

3D-printed passive sensors on fabric: A state-of-the-art review and framework for future applications

Sanjeev Kumar¹, Rupinder Singh², Amrinder Pal Singh¹, Yang Wei³

¹Department of Mechanical Engineering, University Institute of Engineering and Technology, Panjab University, Chandigarh, 160014, India

²Department of Mechanical Engineering, National Institute of Technical Teachers Training and Research, Chandigarh, 160019, India

³Department of Engineering, Nottingham Trent University, U.K

Correspondence to: Rupinder Singh/ rupindersingh@nitttrchd.ac.in

Abstract:

Recent studies have been focused on the 3D-printed wearable **passive** sensor on fabric for health monitoring, tracking users, muscle movement, etc. Also, some review reports have been published on wearable sensors based on their types, applications, design, fabrication techniques, etc. But hitherto less has been testified on the scope of 3D printing in wearable passive sensors **on fabric** for wireless fidelity (WiFi) and fifth-generation (5G) technology applications. In this study, a **state-of-the-art review along with** bibliometric analysis has been presented on the 3D-printed wearable sensors on fabric. Also, a short case study on the wearable passive sensor has been performed by printing thermoplastic polyurethane (TPU) on the woven cotton lycra fabric (WCLF) using fused filament fabrication (FFF). The framework for the sensor design with high-frequency simulation software (HFSS) and FFF has been presented for the resonating frequency (R_f) of 4.90 GHz (for WiFi and 5G applications).

Keywords: Wearable sensors; fabric; 3D printing; cotton; lycra; 5G applications

1. Introduction:

Recently, wearable sensors have been extensively used for wireless medical, health care, military, and mobile communications applications [1]. Wearable sensors play an essential part in the progress, flexibility, and capacities of Internet of Things (IoT)-based systems. Because of its appealing form and practical user interface, the application of wearable sensors in smart glasses and smartwatches has acquired commercial traction [2]. The mechanical properties of wearable sensors such as bending, wrinkling, and stress have widely opened their applications in many fields of modern electronics. Wearable sensors have been used to sense the soil/sand/snow [3], relative humidity [4], pH [5], moisture [6], glucose level [7], etc. The unobtrusive nature of wearable sensors necessitates their incorporation into clothes, eliminating the interruption with the user's typical routine and mitigating the annoyance in daily tasks. Incorporating sensors into textiles (clothing) influences modern living, giving many military and medical applications such as heart or brain disease assessments. The wearable fitness solution industry has shown growth to $\$34 \times 10^3$ million (in 2020) and is expected to increase in the future [8]. Wearable sensors embedded into clothing such as armbands, hats, and outfits have piqued the curiosity of researchers. Wearable antennas have applications in the body area network (BAN) for dependable and robust communication between bodies, enabling enormous IoT to monitor health metrics like pulse rate, body temperature, user position, and so on [8]. To allow for simple application on textiles, wearable sensors should be flexible, allowing for conformability, easy bending, and wrinkling [9]. Studies have shown the use of different materials such as textile, paper, polymers, plastic, and fabrics (due to their flexibility and ease of bending or twisting) but the limited thickness of these substrates has put some constraints on their use. Whereas, the low relative permittivity of the textiles has been improved by printing TPU on WCLF by using FFF with marginal change in flexibility. The study has also mentioned the effect of the human body and wearable sensors on each other [10]. Wearable passive sensors are being widely used to sense micro-surface features, deformations, and body movements and to look after human health [11, 12]. In the coming time, wearable sensors may play an important role in clothing communication among users, the scheduling of spare periods, and navigating the world [13]. The adverse effects of electromagnetic waves on the body are a challenge in wearable sensors-based sensors.

To reduce this problem grounded sensors have been preferred [14]. The microstrip patch antenna (MPA) may be used for wearable sensor applications which also reduces the sensor's losses due to the body. An MPA is usually made up of a dielectric layer (for support and strength), a conductive patch (for radiating waves), and conductive ground (Fig. 1).

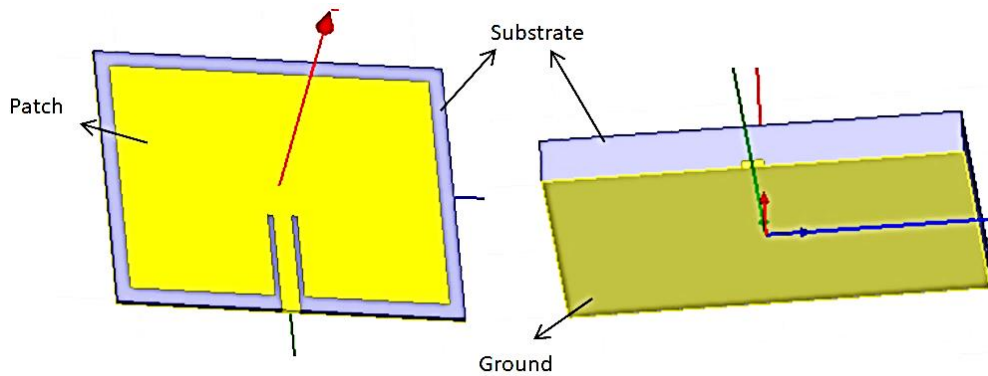


Fig.1: View of MPA as a sensor

1.1 Wearable sensors: Some studies have been reported to expand the performance of sensors, strength, and suitability for different environments by plating with dielectric [15-17] and conductive materials and their shapes and sizes [18-21]. The most important consideration is the material selection for the substrate for the wearable sensors as it should have low losses leading to better sensing characteristics when placed on the body [22]. Researchers have used papers [23], fabrics [24], and plastics [25] as dielectric materials for wearable sensors out of which fabric materials have been mostly used owing to good flexibility and availability. The wearable sensors may be divided into non-textile and fully textile sensors [13] (Fig. 2).

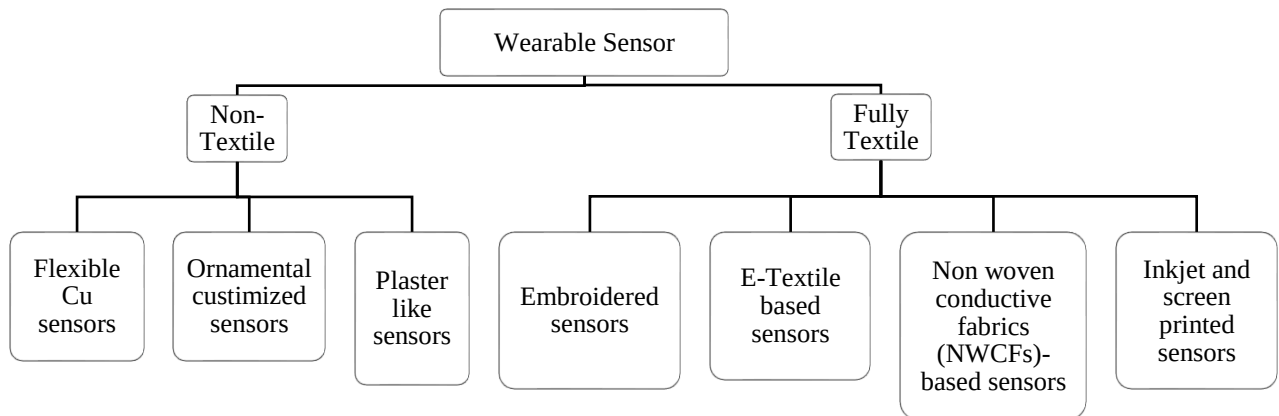


Fig. 2: Types of wearable sensors

Significant studies have been reported on different types of non-textile wearable sensors such as Cu sensors [26, 27], ornamental customized sensors [28-39], and plaster-like sensors [40-44] (Table 1). The non-textile type of sensors is integrated with accessories such as buttons, glasses [44-46], jewelry, bags, shoes, belts, etc. [47-51].

