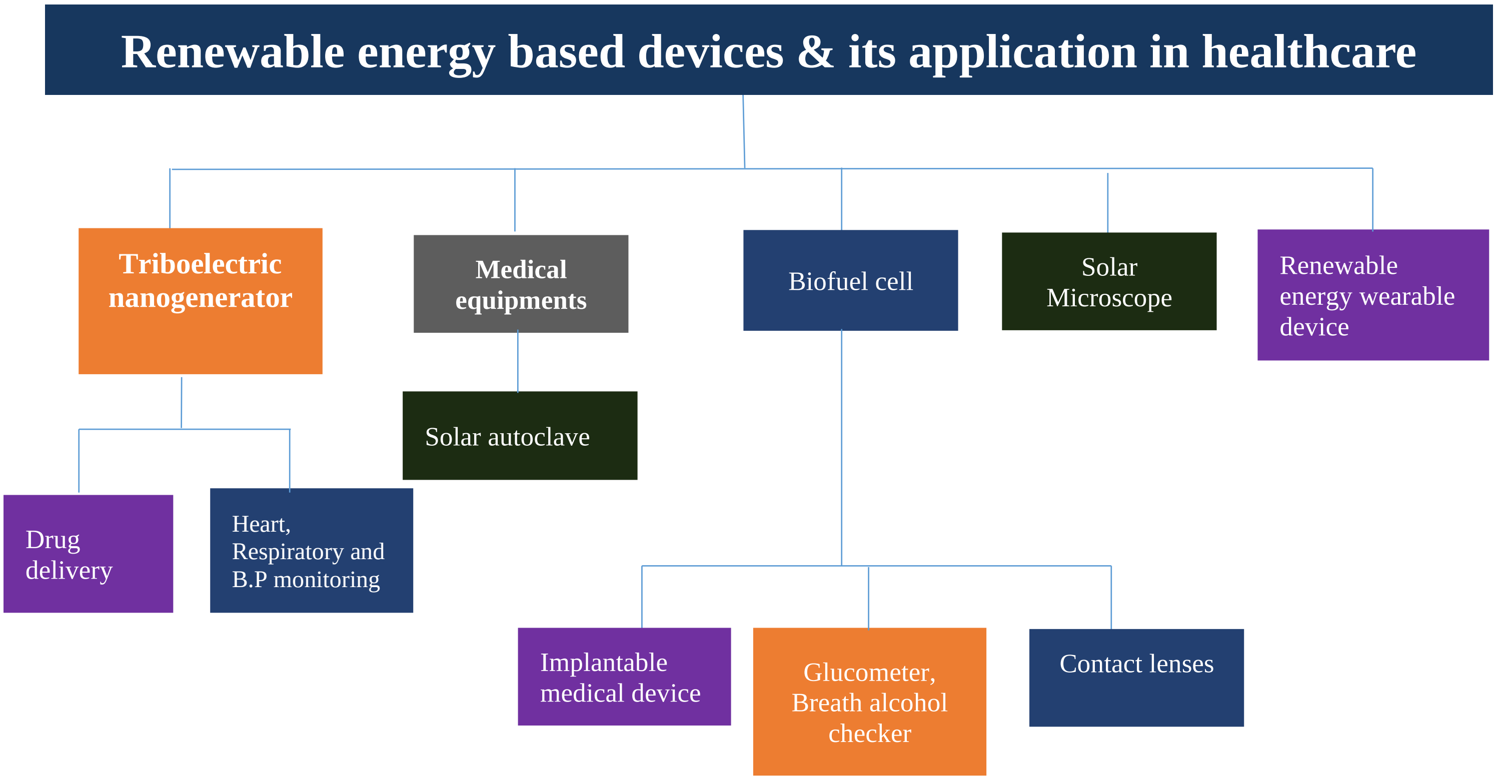

Figure 2: Summary of devices and their application in healthcare field (Prepared in this work)

2.1 Triboelectric nanogenerator (TENG)

The triboelectric nanogenerator (TENG), one of many energy harvesters has drawn a lot of interest because of its high output power in an instant. The wide variety of materials that are readily available, device design, eco-friendly and low-cost production process and numerous functioning modes that are individually created for target applications. By integrating contact electrification and electrostatic induction, a triboelectric nanogenerator (TENG) can turn a variety of mechanical energies into electricity. Healthcare applications based on TENG can benefit greatly from the movements of the human body and interior organs. In addition to drug delivery and neuro prostheses, TENG is also used to regulate the circulatory system, kill bacteria, regenerate hair, produce biodegradable electronics, design heart rate sensors and so on [26-30].

