IOSR Journal of Polymer and Textile Engineering (IOSR-JPTE)
e-ISSN: 2348-019X, p-ISSN: 2348-0181, Volume 11, Issue 3 (May. – June. 2024), PP 01-06
www.iosrjournals.org

An Investigative Assessment Of Inorganic And Organic Teg (Thermo Electric Generator) Embedded Material To Identify The Optimize Body Part, Place And Organic Teg Material For Harvesting Maximum Voltage From Human Body

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Abstract

Nowadays, renewable energy sources play a vital role for humanity. Various devices Li-ion batteries, and microbial fuel cells have been designed for energy storage and conversion systems, which can be seamlessly integrated into textiles without compromising their performance. Textiles, being renewable materials, hold significant importance in addressing future energy and environmental challenges. This paper essentially deals with the computation of the harvested electrical voltages from a TEG device embedded in fabric if clothed on a human body. An inorganic and seven organic types of TEGs are here considered and compared the calculated values obtained from the five different regions of the body exposed to three widely varied temperature of the Indian ambience. As an examplehe application of these harvested energy values includes the requirements of number of TEG devices in fabric for a mobile charging without external power sources.

Keywords: *Thermoelectric Generator (TEG), Seebeck coefficient, conductive yarn, 3D fabric.*

Date of Submission: 26-04-2024 Date of Acceptance: 06-05-2024

I. Introduction

Clothing serves as the foundation of human society, with historical records dating back to around 34,000 BCE mentioning the use of textile-based materials. Initially, the primary purpose of clothing was to provide coverage for the body and protection from the elements. The advancement of materials driven by the developments in science and technology has led to the evolution of traditional textiles into smart textiles capable of harnessing energy from the human body and its surroundings.[1]

To develop flexible and wearable electronic devices that can adapt to various forms of deformation like bending, stretching, compressing, and twisting while maintaining their performance, reliability, and integration are crucial factors. Presently, Thermoelectric textiles find applications across a wide range of industries including electronics, automotive, sensing, electro-energy, and packaging. [2].

The objectives of this research are to calculate the harvested voltage and conduct a comparative analysis between one inorganic and seven organic TEG materials to determine the optimal body part, location, and the organic TEG material for maximizing voltage generation from the human body. Such analysis may address the issue of seamless integration of these devices into garments without compromising their comfort and aesthetic appeal.

Conductive textiles are created by coating, incorporating, or inserting conductive materials into yarns. Smart conductive textiles are produced by using conductive nanoparticles, conductive carbons, and electrically conducting polymers (ECPs) [3].

Thermoelectric effects are reversible phenomena that allow direct conversion between thermal and electrical energy [4]. The conversion of thermal energy into electrical energy is known as the Seebeck effect, which has applications in power generation. Devices used in such applications are called Thermoelectric generators (TEGs) [5-10].

The Seebeck effect occurs when a temperature difference across a conductor creates a voltage at the ends of the conductor. Two different conductors, A and B, are connected to form the junctions of a circuit (Fig 1). These conductors are electrically connected in series and thermally connected in parallel. One junction has a higher temperature, Th, and the other has a lower temperature, Tc, with Th greater than Tc. The Seebeck effect is caused by thermal diffusion, which causes the charge carriers (electrons or holes) to move across (or against) the temperature difference in the conductors, generating voltage.

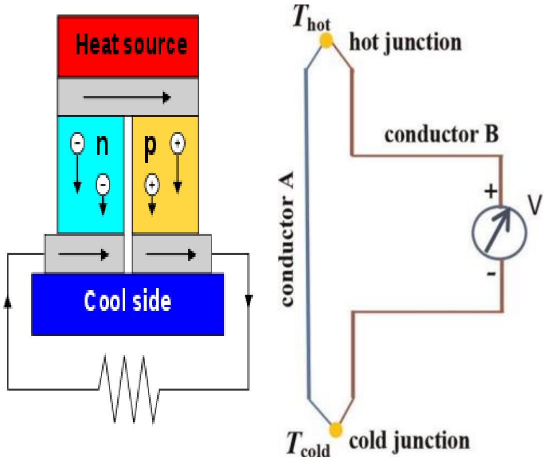

Fig-1: Schematic of the Seebeck effect in an open circuit.

The Thermoelectric generator (TEG) device is made up of one or more Thermoelectric couples [11].

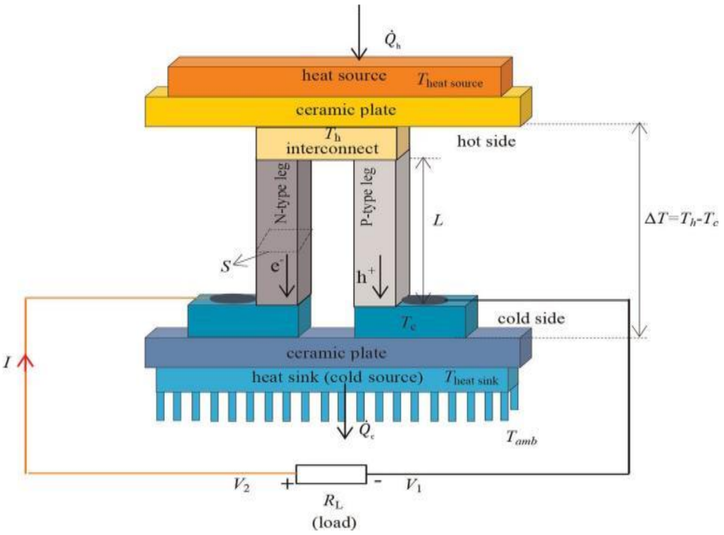

Fig 2: Schematic of a TEG device with a single thermoelectric couple and two legs.