Table 1: Reported studies on different types of non-textile wearable sensors

Type of Non-Textile wearable sensor	Substrate material used	Working frequency	Purpose of Study	Reference
-------------------------------------	-------------------------	-------------------	------------------	-----------

Cu sensors	Poly-dimethyl siloxane (PDMS)	6.2 to 6.4 GHz	Complementary metal oxide semiconductor (CMOS) chips for flexible radio frequency integrated circuit (RFIC) applications	[27]
	Textile	136-176 MHz	Land mobile radio (LMR) application	[45]
	Jeans-cotton -poly cot- polyester	406 MHz and 850 MHz	Body-centered or wearable applications	[46]
	Felt fabric	2.45 GHz	Effect of bending on sensors performance	[47]
	FR4 Poly amide Paper	0.8-0.9 GHz	Radiofrequency identification (RFID) tags using a cutting plotter and solid ink-based tag prototyping	[48]
	Polyamide	-----	The Cu layer was machined using micro-milling technology	[49]
	Cotton woven fabric	60 GHz band	Body centric applications	[50]
	polydimethylsiloxane	2.45 GHz	Sensor robustness was tested based on washing and bending tests.	[51]
Ornamental sensors	Polytetrafluoroethylene (PTFE)	Dual-band	Button size sensors used in Denim jackets for WLAN applications	[28]
	Felt fabric	2.5 GHz	A zip-based tunable sensor has been designed and characterized for WiFi applications	[29]
	Textile	Working for a bandwidth of 3.1 GHz to 12.4 GHz	Button-type sensors	[32]
	RT/duroid®	2.45 GHz	Cuff button sensors for wireless local area network (WLAN), Bluetooth	[33]
	Barium–strontium hexaferrite	0.85 GHz	Magneto-dielectric material was used to miniaturize the sensors	[34]
	Velcro substrate	2.45/ 5GHz	Small-size wearable sensors for WLAN applications	[35]
	Polymer with 6.6 dielectric constant	2.45 GHz	Button-shaped sensors	[36]
	Polyamide	2.4–2.5 GHz	Sensors such as wearable glasses have been purposed and a specific absorption rate (SAR) value has also been kept within range.	[37]
	PDMS	2- 2.9 GHz	A planar inverted F sensor by depositing nanoscale gold and	[42]

Plaster sensors	like	PDMS with barium-titanate	868 MHz	its RF characteristics on 10 % strain has also been discussed. A strain sensor to detect eyebrow or neck skin stretch has been designed	[42]
		Bio silicon	Frequency varies based on the skin type	An epidermal sensor has been modified	[44]

In fully-textile sensors, the conductive, as well as dielectric parts of the sensors, need to be textile. The fully textile sensors can be embedded easily in the garments due to their flexibility and lightweight [13]. The fully textile sensors may be further classified into embroidered [40, 52-62], electro-textiles [51, 63-69], NWCFs [70-74], inkjet [75-79], and screen-printed -based [80-84] (Table 2).

Table 2: Reported studies on different types of fully textile wearable sensors

Fully Textile wearable Sensors	Dielectric Material	Conductive material	Purpose of study	Reference
Embroidered sensors	Taconic RF-45	Amberstrand thread	Stitch direction, spacing on sensor performance	[57]
	Rogers® 6006	AmberStrand® Silver Clad Fiber	The embroidered sensors have been compared with the Cu patch sensors and the effect of stitches geometries was explored	[83]
	Felt Cloth	234/34 2-ply Ag plated nylon type thread	A digital embroidery machine has been used to fabricate a textile-based frequency-selective surface	[58]
	Felt Fabric Denim fabric	Silver-plated nylon threads	The fractal sensors have been designed to resonate at more than one frequency band.	[60]
	PDMS	Elektrisola E-threads	A low-cost and fast embroidery process has been presented to achieve a precision of 0.1mm which is similar to the reported precision on printed circuit board prototypes for applications in neuro potentials	[61]
	Organza fabric	7-filament Electrisola e-threads	A process has been purposed to create colorful textile sensors	[62]
	Woolen felt fabric	1) Ni-plated woven fabric 2) Ag-plated knitted fabric 3) Ag-Cu-Ni plated fabric	The characterization of the 4 different sensors has been done under bending for body wearable applications and it was observed that the sensors	[63]

Electro textile-based sensors			can be bent at a radius of 37.5 mm without affecting the performance of the sensor	
	Fleece fabric	Flectron	The substrate and conductive part have been assembled by using an adhesive sheet and ironing eliminating the need for stitching.	[66]
	Fleece fabric	FlecTron®, Shieldit™ Super, and Zelt	The basic steps to design a textile sensor have been discussed using three different conductive fabrics and a comparison has been performed	[67]
Non-woven conductive fabric-based sensors	Jeans	Nylon self-adhesive conductive non-woven fabric with a Cu plating	Sensors in LACOSTE/ APPLE logos	[70]
	Jeans	Nylon non-woven with a Cu plating	APPLE logo-shaped sensors	[84]
	Leather	NWCFs with a surface resistivity of 0.04Ω/sq.	Sensors working in the global positioning system (GPS) L1 band (1575.42 MHz) and the global system for mobile communication	[72]
Inkjet and screen-printed sensors	Cotton/polyester (CO/PES)	Electrotextile Flectron or conductive ink Electrodag PF 410	This study proposed two washable sensors one using electro textiles and the second using inkjet printing, coating of thermoplastic polyurethane was done against water absorption and corrosion	[74]
	Plain weave 100% cotton fabric and 35% cotton, 65% polyester interlock knitted fabric	Electrically conductive polymer thick film	Different coating materials (acrylic, epoxy, latex, silicone, Polyvinyl acetate adhesive, and Water-resistant polyvinyl acetate adhesive) were used for wash-ability and reliability on screen printed sensors	[75]
	20%CO/80%PES and 100% polyester (PES) woven fabric	DuPont (5025) ink Electrodag PF 410 ink	The screen-printed sensors were tested against washability for TPU-coated and uncoated conditions for 20 washing cycles	[77]
	65/35	Inkjet-printable silver U5714	An interfacial layer of Fabink UV-IF1, using	[78]

polyester cotton
woven fabric

screen printing, was applied to the fabric to fill the gaps in weaves making it easier to use the inkjet printing technique. Sensor's performance was also measured at bending conditions

The wearable sensors in flexible electronics have given a new direction to flexible textile-based sensors [55, 86] providing options for producing smart garments. The current development of textile technologies [87, 88] led to the development of textile-based wearable sensors providing an opportunity to diagnose diseases, therapy, and security robotics [89, 90]. Textiles have gained consideration as a substrate in the construction of wearable sensors called smart garments by directly integrating wearable electronics which have to be flexible, lightweight, and durable [91-93].

Fabric is a liable substance constructed by the twining web of fibers which can be a natural as well as an artificial set of filaments. The literature review outlined that a lot of studies have been reported on wearable textile-based sensors. The classification of the fabrics explored for 3D printing of wearable sensors is shown in Fig. 2. Woven fabrics [94] are manufactured on a loom by interlacing two yarns with each other as shown in Fig.2. The yarn along the length of is known as warp and the yarn's long horizontal direction is called weft [95-100]. The woven fabrics are classified based on the structure [96, 97-100] and how the warp and weft cross each other. Knitted fabric [101-106] is manufactured by interloping yarn.

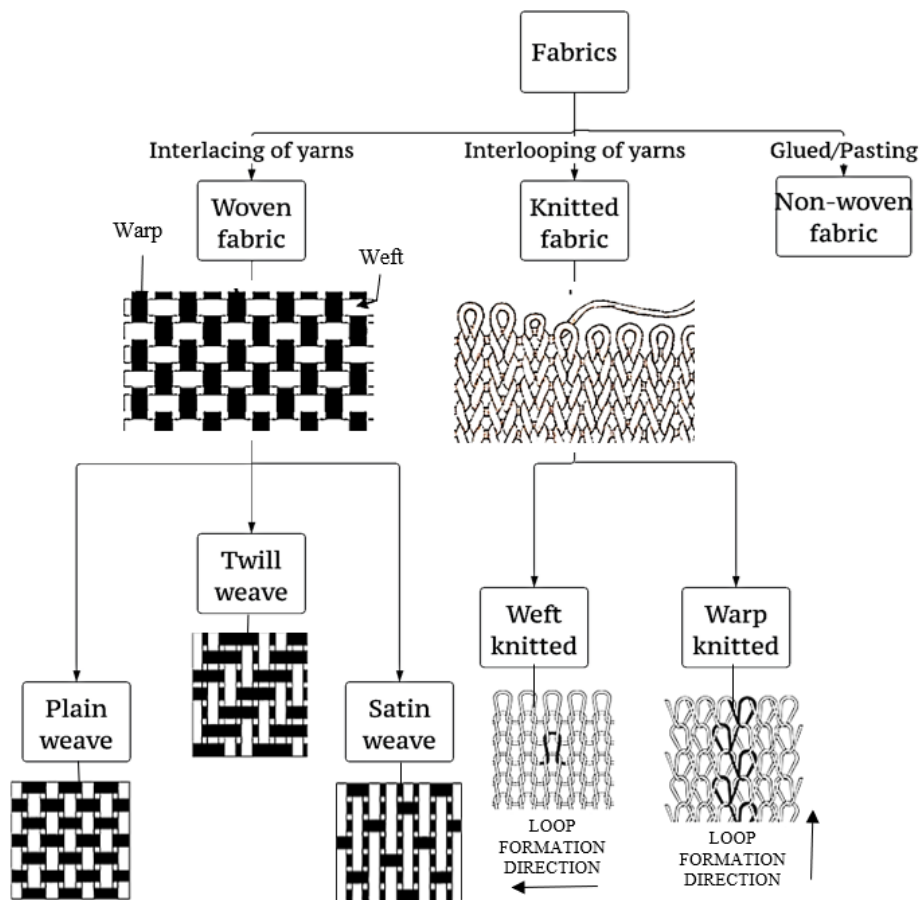


Fig. 3: Classification of fabrics based on their construction

Some recently published articles on wearable sensors are shown in Table 3 (as per classification in Fig. 3).