TENG working principle and mechanism:

Triboelectric nanogenerators (TENG) are a promising energy harvesting device that work on the basis of electrostatic induction and triboelectrification. Triboelectrification, driven by external mechanical energy, causes the generation of electrostatic charges when two distinct materials make contact (Figure 3). An electrical potential arises from the separation of triboelectric charges, leading to charge migration across conductive materials. There is no immediate reversal of the transfer of charges between them. This results in an imbalance of charge, with one side having an excess and the other a deficient. Thus, alternating current (AC) circulates either positively or negatively depending on the charge polarity [31].

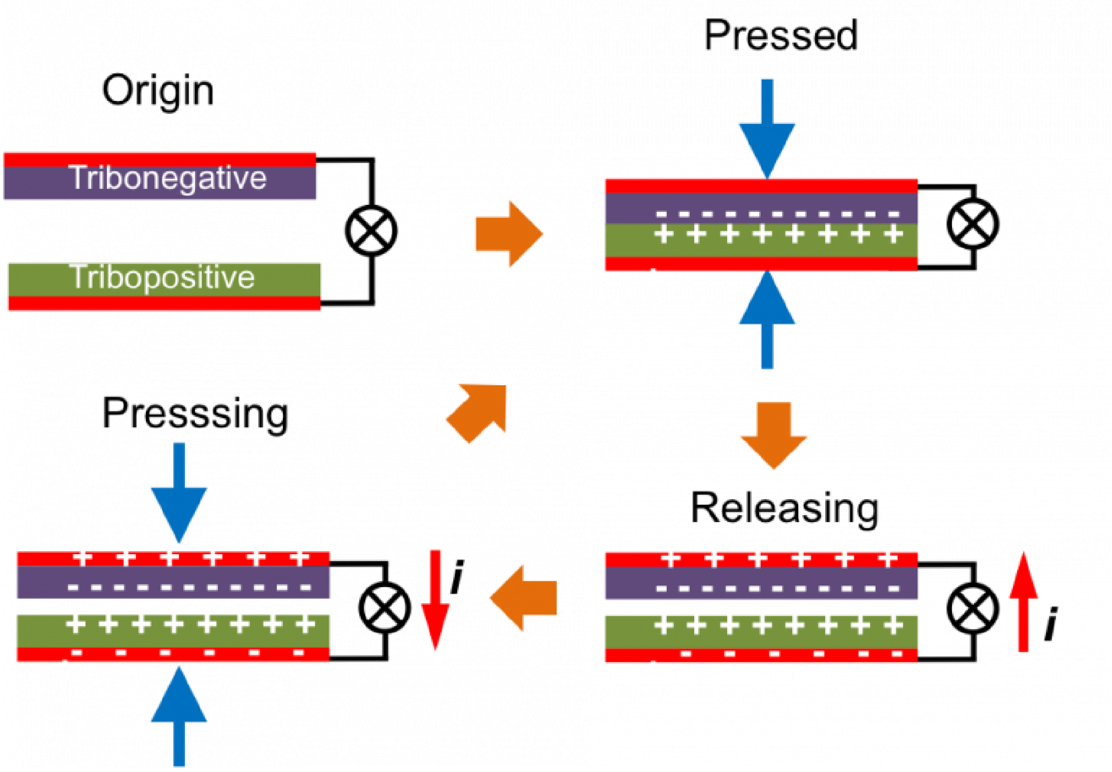

Figure 3: Triboelectric nanogenerator mechanism [32]

2.1.1 Drug delivery via TENG

Systems for on-demand and implanted drug delivery offer outstanding efficiency, controlled release and the opportunity for site-specific therapy [33-36]. The lithium (Li) ion battery used by implantable technology has a finite lifespan. The battery must be replaced through surgery because it has a short lifespan. Surgery is undesired since it is inconvenient, expensive and uncomfortable for the patient and recovering takes a long time. The TENG converts mechanical energy into electrical energy and may provide a power source for implanted systems [37]. The self-powered drug delivery devices based on TENG have seen tremendous progress throughout time. The self-powered drug delivery devices based on TENG have seen tremendous progress some of the illustrations are given below in Table 2.