The simplest form of a TEG includes a thermocouple, which consists of a pair of p-type and n-type thermoelements (Fig 2) or legs connected electrically in series and thermally in parallel. It is crucial to differentiate between n- and p-doped materials. The p-type leg has a positive coefficient, while the n-type leg has a negative coefficient. These two legs are connected on one side by an electrical conductor, typically a copper strip, forming a junction or interconnect. The voltage at the external terminal connected to the n-type leg on the cold side of the TEG is denoted as V2, and the voltage at the external terminal connected to the p-type leg on the cold side of the TEG as V1 (as illustrated in Fig 3(a) [12-14].

An electric circuit is formed by connecting an electrical load with resistance RL in series with the output terminals of a Thermoelectric generator (TEG). When electric current flows through this electrical load, an electrical voltage is produced at its terminals. The TEG device generates DC electricity continuously as long as there is a temperature gradient between its sides. An increase in the temperature difference ΔT = Th -Tc across the TEG device results in higher electric output power being generated.

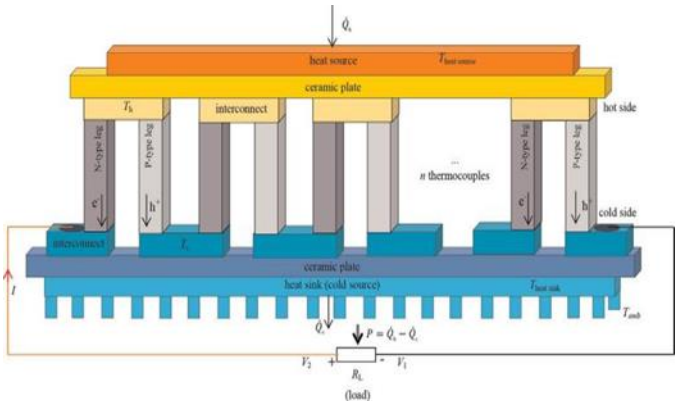

Fig 3(a). A TEG device with a multiple Thermoelectric couple of two legs. [15-17].

To create Thermoelectric yarns, researchers used non-ionic waterborne polyurethane (NWPU) based composites of multiwalled carbon nanotubes (MWCNTs) to coat commercial polyester yarns. The thermoelectric properties of these NWPU composite films and the effectiveness of the yarn coatings were detailed in a previous study [18].

The Fig 3(b) illustrates the fabrication process of a 3D fabric thermoelectric generator (TEG). The process involves preparing a spacer fabric substrate and coated p-type and n-type yarns. First, the p-type and n-type yarns are embroidered into the spacer fabric substrate in an alternating arrangement. Next, silver paint is patterned on the top and bottom of the loops of yarns to connect every adjacent p-type and n-type yarns in series. In the final step, two copper wires are attached to the first p-type and last n-type yarns as output pins of the fabric TEG. Additionally, silver paint is applied to the connections between the yarns and copper wires to reduce contact resistance, resulting in a 3D fabric TEG. [18].

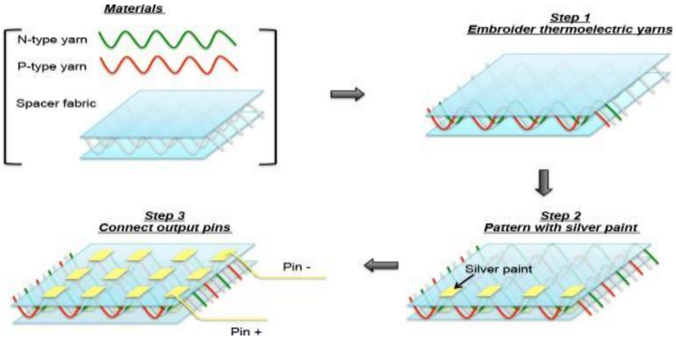

Fig 3(b). Fabrication process of 3D fabric TEG [18]

II. Materials And Methodology

Materials considered for calculation

Wearable thermoelectric devices (TE) divided into two types like inorganic and organic TEG material. Inorganic TEG materials are available, namely Bi2Te3 (Bismuth Telluride), PbTe (Lead Telluride), SnSe (Tin Selenide), Skutterudite (CoAs2), and SiGe (Silicon-Germanium), are preferred for their better thermoelectric performance and stability compared to organic materials TEG material but these are not comfortable for wearable fabric because of higher rigidity hence used only one type inorganic Bi2Te3 as an example in the study.

Organic Thermoelectric devices can be made using both conductive and non-conductive polymers. Among non-conductive polymers, polyvinylidene fluoride (PVDF), Poly(3-hexylthiophene) (P3HT), and poly(3-octylthiophene) (P3OT) are commonly used. For conductive polymers, polyacetylene (PA), polyaniline (PANi), poly 3-methylthiophene (P3MT), polyparaphenylene,polycarbazolevinylene,polythiophenes (PTh), polypyrrole (PPy), Polyphenylenevinylene (PPy), poly 3-butylthiophene (P3BT), and poly 3,4-ethylenedioxythiophene (PEDOT) are major choices. PEDOT:PSS coated carbon nanotubes (CNTs) are particularly popular as a composite material for Thermoelectric applications. Seven organic TEGs are considered for the comparative study.