Table 3: Published review articles on wearable sensors

Basis of review	Reference
Smart textiles have been reviewed for wearable electronics	[107]
Challenges faced in embroidery and related techniques have been discussed	[108]
A survey on textile materials available for wearable electronics has been done	[92]
Wearable sensors for medical applications	[109]
Wearable sensors for wireless body area network (WBAN)	[110]
The challenges for designing wearable microstrip patch sensors have been reviewed with future directions in this field.	[111]
Wireless body-centric applications	[112]
Wearable sensors operating below 1 GHz	[113]
5G wearable sensors	[114]

Based on Table 3, it has been ascertained that a lot of work has been reported on wearable sensors specifically on the different techniques, materials, and applications. However, the part of 3D printing in the field of wearable sensors has not been much discussed.

1.2 The role of 3D printing in sensor applications: 3D printing is an additive manufacturing (AM) process that can fabricate certain designs by adding layers of certain metals or plastics [115-116]. Different materials are printed into different complex 3D products using layer-by-layer deposition [118-121]. Different printing technologies (Fig. 4) have been used to fulfill the different applications, materials, and needs [122].

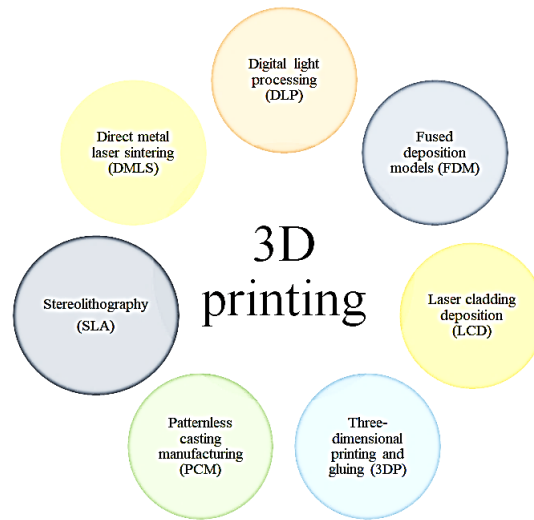


Fig. 4: Different 3D printing techniques

3D printing has attracted a lot of enthusiasm in certain fields like the wireless electronics industry [123,124]. This fabrication method provides a substrate with the desired thickness, filling, shape, permittivity, weight, and flexibility [125]. Commercially, there are a lot of 3D printing techniques but FFF has given flexibility in structure and material density [126] permitting the change in dielectric constant and loss tangent. The effect of complex substrate structures, printed using FDM, has been discussed by some researchers [127]. In another study [128], authors printed ZnO nanoparticle-reinforced PVDF composite for the fabrication of biomedical sensors. Overall, for wearable

applications 3D printing has been developed as a simple, economical, and fast fabrication technique as compared to conventional processes [129]. It has also shown application in fabricating customized wearable sensors [130,131]. Ninjaflex was successfully printed with FFF as a substrate of wearable sensors by some researchers [132, 133]. Further, flexible polymeric materials such as polydimethylsiloxane (PDMS), TPU, and photosensitive resin (UV resin) have also been used as flexible 3D printed substrates for wearable and flexible sensors [134-137]. Some recent studies on 3D-printed wearable sensors using different printing techniques are shown in Table 4.

Table 4: Different AM techniques used in wearable sensors

Technique	Purpose	Reference
FFF	A wearable sensor using Ninja Flex as a substrate has been proposed for on-body applications. For scientific and medicinal applications by attaching to clothes, hats caps, etc.	[125]
	An RFID sensor was developed by pasting stretchable silver paste (dispensed with direct write method) on 3D printed Ninjaflex substrate	[138]
	A combination of ABS and Ninja Flex material has been printed for the substrate where Ninja Flex provided flexibility and ABS provided good R_f properties for medical and defense applications	[139]
	Polyethylene naphtha late (PEN) has been used as a substrate for Sub-6 GHz 5G Wireless Transceivers	[140]
	A 3D-printed ninja flex was used as a substrate for circularly polarized sensors and for radiating patches, the conductive fabric was used	[141]
	A wearable sensor has been purposed for breast hypothermia applications by using 3D-printed TPU as a substrate	[142]
FFF (substrate) Pneumatic dispenser (patch)	A fully 3D printed patch sensor for 5G with a necklace medallion has been proposed	[143]
FDM Screen printing	PREFERM1 ABS300 substrate was printed on FDM and the conductor paste DuPont PE819 was screen printed on these 3-D printed substrates and cured in an oven at 70 °C for 2 h. The sensors have been designed for IoT applications	[144]
FFF (for substrate printing) Direct writing of silver paste	FFF was used to make the substrate of the sensors and support the ring and the radiating patch was pasted by direct writing.	[145]
Aerosol Jet micro-additive manufacturing	Silver nanoparticle ink and UV-curable Acrylic Urethane were used as conductive and dielectric material respectively showing applications in 3D passives and mm-wave sensors.	[146]
Inkjet printing	The challenge of difficult inkjet printing on the textile has been overcome by using an interface-coated layer of polyester cotton fabric providing a smooth surface.	[147]
	Silver ink was printed on standard 65/35 polyester cotton fabric further can be used as Garments for medical and scientific applications	[82]
	A conformal and flexible multiband sensor has been proposed	[148]

Silver ink was printed on polyester/cotton T-shirt for tracking the user by smartphone	[149]
Inkjet printing and embroidery techniques have been combined to develop an RFID sensor integrated into textile	[150]
Epidermal RFID sensors have been fabricated using the inkjet printing technique.	[151]
A concept for 3D-printed wearable sensors on Polytetrafluoroethylene has been given for human activity recognition	[152]
A miniaturized patch sensor with a Split Ring Resonator (SRR) was printed	[153]

As observed from Table 4, FFF has been used in wearable sensors but is not directly connected with textiles as the prepared sensors are either used as standalone devices or some bands whereas inkjet printing has shown its full application in textile wearable sensors to develop the smart garments by directly printing the silver ink on the textiles. In the inkjet printing deposit conductive ink droplets from a nozzle on the flexible substrate for wearable sensors applications [154,155]. It has been widely used due to its accuracy and speed. Although FFF has shown its applications in the textile industry [156-161], less has been reported on the use of FFF in textile wearable sensors.

1.3 Relationship between mobile communication technology and sensing devices: Significant studies have been reported in the past for establishing the relationship between mobile communication technology and sensing devices [162-165]. Usually, AM processes (like powder bed fusion, direct metal laser sintering (DMLS), and FFF) are used to fabricate the components based on the MPA. For MPA-based solutions a substrate (of thermoplastic material), ground, and patch (metallic) act as a passive sensor. The industrial, scientific, and medical (ISM) band (2 to 2.5 GHz or 5 GHz for Wi-Fi) is being explored by most researchers for the tuning of MPA. The overall change in resonance frequency of the thermoplastic substrate due to the change in the substrate's dielectric properties is being calibrated for sensing applications [165]. With this shift to an IoT-based solution, little investment in hardware or software is required, as one may use a Bluetooth-equipped smartphone. The working principle of the sensor is shown in Fig. 5.