2.1.2 Monitoring of the heart, lungs and blood pressure with TENG

For numerous health conditions, continuous monitoring of physiological parameters like respiration rate, blood pressure (BP), and heart rate is crucial, as any significant changes in these indicators may signal a life-threatening condition. TENG is appropriate for in-vivo and in-vitro healthcare monitoring due to its many benefits, including affordability, material and design flexibility and reasonable power [38-41]. The use of TENG for healthcare monitoring can help with early disease detection and assessment.

Table 2: TENG based self-powered drug delivery systems (Prepared in this work)

Authors &Year	Summary	Reference
Song et al., 2017	TENG-based implanted drug delivery system (idds), which uses TENG as the electrochemical microfluidic pump's power source. The iDDS is powered by energy harvested from human body motion via a TENG, enabling drug delivery.	[42]
Ouyanga et al., 2019	A triboelectric nanogenerator (TENG)-powered, self-sufficient transdermal drug delivery system is developed for on-demand release. The TENG captures biomechanical energy, and a power management circuit conditions the electricity for controlled drug delivery. Ex vivo testing on porcine skin revealed a ∼50% improvement in drug delivery compared to traditional patches.	[43]
Liu et al. 2019	Self-powered intracellular drug delivery device based on TENG. There are four components to the system utilized for in-vitro research: - Al electrode, TENG, Nano needle array electrode and bridge rectifier. For in-vitro experiments, the disc or circular TENG was utilised. This system delivers exogenous materials (small molecules, macromolecules, siRNA) into various cells, including primary cells, with 90% efficiency and over 94% viability.	[44]
Zhao et al., in 2019,	A controlled drug delivery system (DDS) was used, which made use of a magnetic TENG (MTENG). A small magnet was attached to the back of the frictional layers of titanium and nanostructured PTFE utilized in the fabrication of the MTENG. The results proved that an electric field accelerated drug release. The drug is released by the formation of Nano holes on the surface of red blood cells (RBCs), which were afterwards repaired when the electric potential was diminished. The results proved that an electric field (EF) accelerated drug release. An EF generated by MTENGs induced a 40.3% release of DOX from RBCs after a 1-hour exposure. The outcomes confirmed the outstanding performance of MTENG controlled DDS on HeLa cells, 3D multicellular spheroids (MCTS) and BALB/c-nu tumor-bearing mice.	[1]

A wireless in vivo self-powered cardiac sensor was developed by Zheng et al. using iTENG [45]. A multilayered keel structure formed of durable titanium strips, nanostructured PTFE (Polytetrafluoroethylene) (50µm) as a triboelectric layer atop a Kapton film with ultra-thin Au as electrode, and Al foil (100µm) as another triboelectric layer and electrode constitutes the proposed framework. Long-term dependability and excellent output performance are provided by the robust system, which has an in vivo output voltage of 14 V and an output current of 5μA. The proposed device which can display the physiological heartbeat directly includes a wireless implantable transmitter for real-time cardiac monitoring along with a self-powered wireless data transmission system. Using basic data processing and a wirelessly sent signal, the experiment was conducted on an adult Yorkshire porcine. The use of wireless healthcare monitoring systems is encouraged in this work [45].

A self-powered, adaptable and implanted triboelectric active sensor (iTEAS) for constant monitoring of cardiac and respiratory problems has been proposed by Ma et al. [4]. The iTEAS is made of many purpose-specific biocompatible materials including:

- PTFE with nanostructures (n-PTFE) acting as a negative triboelectric layer
- A flexible Kapton surface,
- An extremely tiny gold electrode
- Al film serving as an electrode and triboelectric layer
- An elastic titanium strip is placed over the Kapton film to ensure separation and contact.

The contact separation between the n-PTFE and Al triboelectric layers was brought on by the contraction and relaxation of the heart. Through the combination of contact electrification and electrostatic induction, this repeating motion produces output signals for alternating current (AC). The contact-separation mode of TENG is used to directionally harvest the motion of the heart and respiration while implanting the self-powered, core-shell packaged iTEAS into the pericardium of a living swine. The multifunctional iTEAS is used in conjunction with an arterial pressure catheter to detect blood pressure, blood flow velocity, and to constantly track heart rate, respiration rate and arrhythmia. As a thin-film device, the iTEAS can be inserted into the body during minimally invasive surgeries and provides 99% accuracy in monitoring heart rate. The fact that the device must be implanted in the human body for it to function, however, may limit its application [4].