The present work in the analysis is to calculate the voltage generated from a TEG device if used in clothing worn by the human being exposed to different ambience of India. The TEG device in clothing thus detects a temperature differential between relatively cold temperature in contact with human skin and other part of it exposed to external atmosphere of relatively hot temperature or vice versa. Which would result in generation of voltages. A comparative study is also carried out to find maximum and minimum voltages generated from the inorganic and organic types TEG at five different body parts and three different locations of India.

III.Calculation Of Voltage From The Inorganic And Voltage, Current, Power From Organic Teg Material

The Fig 4 is the relation between voltage (V) and temperature differential(ΔT) of Bismuth Telluride collected from the literature [19].

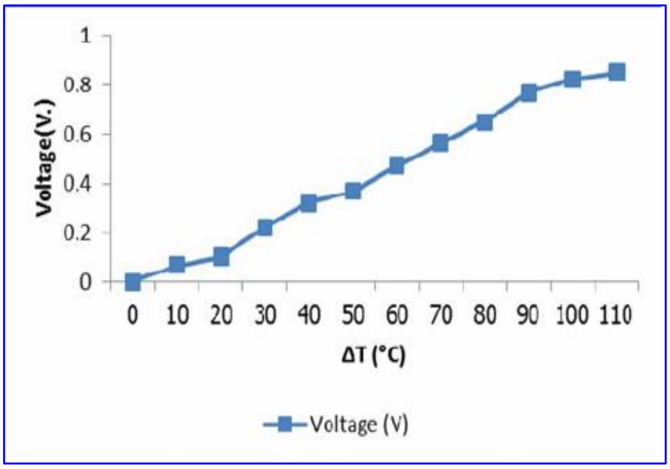

Fig. 4 Relation between voltage (V) and temperature difference(ΔT)

By using the software namely "Origin" [20] following data in the Table 1 are obtained from the graph in Fig 4.

Table 1: Temperature-differential and Voltage from the Fig 4.

Temperature differential (◦C) (X in linest function)	Voltage(V) (Y in linest function)
0.1129	0.0048
10.2460	0.0616
20.2188	0.0979
30.1701	0.2150
39.9499	0.3161
50.3087	0.3684
59.681	0.4695
70.0399	0.5581
80.2057	0.6428
90.3715	0.7643
100.7303	0.8326
110.4886	0.8529

The "Origin" is an analysing and graphing software which can take out X (temperature differential) and Y (voltage generated) data from the Fig 4. The interpolated voltages(V) are calculated in the mentioned different body parts temperature using "LINEST" function in Excel. The LINEST function is = Known X value*Linest([known_ys],[known_xs]) ----(i)

For example, temperature differential (ΔT) between the place Kolkata of minimum average temperature (from the Table 3) and the human shoulder (from the Table 4) is (309.15-286.05=) 23.1°C. The corresponding voltage from the Table 1 is obtained by LINEST in excel using the equation(i) =23.1*Linest([known_ys],[known_xs]) . After entering the value of the differential temperature that mean

harvested voltage is found to be (Y value from the Table 1) 0.1924 V. The remaining cases of body parts at three places are calculated by this method for the inorganic material.
In case of organic material, the harvested voltage can be calculated by using the formula $V = \alpha(\Delta T)$ ……(ii) [21],[22]
where V = Voltage generated,
α = Seebeck coefficient given in the Table 2 for different organic materials,
ΔT=Temperature differential.

For example, considering the maximum average temperature at Kolkata 35.4°C and human body temperature of 37°C, for the organic material Poly(carbazo lenevinylene) ,Voltage generated $V = \alpha(\Delta T) = 230 \times (37-35.4) = 230 \times 1.6 = 368\ \mu V = 0.3680 mV$. Here Seebeck coefficient (α) of Poly(carbazo lenevinylene) = 230 µV/K(Table 2). All the remaining organic cases are calculated by this method and for the calculation current the formula has been used V=IR [26] ……………………(iii)
where V = Voltage,
I = Current generated,
R = Applied Resistance of constant 2 ohm. [27].
For Example, $I=V/R= 0.3680/2= 0.1840$ mA and Power is calculated by the formula $P=V \times I$ ……………………..(iv)
where V= Voltage,
I= Current
the power $P= 0.3680 \times 0.1840 = 0.0677 \mu W$.

Table 2: Seebeck coefficient of different organic materials

Name of the organic TEG material	Seebeck Coefficient α (µV/K)	Reference
PEDOT: PSS.	163	23
Poly(para-phenylene)	12	24
Polypyrrole	26.9	25
Poly(carbazo lenevinylene)	230	24
Polyacetylene	20	24
Polythiophene	21	24
Polyaniline (PANI)	110	25

Similarly other cases of organic TEGs are calculated on different body parts at five locations. All the calculations are done based on Table 3 and Table 4 below.

Table 3: Maximum and minimum temperature at three locations [28]

Temperature(K)	Kolkata	Rajasthan	Ladakh
Maximum average temperature(K)	308.15	311.15	287.15
Minimum average temperature(K)	286.05	291.15	266.15

Table 4: Temperature at ddifferent body parts [29]

Different body parts	Shoulder	Arm	Wrist	Thigh	Knee
Temperature(K)	309.15	305	301.15	307.15	304.15

IV. RESULTS AND DISCUSSIONS

The calculated values of the harvested voltages at different places and the body parts with varied TEG materials are plotted in bar charts and compared and indicated its utility in designing TEG embedded clothing system.