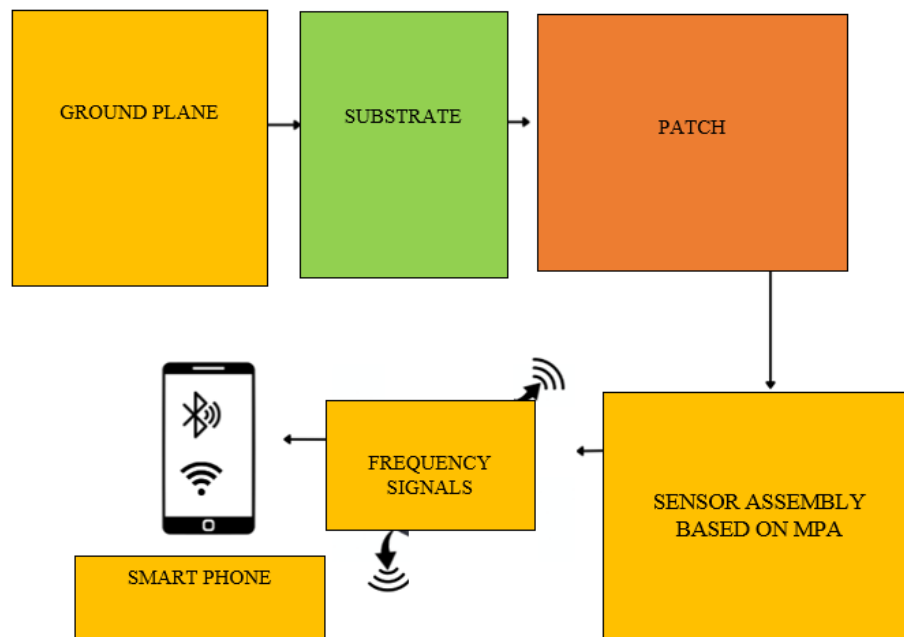


Fig. 5: Working principle of sensor

2. Bibliometric analysis:

The bibliography was compiled using the Web of Science (WOS) database as per previously reported studies [165, 166]. Initially, the keyword “wearable sensors” was explored on the WOS database. A total of 1499 articles (out of which 1417 are journal articles and 66 are review articles) were published across the world since 1996 (till 2022). It was observed that there has been significant growth in the field of wearable sensors leading to the continuously increased number of publications and citations each year as shown in Fig. 6. The most cited articles were recognized and have been enlisted in Table 5. Further, the WOS database about wearable sensors was processed by VOS viewer open-source software. For 1499 results as per the WOS database, selecting a minimum of 7 numbers of occurrences of the keyword 171 meets the threshold, for which a network diagram was developed (Fig. 7). From Fig. 7 it was observed that there are 7 clusters with a different color each representing different domains of work that have been covered under the wearable sensors. Fig. 8 shows the strong connection of wearable sensors with textiles, design, compactness, specific absorption rate (SAR), etc. So, these must be the major factors that should be considered by the researcher while studying wearable sensors. It may be noted that firm lines show a strong relation among different nodes and dim/ faded lines represent a lack of relationship. To observe the growth of 3D-printed wearable sensors, the publication and citation reports were prepared (Fig. 9). Based on the WOS database, 15 top-cited articles have been enlisted in Table 6. Further, the scope of 3D printing in the field of wearable sensors was explored with the keywords “wearable sensors” and “3D printing, additive manufacturing” which shows 31 results (26 research articles, 5 review papers) worldwide (1 in India and highest in 8 in the USA) as on 2022 (on WOS database). A network diagram was developed using a VOS viewer as shown in Fig. 10.

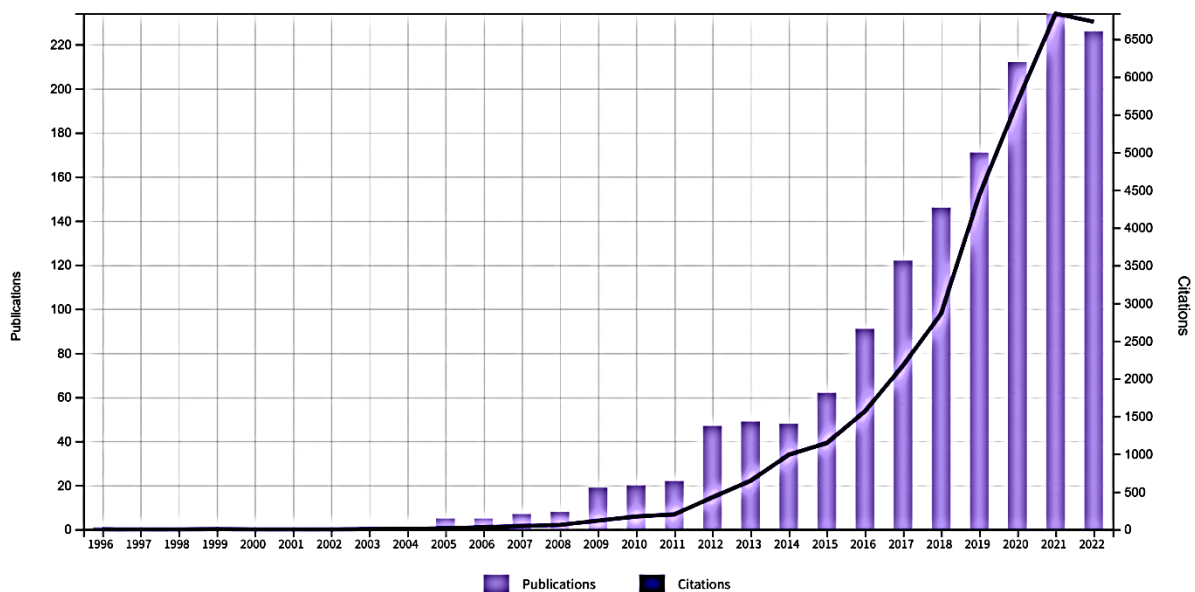


Fig. 6: Growth in research of wearable sensors (from WOS database)

Table 5: Most cited articles in the field of wearable sensors since 1996

S. No.	Title	Year	Total Citations	Average citation per year
1	Wearable Electronics and Smart Textiles: A Critical Review	2014	1244	138.22
2	Stretchable and Soft Electronics using Liquid Metals	2017	1857	142.83
3	Ultra-Dense Networks: A Survey	2016	555	79.29

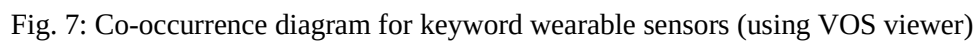
4	Dual-Band Wearable Textile Sensors on an EBG Substrate	2009	385	27.5
5	RFID Technology for IoT-Based Personal Healthcare in Smart Spaces	2014	333	37
6	Design and characterization of purely textile patch sensors	2006	299	17.59
7	Textile Sensors for Off-Body Communication Integrated into Protective Clothing for Firefighters	2009	291	20.79
8	Smart Textile-Integrated Microelectronic Systems for Wearable Applications	2020	278	69.5
9	Adhesive RFID Sensor Patch for Monitoring Sweat Electrolytes	2015	268	33.5
10	A New Frontier of Printed Electronics: Flexible Hybrid Electronics	2020	258	64.5
11	All-Printed Flexible and Stretchable Electronics	2017	246	41
12	2D titanium carbide (MXene) for wireless communication	2018	243	48.6
13	Flexible and Compact artificial magnetic conductor (AMC)-based Sensors for Telemedicine Applications	2013	243	24.3
14	Three-dimensional integrated stretchable electronics	2018	222	44.4
15	Compact, Low-Profile Metasurface-Enabled Sensors for Wearable Medical Body-Area Network Devices	2014	216	24

Table 6: Most cited articles in the field of 3D-printed wearable sensors

S. No.	Title	Year	Total Citations	Average citation per year
1	Stretchable and Soft Electronics using Liquid Metals	2017	857	142.83
2	All-Printed Flexible and Stretchable Electronics	2017	246	41
3	Turning Trash into Treasure: Additive Free MXene Sediment Inks for Screen-Printed Micro-Supercapacitors	2020	130	43.33
4	The aerosol-based direct-write micro-additive fabrication method for sub-mm 3D metal-dielectric structures	2015	57	7.13
5	Advancing the frontiers of silk fibroin protein-based materials for	2018	52	10.4

	futuristic electronics and clinical wound-healing			
6	Harnessing the Rheological Properties of Liquid Metals To Shape Soft Electronic Conductors for Wearable Applications	2019	43	10.75
7	Liquid Metal Sensors: Materials, Fabrication and Applications	2020	31	10.33
8	Electronic Contact Lens: A Platform for Wireless Health Monitoring Applications	2020	30	10
9	Inkjet Printing of Epidermal RFID Sensors by Self-Sintering Conductive Ink	2018	29	5.8
10	Wearable UHF RFID Sensor-Tag Based on Customized 3D-Printed Sensors Substrates	2018	21	4.2
11	Textile-integrated three-dimensional printed and embroidered structures for wearable wireless platforms	2019	13	3.25
12	Wearable Sensors for Cross-Body Communication and Human Activity Recognition	2020	12	4
13	3D Printed Fingernail Sensors for 5G Applications	2020	10	3.33
14	Small Wearable Meta Materials Sensors for Medical Systems	2016	9	1.29
15	Additive Manufacturing of Shape Memory Polymer Composites for Futuristic Technology	2021	8	4

The scope of 3D printing in the field of sensors has been shown in Fig. 10 which shows the relation of 3D printing with sensors, wearable sensors, mechanical properties of sensors, fabrication of sensors, and use of silver nanoparticles in sensors. The co-citation network diagram for co-citation of authors was also explored by choosing at least 6 citations of authors met by only 16 authors out of 1371 authors as shown in Fig. 12. Further, the scope of FFF was explored in wearable sensors by searching the keywords “wearable sensors” and “Fused deposition modeling or Fused Filament method” on the WOS database which shows only 1 publication in this field ascertaining the gap in the literature. From this study, it was ascertained that little work has been reported on the 3D printing of plastics on the textile for wearable sensor applications.