2.2 Biofuel cell

In order to transform chemical energy into electrical energy, biofuel cells employ living things or enzymes. There are several varieties of biofuel cells including enzymatic, microbial, and mammalian ones depending on the catalyst being employed [46]. The Proton Exchange Membrane (PEM) located in the center of the fuel cell system, along with the anode and cathode electrodes are the three most crucial parts of a fuel cell. Hydrogen or methane as well as more sophisticated compounds like glucose or hydrocarbons can be used as fuel for the biofuel cell. The primary fuel used is glucose. Fuel was oxidized at the anode side, resulting in the production of protons and electrons as a byproduct. The PEM will allow the protons to move from the anode to the cathode surface while the electrons will use an external circuit and electric potential to do so [47,48].

Fuel Cell Reactions:

Anode: $C_6H_{12}O_6$ (Glucose) + $H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$

Cathode: $24H^+ + 24e^- + 6O_2 \rightarrow 12H_2O$

The development of biofuel that might be injected into a living organism for medical devices or biosensors is the current focus of research into alternative power sources.

2.2.1 Implantable medical devices (IMDs)

IMDs have been broadly utilized in animal studies for the detection of diseases, therapeutic uses and biological sciences. They are currently a crucial component of research on human in vivo physiology and treatment. Microbial biofuel cells (MFCs) are new technologies that have attracted a lot of attention recently since they open up great opportunities for producing sustainable energy from a variety of chemicals, solubilized carbon-based waste and renewable bioactive. The MFC is a machine that uses microbes to directly degrade sugars in order to produce electricity. Through the MFC system, voltage and current produced by the glucose oxidation process in Escherichia coli, Justin et al. demonstrated that Escherichia coli and human white blood cells may produce electricity [49]. While Escherichia coli and human white blood cells were used as catalysts in earlier investigations, the present value in the Justin group experiment is lower than those results. The possibility of using human cells and bodily fluids to generate energy in the future to run the IMD is being investigated [49,50]. If Mammalian biofuel cells (MBFCs) produces a considerable amount of energy in a single spot, it might be used to power implantable sensor devices for medical monitoring [51,52]. Human white blood cells could be utilized to generate electrical energy, which could then be used to power a variety of implantable medical devices including an insulin pump, cochlear implants, stomach inducers, spinal cord stimulators and neuro-stimulators [51]. The device's cathode is composed of unmodified carbon mesh, whereas the anode is made of PLL-doped carbon mesh. Cyclic voltammetry was used to study the electrochemical activity of immobilized leukocytes (white blood cells). Peaks in oxidizing factor were seen in the presence of leukocytes but not when they were absent. Peak currents were determined to be 0.58 and 1.92μA for Ag/AgCl at 0.33 V vs 1×10^6 leukocyte cells and 2×10^6. By adding activators, the peak current was raised to 2.106 A between 1.92 and 3.62μA. New techniques like direct electron transfer (DET) and compressing carbon nanotubes substantially enhanced voltage and power output [53].

2.2.2 Glucometer based on biofuel cells

Insulin monitoring is strongly advised to manage diabetes, one of the most prevalent deadly diseases. The flow meter and colorimetric methods are the two most popular ways to measure blood sugar. For a short period of time, a tiny sensor is implanted under the skin as part of the continuous glucose monitor (CGM) technology to assess blood glucose levels. Reports state that this technology has poor accuracy. Therefore, the three-dimensional multi-walled carbon nanotubes (MWCNTs) immobilized by anodic and cathodic enzymes, pyrroloquinoline quinone glucose dehydrogenase PQQ-GDH and lactase constitute the self-powered glucose biosensor (SPGS) technique proposed for the bio electrode fabrication. The advantages of doing it this way include glucose sensing that is continuous and an insulin delivery system that bridges the gap between monitoring blood glucose levels and delivering insulin [54]. Self-powered glucose biosensors thereby demonstrated an excellent performance to address the drawback of the outdated glucometers and continuous glucose monitors (CGMs) [55].

The development of biofuel cell glucometers signals a significant innovation in glucose monitoring, potentially leading to more convenient, comfortable, and sustainable solutions [56,57].