Effect on five body zones with inorganic TEG material Bi2Te3 (Bismuth Telluride) in Kolkata, Rajasthan, Ladakh during summer (maximum temperature) and winter (minimum temperature).

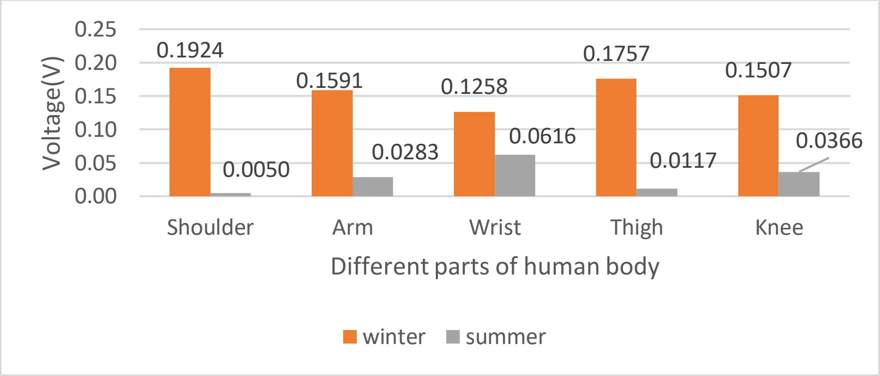

Fig 5(a) voltage generated on different body parts in Kolkata

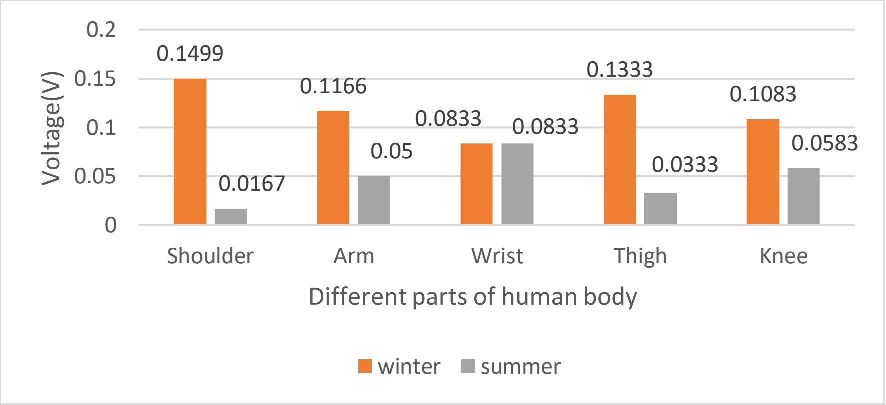

Fig 5(b). Voltage generated on different body parts in Rajasthan

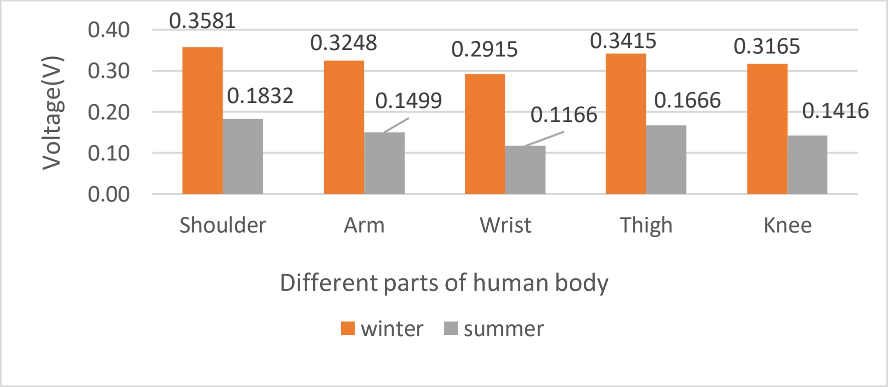

Fig 5(c). Voltage generated on different body parts in Ladakh

During winter, the Fig 5(a) (b) and (c) provide the maximum voltages (0.1924V) (0.1499V) and (0.3581V) at the shoulder part of the body in the Kolkata, Rajasthan and Ladakh respectively. But during summer relatively lower maximum voltage are produced (0.0616V), (0.0833V) at wrist in Kolkata, Rajasthan respectively and (0.1832V) at shoulder part in Ladakh. As an example of application during summer at Kolkata, for any cell phone charging requires (5/0.0.0616) = 81 TEG units at the lowest generated value. (taking cell phone voltage 5V [30]).

Effect on five body parts with TEG Organic material Poly(carbazo lenevinylene)in Kolkata, Rajasthan, Ladakh during summer (maximum temperature) and winter(minimum temperature)

The Poly(carbazo lenevinylene) is only considered in this section as it is found to generate relatively high voltages in wide variety of the ambiance.