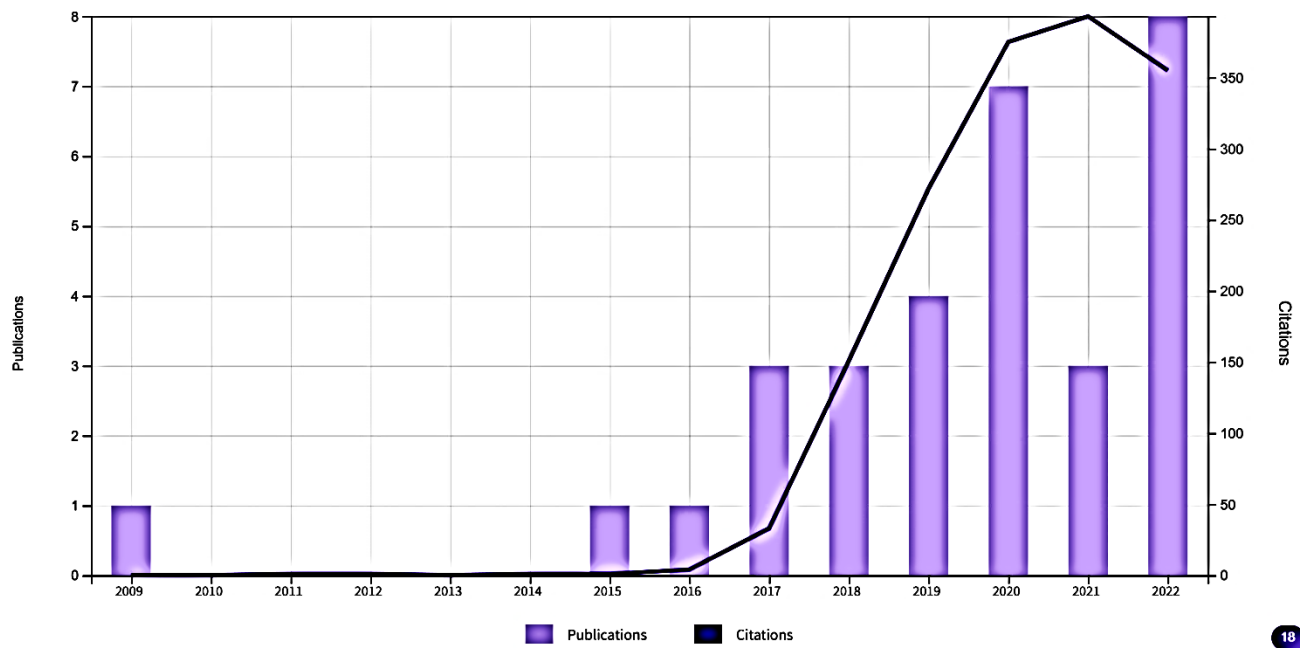


Fig. 9: Growth in research of 3D printed wearable sensors (from WOS database)

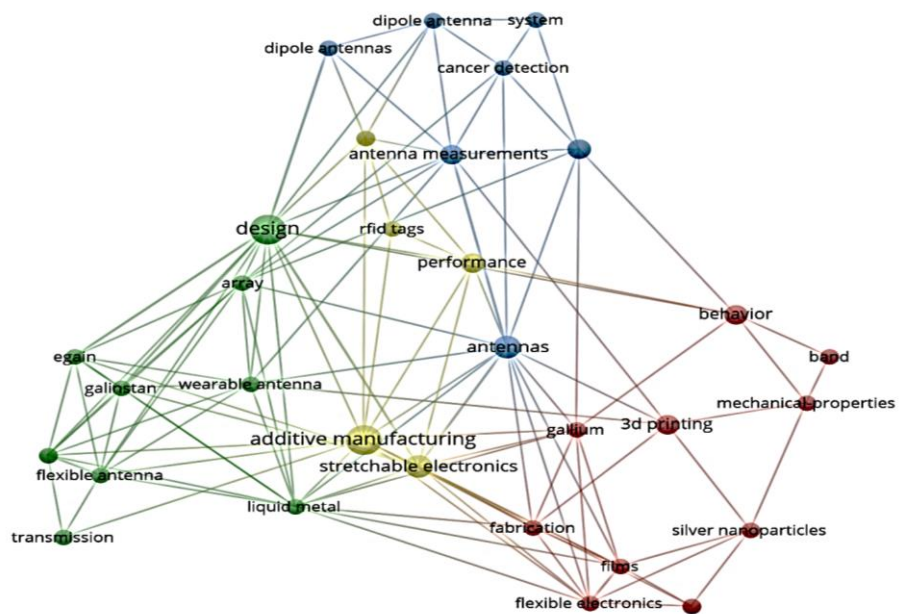


Fig. 10: Network for 3D printed wearable sensor (using VOS viewer)

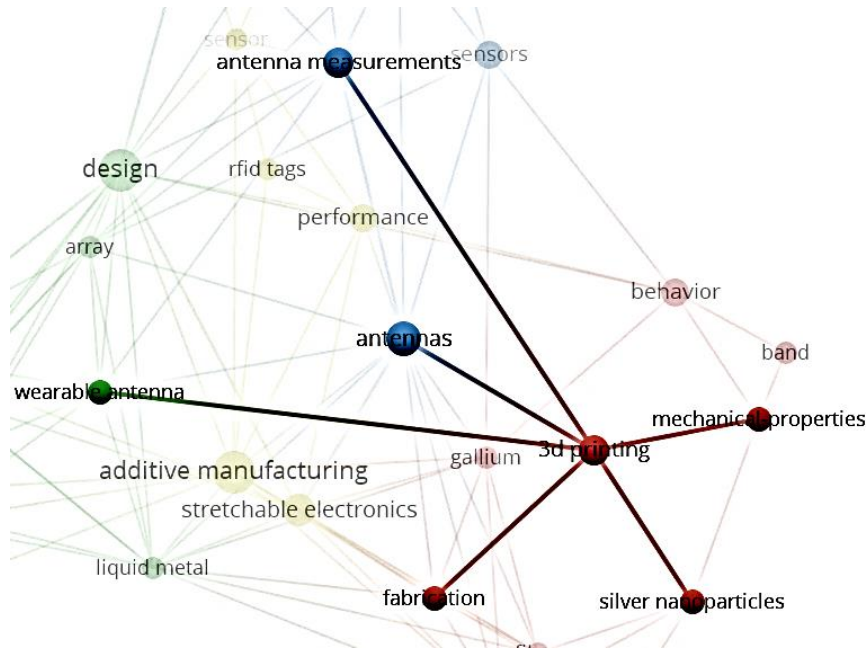


Fig. 11: Connection of keyword “3D printing” with other keywords

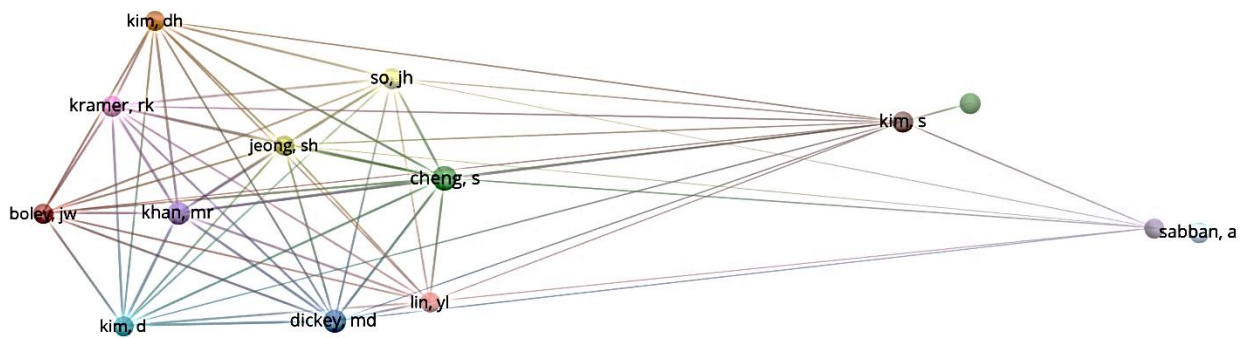


Fig. 12: Authors co-cited at least 6 times

2.1 Research gap based on bibliographic analysis: Recent studies have focused on the 3D-printed wearable passive sensor on fabric for health monitoring, tracking users, muscle movement, etc. Also, some review reports have been published on wearable sensors based on their types, applications, design, fabrication techniques, etc. But hitherto less has been testified on the scope of 3D printing in wearable passive sensors on fabric for WiFi and 5G technology applications. Significant studies have been reported on wearable sensors, however, 3D-printed wearable sensors may be explored for tuneable characteristics. The inkjet printing technique has been widely used for printing conductive ink on a textile substrate for wearable sensors. Also, some authors have used FFF techniques for developing wearable sensors (mostly as standalone devices) but are limited to textile-based sensors. Overall, the bibliometric analyses show growth in 3D-printed wearable sensors.