2.2.3 Potential of biofuel-powered smart contact lenses

Intelligent development techniques for medical devices are required in order to create current and advanced medical gadgets. Shape memory polymers (SMPs) are a medical device that is frequently targeted. Smart biomedical cell-encapsulated equipment, self-annulus fibrosis closure devices, self-deployable, self-tightening structures, cell transplantation and tissue engineering etc. are some applications for such systems. According to other findings, multifunctional hydrogel fibers are frequently utilized in smart biomedical devices, particularly in the fields of encapsulated cells, tissue engineering, and cell transplantation [58]. Recent studies have looked into the impacts of thin-film lacquers when added organometallic catalysts, such as titanium TIB KAT®216, titanium TIB KAT®519 as coating materials for electronic systems with regard to their biological use. By reducing toxicity and expediting the curing process, these catalysts shown good accomplishment [59]. Due to their capacity to track intraocular pressure, eye movements, electro retinograms, and the physiology of tears, contact lenses have attracted attention as one of the new generations of smart biomedical devices [60].

According to study, materials frequently used in biofuel cells have the ability to make contact lenses. In this instance, 100 mm gold micro wires coated with au nanoparticles (AuNPs) were used to build 3D microelectrodes in order to monitor a little amount of basal tear [61]. The micro-biocathode and microanode were also carried out using Au micro wires and AuNPs, which have an average diameter of 17 nm. The result was a 100-fold increase in real surface area [62]. These tools can be utilized for refractive issues, electromagnetic interference and other therapeutic purposes.

A biosensor with the ability to self-power on a contact lens has been designed in response to the growing demand for rapid disease diagnosis and screening in an effort to lower the expense and strain on our healthcare system.

2.2.4 Biofuel based breath alcohol checker

Platinum electrodes and an acidic porous electrolytes layer are used in a fuel cell detector. A voltage parallel to the alcohol concentration is created as the oxidation process for the alcohol in the air exhaled through the nose produces the output products acetic acid and water. Due to their integration with the Bluetooth gel-immobilized enzyme and ability to be connected to a smartphone, alcohol testers known as BAC track that are already on the market will continue to garner attention. In accordance with the response current, the measured glucose concentration ranges from 0.05 to 4.75mmol/L. This product's advantage is that it will show whether the driver is drunk and how long it will take for the alcohol to leave their entire body [63].

2.3 Solar energy harvesting

Several medical devices need electrical or thermal energy, including the following:

2.3.1 Solar Autoclave

The correct approach for off-grid sterilization of medical and dental tools is a solar-powered medical autoclave, according to research conducted in this area. An autoclave is a closed container that operates under high pressure and temperature to hold fluids. It is required to employ thermal energy in the autoclave to produce fluid with high pressure and temperature. The necessary thermal energy can be produced using solar energy. The cost of heating the autoclave with solar energy was reduced by 313.50 GBP per year [64] compared to using LNG or electricity. The thermal energy required for steam generation is provided by concentrated sun radiation. The generated steam goes into the sterilization device and then after condensing, it goes back to the solar collector. Due to the thermo physical characteristics of Nano fluids, using it in this setup caused the temperature of the water and steam to rise more quickly [65-67]. It was feasible to maintain the pressure and temperature in the ranges of 12-14 psig, and 115-140°C respectively, during the sterilizing process by using this cycle. These statistics show that the system is functioning properly [68].

Solar autoclaves offer a viable substitute for traditional energy sources for sterilisation. The production of inexpensive solar collector materials has increased the accessibility of solar autoclaves, especially in developing nations with limited access to traditional energy sources [69]. Also, by drastically reducing dependency on fossil fuels, solar autoclaves help to reduce carbon footprints and encourage sustainable healthcare practices [70].

2.3.2 Dental Toothbrush

Recently, a novel kind of toothbrush with titanium oxide (TiO_2) N-type semiconductor was unveiled. The neck of the employed brush has a TiO_2 rod placed within it. The positively charged TiO_2 was connected to the positively charged stainless steel rod by a copper wire, which resulted in the generation of energy. Solar panels served as the electron generation's energy source. These toothbrushes function primarily by reducing the H^+ ions produced by the organic acids in plaque, which causes the destruction of the plaque [71]. The results of the study showed that using this kind of toothbrush can significantly improve dental caries prevention.