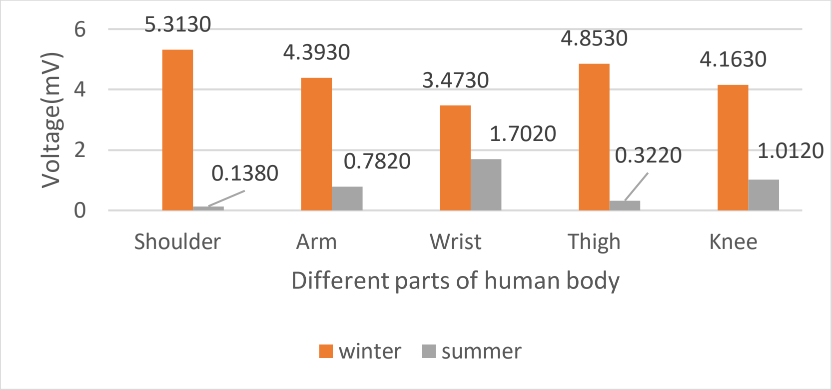

Fig 6(a) Voltage generated on different body parts in Kolkata

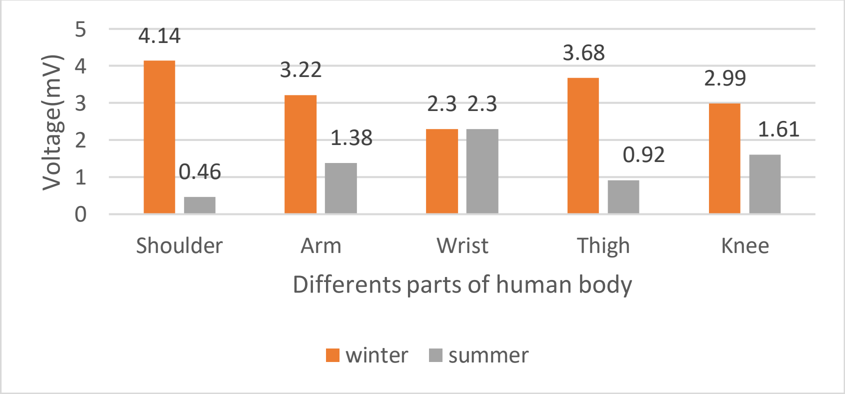

Fig 6(b). Voltage generated on different body parts in Rajasthan

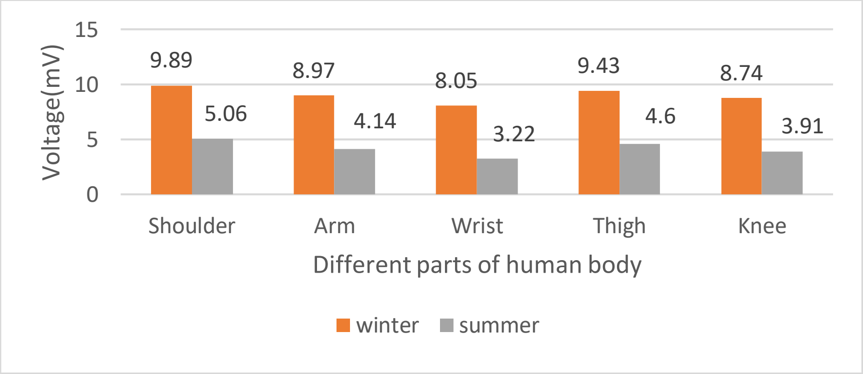

Fig 6(c). Voltage generated on different body zones in Ladakh

In the Fig 6(a).,6(b) and 6(c), for the organic material Poly(carbazo lenevinylene) ,the shoulder part also shows harvesting maximum voltage (5.3130 mV),(4.14mV) and 9.98mV during the winter in the Kolkata ,Rajasthan and Ladakh respectively. In the summer the wrist produces maximum voltage 1.7mV, 2.3mV in the Kolkata Rajasthan region respectively and 5.06mV in Ladakh. Here it can be inferred that the organic TEG produces relatively low voltages requiring larger number of units for a given application. Here also requires (5x1000/1.7020) = 2938 TEG units for cellphone charging when using TEG producing lower voltage. (taking cell phone voltage 5V [30]) during summer at Kolkata.

Effect of the three different places with inorganic material (Bi2Te3 (Bismuth Telluride)) and organic Poly(carbazo lenevinylene) with uniform human body temperature of 37ºC.

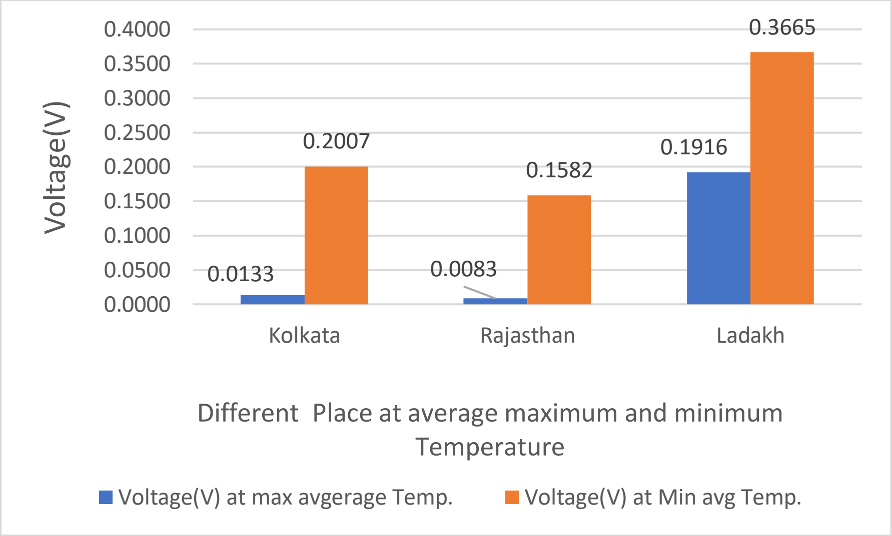

Fig 7(a) Voltage generation from Bi2Te3 in different places at the average maximum and minimum temperature.