3. Framework for future applications:

As a framework for future applications, a case study was conducted in which the TPU was printed (using FFF) on woven fabric made up of cotton and lycra. The dielectric constant (ϵ_r) of the combined substrate was calculated using the ring resonator (RR) test [163].

3.1 Case study: The methodology used in this work is shown in Fig. 13 and the route for 3D printing of TPU on fabric using FFF is shown in Fig. 14.

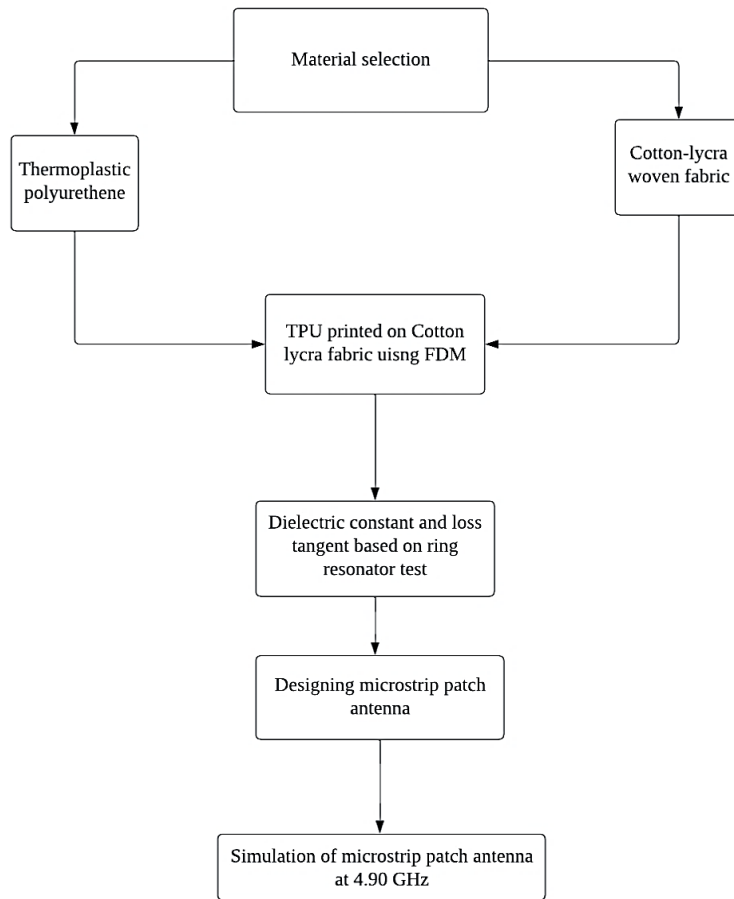


Fig. 13: Methodology used in this study

The recycled TPU granules were procured from the local market and their melt flow index (MFI) was tested as 29.758 g/10min (as per ASTM D 1238) (Fig. 14 a, b). Then filament ($\phi 1.75 \pm 0.05$ mm) of TPU was extruded using a single screw extruder (at 170°C temperature and 7 rpm) (Fig. 14 c). The extruded filament was used to print functional prototypes (Fig. 14d) on FFF setup as per Table 7 and Table 8 (based on Taguchi L_9 orthogonal array [10]). Further, based on observed mechanical properties (Fig. 14 d, e), optimized printing settings of the TPU on the fabric were ascertained using multifactor optimization (Fig. 14f).

Table 7: Selected parameters of FFF [10]

Level	Inputs for FFF		
	A Nozzle temperature (°C)	B Printing speed (mm/s)	C Infill density (%)
1	215	15	100
2	220	18	80
3	225	21	60

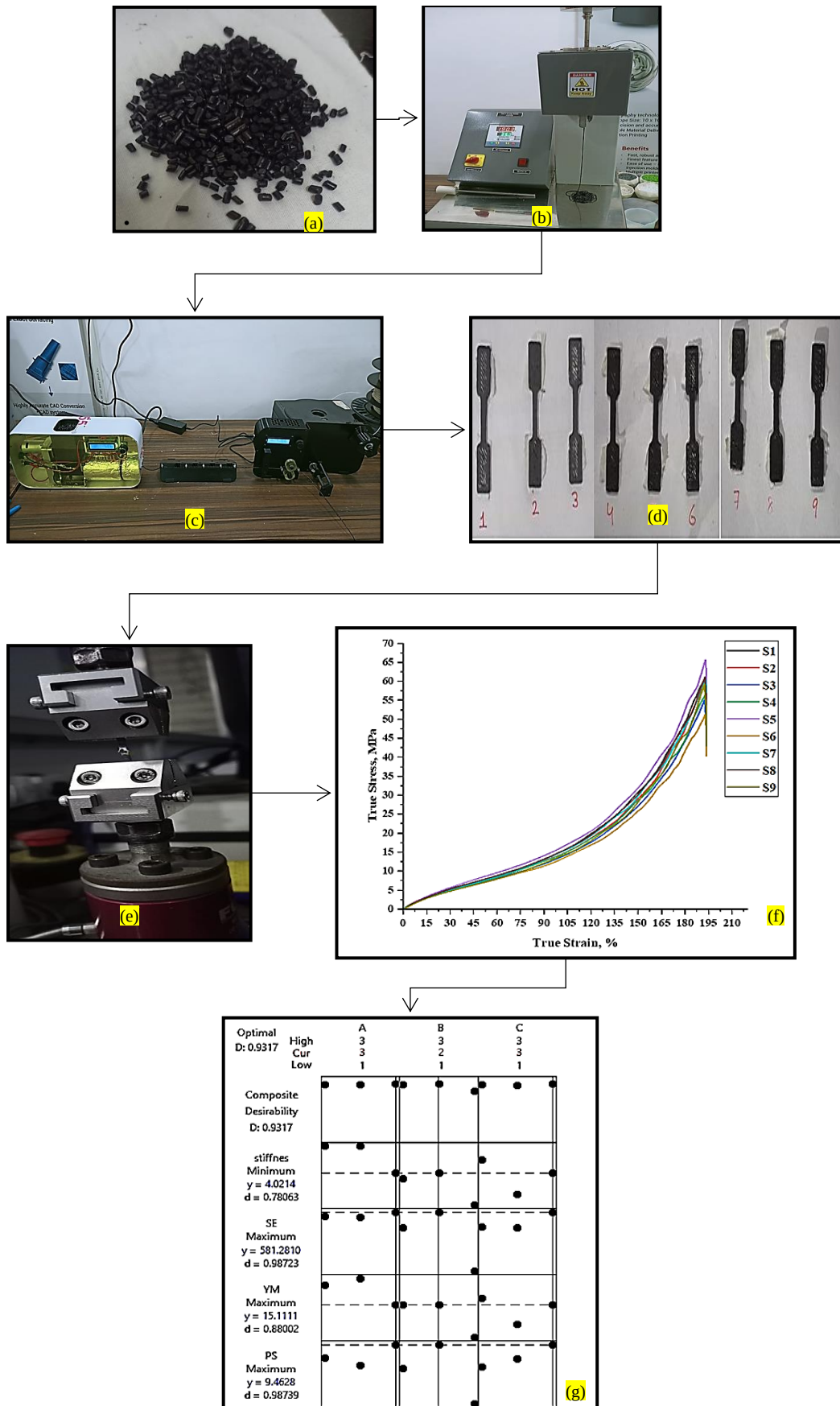


Fig. 14: Route for 3D printing of TPU on fabric using FFF

Table 8: Control-log for FFF [10] (Average of 3 repetitions)

S. No.	Input parameters			Output parameters			
	A	B	C	Peak strength (PS) (MPa)	Stiffness (N/mm)	Strain energy (SE) (N.mm)	Young's modulus (E) (MPa)
S1	215	15	100	8.89	4.62	561.13	17
S2	215	18	80	8.73	4.09	546.46	15
S3	215	21	60	8.05	3.82	500.17	14
S4	220	15	80	8.27	3.89	531.24	15
S5	220	18	60	9.54	4.51	595.32	17
S6	220	21	100	7.46	4.12	478.89	15
S7	225	15	60	8.79	3.94	551.99	15
S8	225	18	100	8.89	4.05	555.76	15
S9	225	21	80	8.66	3.50	515.13	13

Further for multifactor optimization, stiffness, SE, E, and PS (observed in Table 8) were analyzed by assigning the importance and weightage as shown in Table 9, and composite desirability was deduced.