2.3.3 Solar microscope

One of the key methods to achieve a clean future is through harnessing and using solar energy. Solar energy is expanding alongside the green industry and is now a significant component of sustainable growth. In addition to causing chemical reactions, solar energy can also produce electricity. One of the affordable energy sources is solar energy, when compared to others like fossil fuel energies, or other renewable energies like natural gas, wind and hydroelectric power. It is simple to install, run, and maintain making it perfect for rural locations with erratic electricity. One of the keys uses for alternative energy is powering medical equipment with solar energy. The rural areas that are largely cut off from urban areas, due to poor road connections wouldn't be able to assess the national electrical transmission system. Therefore, in order to generate an electric supply, a PV encapsulation and fabricating solar system is used that is employed in health centers in order to make medical services available. Solar energy usage to power a microscope (60 watts) (Figure 4) is dependent on two factors: the time of day and when the equipment is turned on. Two approaches had been evaluated: 1) AC method: by using an inverter to convert the DC solar output into AC. DC method: By cancelling the transformer, switching the microscope's power source from AC to DC, using a 12 volt Zener diode as a voltage regulator.

Typical solar system components

a) **PV module:** A photovoltaic module is a group of solar cells that are electrically coupled to one another and fixed in a frame or support structure.

b) **The battery:** In a photovoltaic system, a battery serves two crucial functions: first, it provides electrical energy when the array of solar panels is unable to do so and second, it stores any excess energy that the panels produce when their output exceeds the required amount of power.

c) **The regulator:** It is used to make that the battery is operating under the proper circumstances and to prevent overcharging or over discharging, both of which drastically shorten battery life.

d) Convertor: The two primary categories of convertors are: 1) DC/DC converters 2) DC/AC converter (or inverter)

e) Equipment or load: The load, or microscope, is the piece of machinery that draws energy from your energy system. Utilizing energy-efficient and low-power equipment in this type of system is essential to prevent energy waste. It should be clear that the cost of the photovoltaic system rises as electricity requirements grow [73].

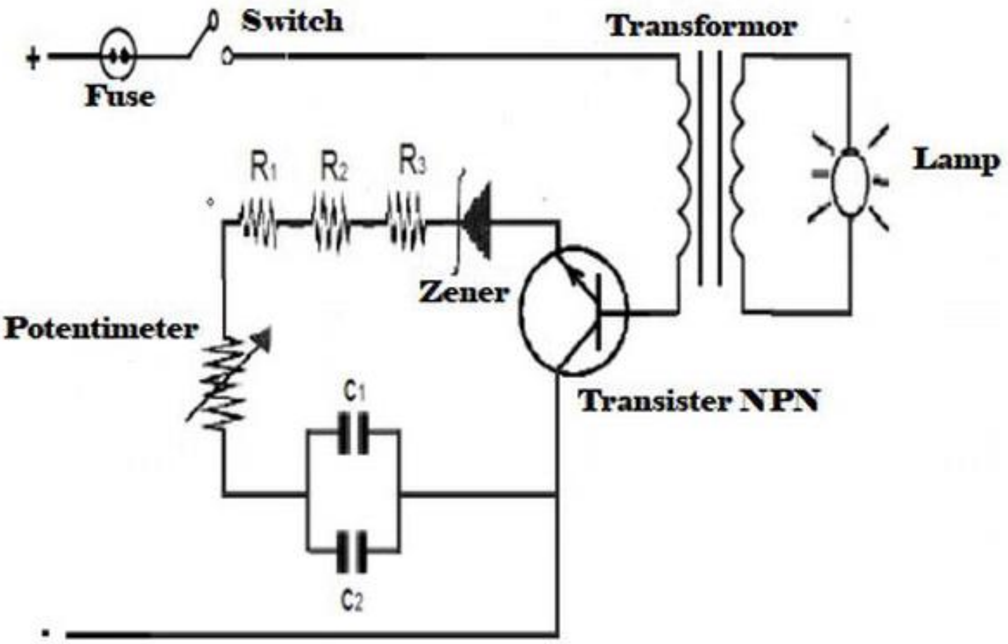

Figure 4: Microscope circuit diagram [72]

Design circuit

The microscope's circuit was altered as a result of:

1. Although solar cells produce DC, the device uses AC.

2. The inverter should not be used because it is high cost. Transformer was eliminated, two potentiometers were wired in series as shown in Figure 5, a Zener with a 12 volt value was added (to keep the effort value constant), and a 12 volt halogen bulb, switch and fuse were utilized. Lastly, assemble the circuit by connecting each component while considering polarity.