While comparing the location-wise for the inorganic material illustrated in Fig7(a), Ladakh estimates to give the maximum generated voltage (0.1916 V) for the human body temperature(37ºC) with the maximum average temperature (summer) at Ladakh while the same is (0.3665 V) at the minimum temperature(winter) of the ambience.

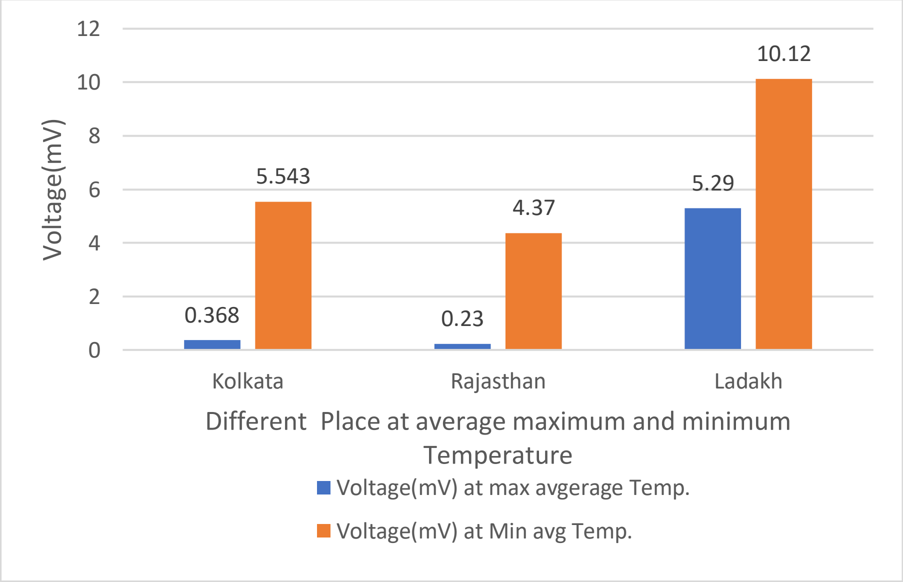

Fig 7(b) Voltage generation from Poly(carbazo lenevinylene) in three places at average maximum and minimum temperature

Also, similarly for the organic TEG material as illustrated in the Fig 7(b), the Ladakh estimates the 5.29 mV at maximum average temperature but 10.12 mV at the minimum average temperature. The lowest value of voltage is obtained in Rajasthan in the summer and winter time also.

Comparative study of seven different organic TEG materials in Kolkata, Rajasthan and Ladakh in maximum and minimum average temperature ambiance with human body temperature of 37ºC.