Table 9: Output optimization: Stiffness, SE, E, and PS (based upon Table 8)

Output	Goal	Wt.%	Importance
Stiffness	Minimum	0.4	1
SE	Maximum	0.1	4
E	Maximum	0.2	3
PS	Maximum	0.3	2
Solution			Composite Desirability
A	B	C	0.931657
3	2	3	

Further, the porosity analyses of the lowest, highest, and optimized mechanical properties (peak strength (PS) and strain energy (SE)) were performed using scanning electron microscopy (SEM) images ($\times 100$ magnification) (Fig. 15a). After this, the TPU was printed on stretched and unstretched fabric to ascertain printing on fabric (Fig. 15b). Thermal analysis was also performed by using a differential scanning calorimeter (DSC) (Fig. 15c), which justifies the controlled thermal properties in repeated cycles.

Then, TPU (52 $\times$ 58 $\times$ 0.65 mm) was printed on fabric (thickness 0.20 mm) using FFF at optimized settings (nozzle temp. 220 °C, bed temperature 60 °C, printing speed 25mm/s) as shown in Fig. 16. After that, the RR was designed and fabricated (Fig. 17 (a)) for dielectric constant and loss tangent calculations were made as 1.74 and 0.0047 respectively. Further, MPA has been designed [164] for an R_f of 4.90 GHz (length of patch, L_p = 42mm and width of a patch, W_p = 53mm) as shown in Fig. 17 (b). After this, the simulation was performed using the HFSS software.

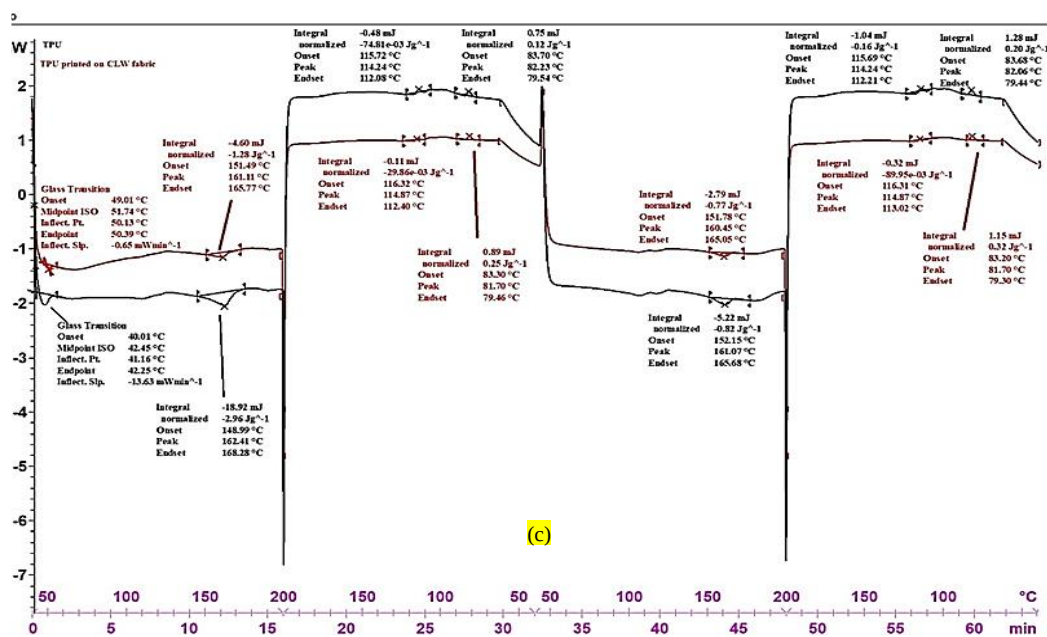
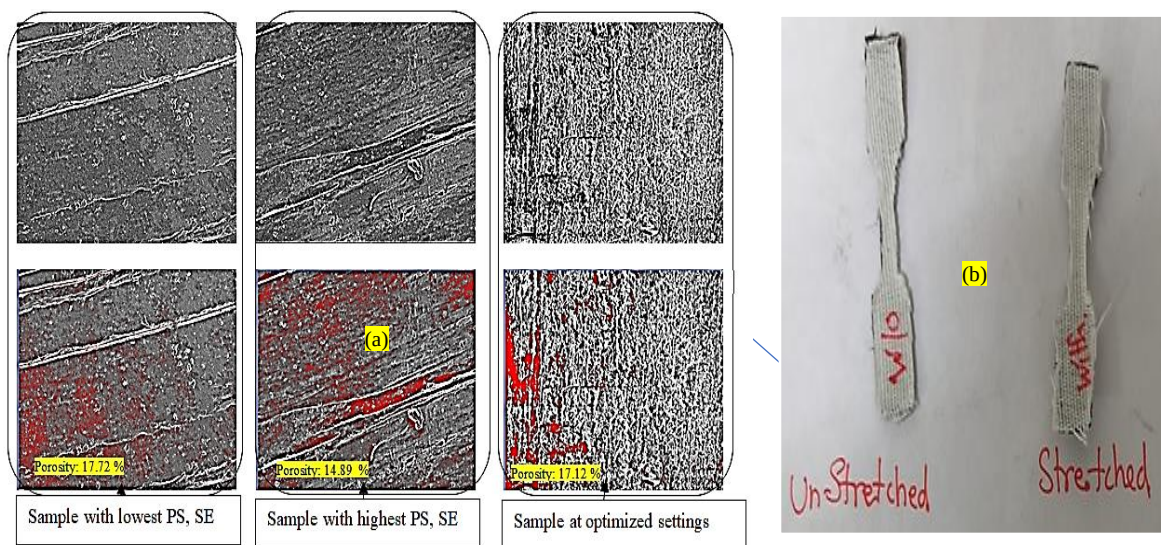


Fig. 15 Morphological and thermal analysis

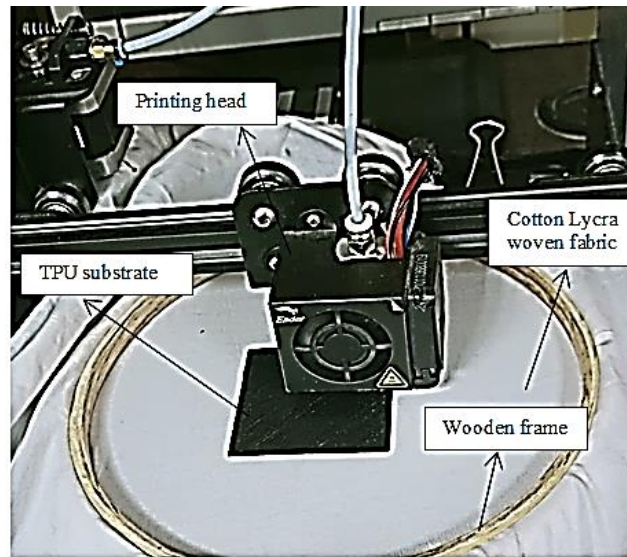
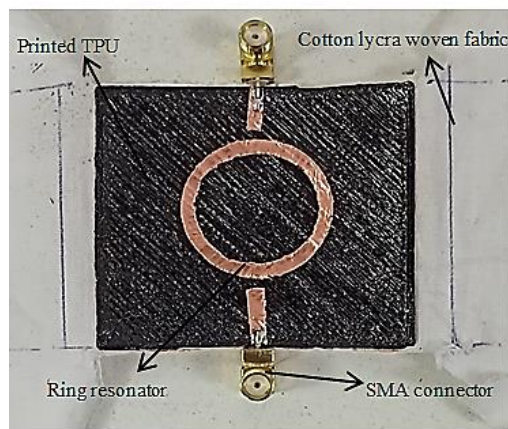
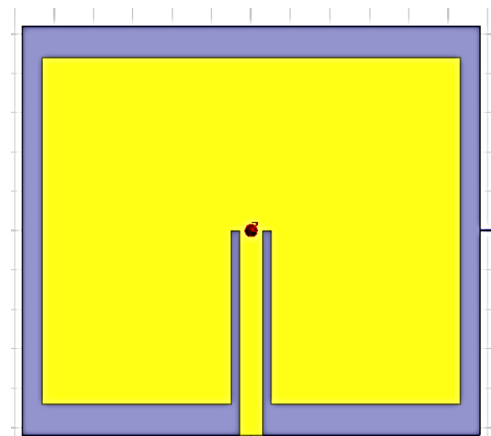


Fig. 16: 3D printing of TPU on Cotton-lycra fabric

The designed sensors resonated at 4.90 GHz as shown in Fig. 17(c). The SAR value of the sensor was also simulated which shows 16.4 W/kg as shown in Fig. 17(d). This relatively higher SAR value needs to be controlled for wearable applications by using a defected ground surface concept or by playing with patch dimensions/shapes as per the concept of low electric field intensity.