As a result, a PV encapsulation and fabricating solar system is utilized to generate the electricity that was once used to feed rural and isolated places and the microscope's circuit is modified to produce the desired results [72].

In terms of accuracy and efficiency, solar microscopes perform far better than traditional energy sources, especially when it comes to characterising solar cells. These microscopes offer uninterrupted spectral analysis and customizable spectral profiles, enabling accurate optical-beam-induced current mapping in solar cells [73]. Conventional energy sources, on the other hand, lack the accuracy and adaptability necessary for such a comprehensive investigation. Solar energy systems have shown they can reduce energy consumption and boost efficiency in diverse settings, such as educational institutions, healthcare sector and industries [74].

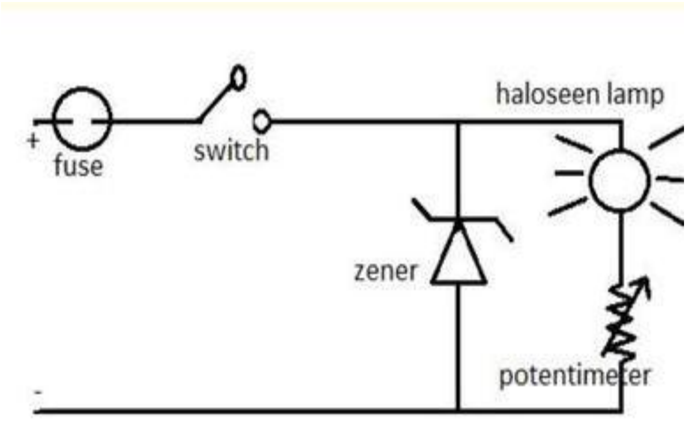

Figure 5: Designed circuit [72]

2.4 Wearable Flexible Hybrid Electronics

Recent improvements in electrical sensing and flexible technology have shown significant promise in a variety of practices, particularly wearable medical and fitness technology (Figure 6).

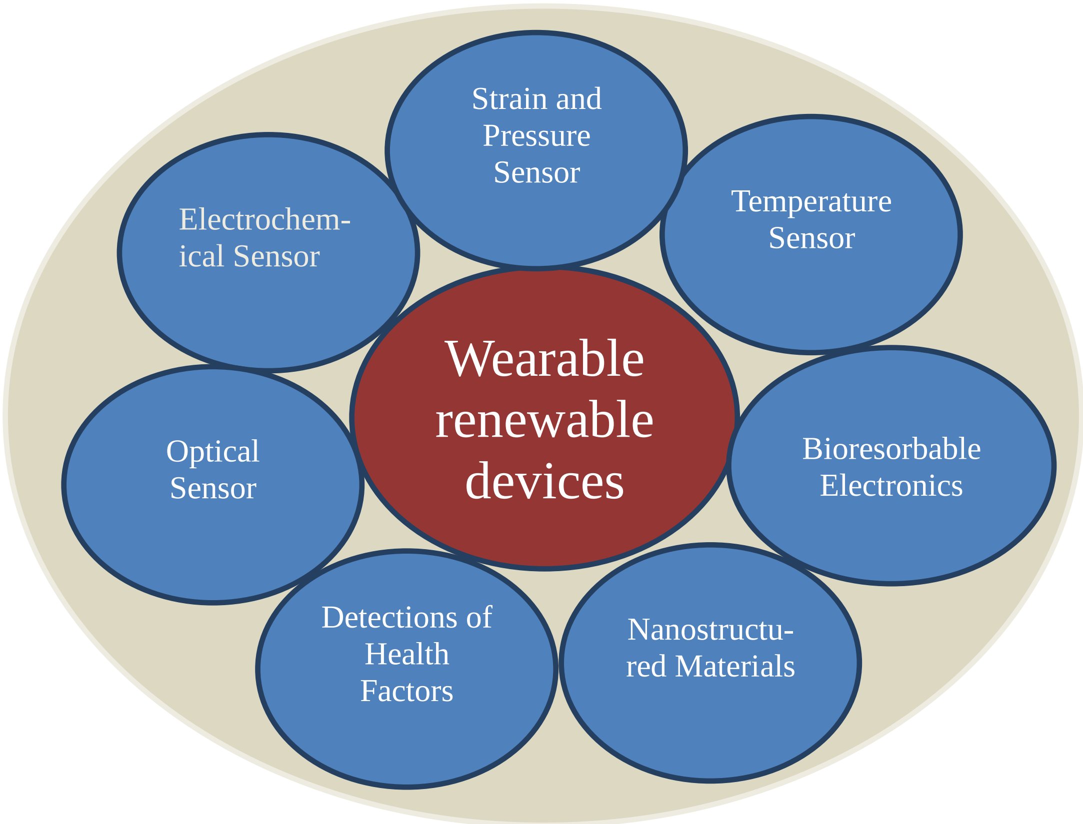

Figure 6: Role of wearable devices in sensor and health monitoring [75]