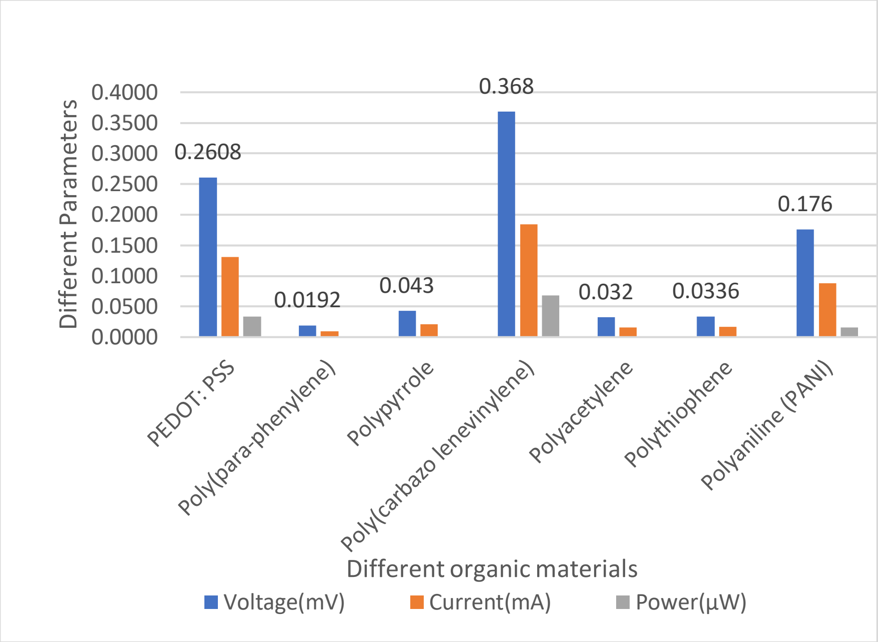

Fig 8(a) Voltage generation at Maximum average Temperature in Kolkata

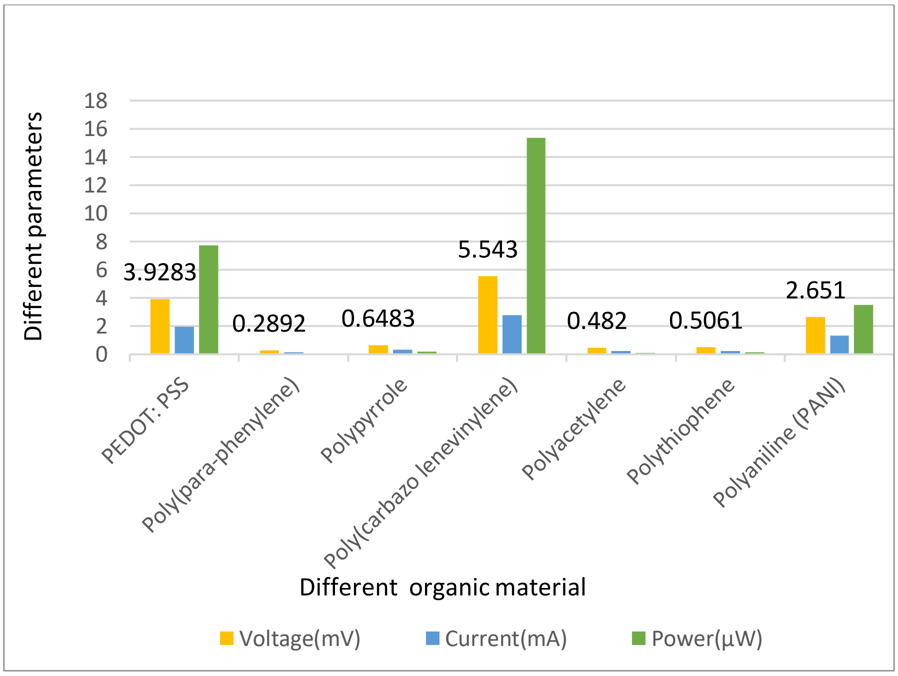

Fig 8(b) Voltage generation in minimum average Temperature in Kolkata

Among the different types of organic materials shown Fig 8(a),8(b). poly(carbazo lenevinylene) estimates the maximum voltage(0.368mV),corresponding current(0.184mA), and power(0.0677µW) in the maximum average temperature(summer) of the Kolkata while that would give the maximum voltage (5.543 mV), and the maximum current(2.7158mA), maximum power(15.3624 µW) with minimum average temperature(winter).The bar diagram as illustrated in Fig 8(c) , shows the poly(carbazo lenevinylene) producing the maximum voltage 0.230mV with corresponding current 0.1150mA, power 0.02645µW in the maximum average temperature of Rajasthan but generates maximum voltage (4.3700mV), current(2.1850mA),power(9.5485µW) in the minimum average temperature of the Rajasthan as represented by Fig 8(d).

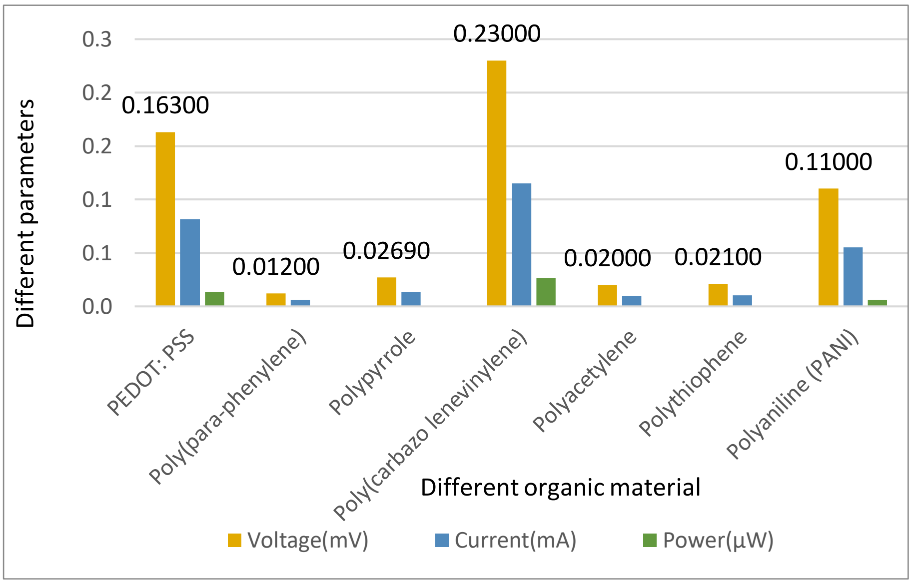

Fig 8(c) Voltage,current and power generation at Maximum average Temperature in Rajasthan