These gadgets cannot be powered or recharged while in use by a wall outlet because they are made to be worn on the human body for longer periods of time (such as days or more). It is therefore especially appealing to use Energy Harvesting (EH) to obtain energy from movement or heat in ambient environmental sources in order to create self-sustaining systems [76,77]. The most feasible forms of energy for capturing on and near the body include thermal, vibrational, optical, and radio frequency (RF). T76he idea behind energy harvesting is to take energy from the atmosphere and transform it into an electronic energy that can be employed to run a gadget and replenish its battery. Since they offer the most power per area [78] which is crucial in such size-restricted systems, solar and thermal energy are the most frequently used sources.

2.4.1 On-body Sensors

The purpose of biomedical sensors is to examine the human body. The primary goal of this research is to demonstrate that it is feasible to create a self-sustaining adaptable tool, therefore we linked a pulse oximeter and an accelerometer to bracelet, and however more sensors can be coupled to it. The arterial oxygen saturation and heart rate can both be measured non-invasively with a pulse oximeter. The environment that the body is moving through is measured by a temperature and humidity sensor. An accelerometer not only measures vital signals but also tracks motions that can be utilized to evaluate user activity and correct for movement-related sensor measurement inaccuracies.

The ability to power electronic components for long enough to employ WFHE is one of the issues faced by wearable electronics. In contrast to wearable devices powered by batteries, which need to be periodically replaced or recharged, the full potential of wearable electronics can be fulfilled with a battery-free solution. The most recent innovations in adaptable, self-powered technology are ones that can really benefit from WFHE. Transparent Piezoelectric Energy Harvester composed of soft, flexible piezoelectric harvesters which transform mechanical work from physical movements in to the electrical energy. According to the research, the device put on various body parts can produce electricity by regular physiological motions. In a research it was demonstrated that 2.5 V for the foot, 1.98 V for the ankle, 1.05 V for the knee, 0.75 V for the wrist, and 0.48 V for the neck. It is suitable for powering wearable sensors and small electronic components because it can generate a peak power of 40 W with a power density of 0.106 Wcm^{-3}. Similar results are shown by these devices voltage supervisors [79] or ECG monitoring system-on-chips [80]. Wearable thermoelectric generators (TEGs), which may generate energy by leveraging the temperature difference between the skin and the surrounding environment, are another potential technology for self-powered devices. These innovations hold promise for long-lasting human-machine interfaces and future biomedical systems.

3. Conclusion

This review provides a comprehensive analysis of renewable energy-based technologies and their applications in the healthcare sector. It highlights various innovations, including triboelectric nanogenerators, solar-powered systems, biofuel cells, and hybrid technologies, emphasizing their roles in medical diagnostics, patient monitoring, and energy supply. By integrating diverse advancements into a unified framework, this study addresses a significant gap in existing literature and underscores the potential of clean energy solutions in healthcare. The findings suggest that while renewable energy technologies offer promising benefits, further research is required to enhance their efficiency, scalability, and cost-effectiveness for broader implementation in real-world healthcare applications.

Abbreviations

- CGM Continuous Glycometer
- DET Direct Electron Transfer
- IDDS Implanted Drug Delivery System
- IMDs Implanted Medical Devices
- iTENG Implanted Triboelectric Nanogenerators
- MBFCs Mammalian Biofuel Cells
- MFCs Microbial Biofuel Cells
- MTENG Magnetic Triboelectric Nanogenerators
- MWCNTs Dimensional Multi-Walled Carbon Nanotubes
- PEM Proton Exchangeable Membrane
- PTFE Polytetrafluoroethylene
- R6G Rhodamine 6G dye
- RBCs Red Blood cells
- SMPs Sharp Memory Polymer
- SPGs Self-Powered Glucose Biosensor
- TDD Trans Dermal Drug
- TENG Triboelectric Nanogenerators
- WFHE Wearable Flexible Hybrid Electronics

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