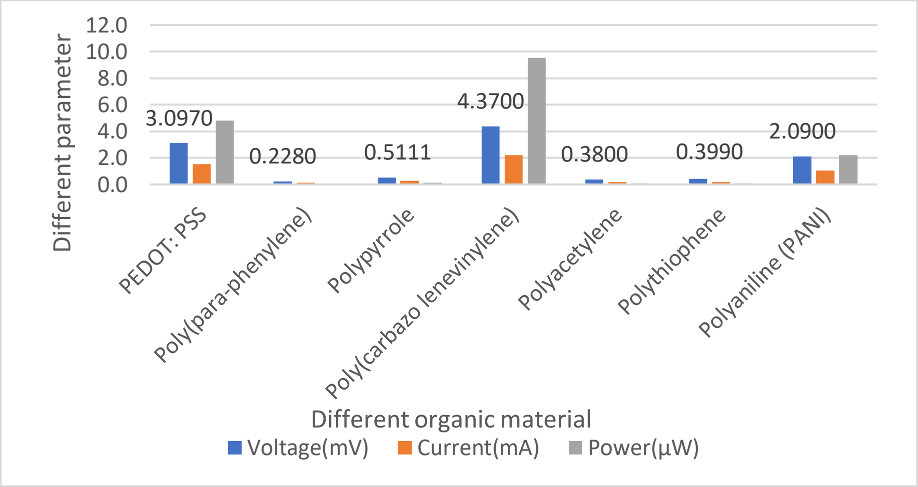

Fig8(d) Voltage generation in average minimum temperature in Rajasthan

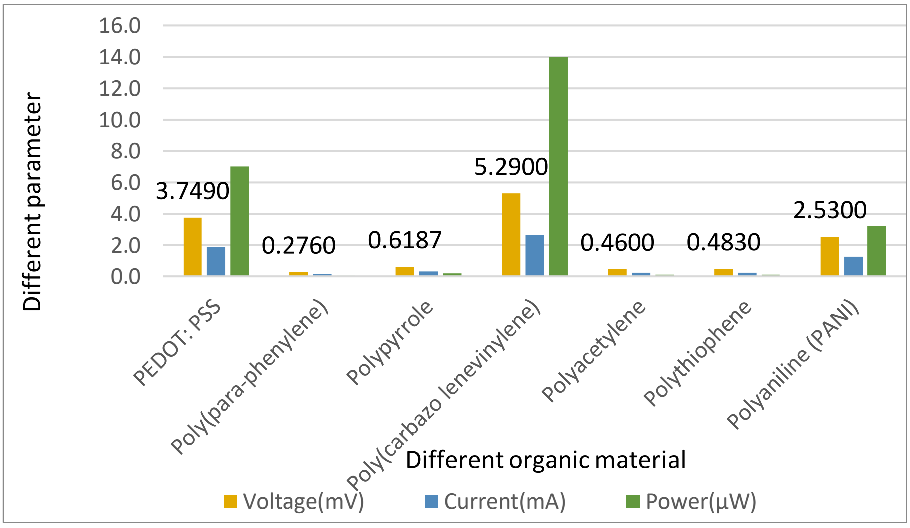

Fig 8(e) Voltage current and power generation at maximum average temperature in Ladakh

The Fig 8(e) depicts the maximum voltage (5.2900 mV) obtained from the organic TEG material, poly(carbazo lenevinylene) at Ladakh in maximum average temperature ,the corresponding current and power is (2.6450 mA),and (13.9921 µW) . The same place as illustrated in Fig 8(f) provides the maximum voltage (10.120mV) with corresponding current (5.060mA) and the power (51.2072µW) in the minimum average temperature .

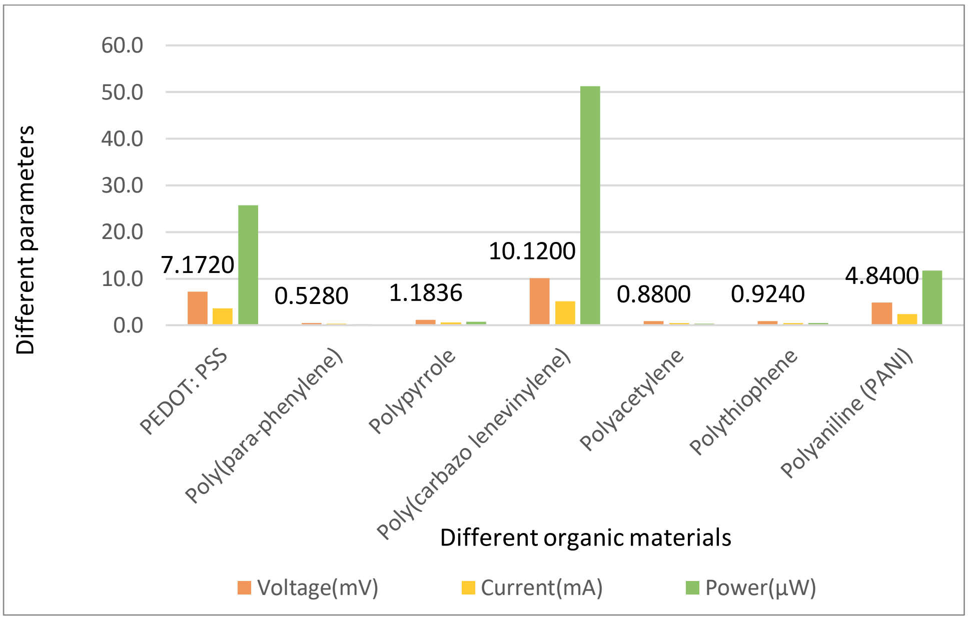

Fig 8(f) Voltage generation at minimum average Temperature in Ladakh

V. Conclusion

The present study compares the voltage generation from one inorganic and seven organic TEG materials and identifies the optimized body part, ambience in India. The characteristic relation between the voltage - temperature differential of different TEG materials are collected from the various literature. The “origin” software was used to collect the data from the graphical form. Three different places in India like Kolkata, Rajasthan and Ladakh with their maximum and minimum temperature variation at five different parts of the human body with different TEG materials provide the generated maximum and minimum voltages. From the study it may be concluded as below.

1.Among five different parts of the human body the shoulder produces the maximum voltage irrespective of inorganic or organic TEG materials and places during winter season but wrist mostly in summer time. The inorganic type TEG always produces higher harvested voltage than organic ones requiring less number of units than organic TEG materials to supply desired voltage in a given application device.

2. The inorganic TEG material Bismuth Telluride, embedded at the shoulder gives the maximum voltage (0.3581 V) at winter in Ladakh.

3. The organic TEG material Poly(carbazo lenevinylene) embedded at shoulder generates the maximum voltage (9.89 mV) in winter in Ladakh.

4.The inorganic material in Ladakh would give the maximum voltage (0.1916 V) at maximum average temperature(summer) and voltage (0.3665 V) at minimum average temperature during winter with human body temperature of 37◦ C.

5.With the organic materials poly(carbazo lenevinylene) , the Ladakh generates the maximum voltage (5.29 mV) at maximum average temperature and voltage (10.12 mV) at minimum average ttemperature during winter with human body temperature of 37◦ C.

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