(a)



(b)

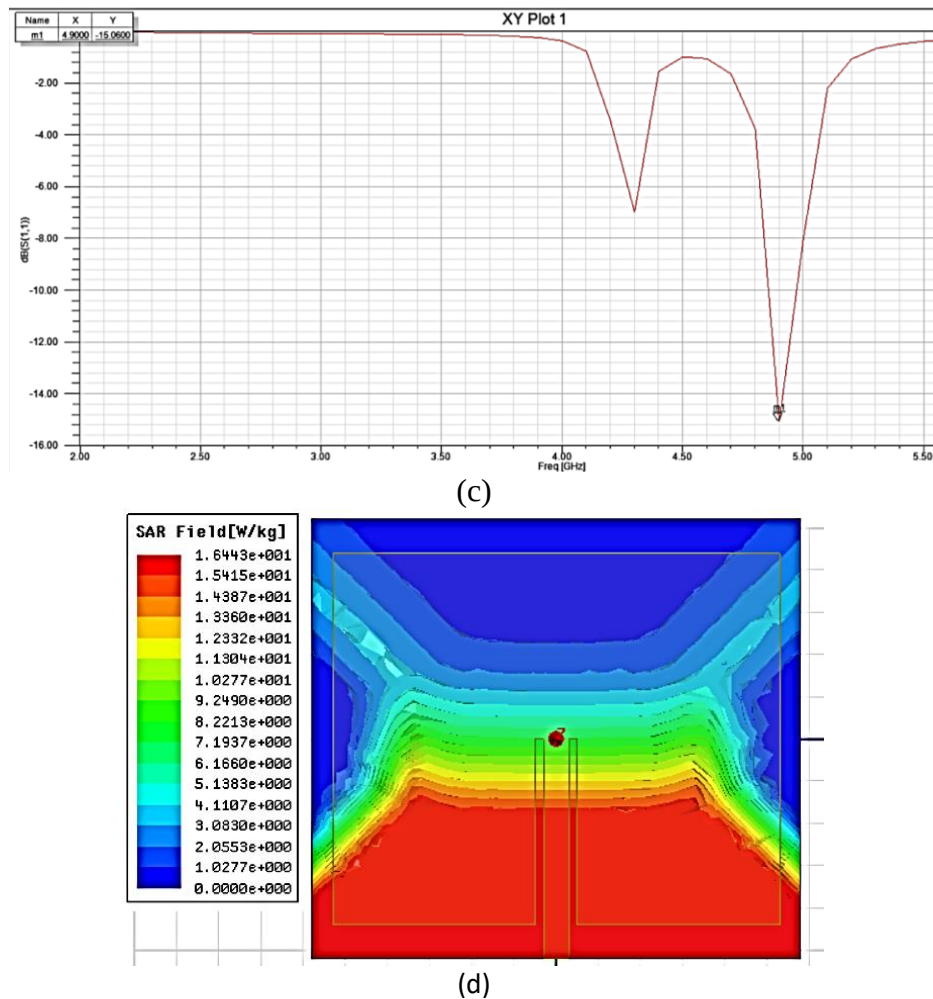


Fig. 17: RR (a), designed patch sensors (b), simulated results (c), calculated SAR value (d)

Conclusions: -

- Significant studies have been reported on wearable sensors, however, 3D-printed wearable sensors may be explored for tunable characteristics.
- The inkjet printing technique has been widely used for printing conductive ink on a textile substrate for wearable sensors. Also, some authors have used FFF techniques for developing wearable sensors (mostly as standalone devices) but are limited to textile-based sensors.
- Bibliometric analyses show growth in 3D-printed wearable sensors. In the reported case study, TPU was successfully printed on WCLF using FFF. The TPU printed on WCLF was used as a substrate for wearable MPA which may be used in WiFi or 5G technology.
- In further studies, the use of FFF in textile-based wearable sensors may be explored. Also, wearable sensors based on a composite of textile and thermoplastic may be explored. SAR values may be improved by providing different patch designs and by providing the cut on the patch. Finally, on-body measurements may also be explored in further studies. Also, the combination of different polymers and textiles may be used for substrates of wearable patch sensors.

Acknowledgment: The authors acknowledge the research support provided by the National Institute of Technical Teachers Training and Research Chandigarh.

Funding: The authors are thankful to the Department of Science and Technology for funding under FIST Level-0, Project No. SR/FST/College-/2020/997

Conflicts of interests/Competing interests: The authors do not have any conflict of interests/competing interests.

References

- [1] Lee H, Tak J, Choi J. Wearable antenna integrated into military berets for indoor/outdoor positioning system. *IEEE Sensors and Wireless Propagation Letters*. 2017; 16:1919-22.
- [2] El Gharbi M, Fernández-García R, Ahyoud S, et.al. A review of flexible wearable antenna sensors: design, fabrication methods, and applications. *Materials*. 2020; 13(17):3781.
- [3] Denoth A. The monopole-sensors: A practical snow and soil wetness sensor. *IEEE transactions on geoscience and remote sensing*. 1997; 5:1371-5.
- [4] Chang K, Kim YH, Kim YJ, et.al.. Patch antenna using synthesized polyimide for RFID sensing. In 2006 European Conference on Wireless Technology 2006; 83-86.
- [5] Islam MT, Ashraf FB, Alam T, et.al. A compact ultrawideband antenna based on hexagonal split-ring resonator for pH sensor application. *Sensors*. 2018; 18(9):2959.
- [6] You KY, Salleh J, Abbas Z, et.al. A rectangular patch antenna technique for the determination of moisture content in soil. *Progress in Electromagnetics Research C*. 2010; 850-4.
- [7] Wiwatwithaya S, Phasukkit P, Tungjitkusolmun S, et.al. Real-time monitoring glucose by used microwave sensors apply to biosensor. The 4th 2011 Biomedical Engineering International Conference 2012 (pp. 135-137). IEEE.
- [8] Vooris R, Blaszk M, Purrington S. Understanding the wearable fitness tracker revolution. *International Journal of the Sociology of Leisure*. 2019; (4):421-37.
- [9] Paracha KN, Rahim SK, Soh PJ, et.al. Wearable antenna: a review of materials, structures, and innovative features for autonomous communication and sensing. *IEEE Access*. 2019; 7:56694-712.
- [10] Kumar S, Singh R, Singh AP, et.al. Three-dimensional printed thermoplastic polyurethane on fabric as wearable smart sensors. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. 2023 Jan 11:14644207221149693.
- [11] Liu Y, Wang H, Zhao W, et.al. Flexible, stretchable sensors for wearable health monitoring: sensing mechanisms, materials, fabrication strategies, and features. *Sensors*. 2018; 18(2):645.
- [12] Azeez HI, Yang HC, Chen WS. Wearable triband E-shaped dipole sensors with low SAR for IoT applications. *Electronics*. 2019; 8(6):665.
- [13] Corchia L, Monti G, Tarricone L. Wearable antenna: Nontextile versus fully textile solutions. *IEEE Antenna and Propagation Magazine*. 2019; 61(2):71-83.
- [14] Mehmman A. Textile Antenna. In *Smart Textiles* Springer, Cham. 2017 (pp. 139-159).
- [15] Khaleel H, editor. *Innovation in wearable and flexible antenna*. Wit Press; 2014.
- [16] Moro R, Agneessens S, Rogier H, et.al. Textile microwave components in substrate integrated waveguide technology. *IEEE Transactions on Microwave Theory and Techniques*. 2015; 63(2):422-32.
- [17] Koo YS, Kazemi R, Liu Q, et.al. Development of a high SAR conformal sensors for hyperthermia tumors treatment. *IEEE Transactions on Antenna and Propagation*. 2014; 62(11):5830-40.
- [18] Costanzo A, Masotti D, Aldrigo M. Compact, wearable antenna for battery-less systems exploiting fabrics and magneto-dielectric materials. *Electronics*. 2014 ;3(3):474-90.
- [19] Yang HL, Yao W, Yi Y, et.al. A dual-band low-profile metasurface-enabled wearable sensors for WLAN devices. *Progress In Electromagnetics Research C*. 2016;61:115-25.
- [20] Lin Y, Xianbao Z, Xi L. New design of multilayer wideband GNSS sensors with dual layer strip lines fed. In 2016 International Symposium on Antenna and Propagation (ISAP) 2016 (pp. 806-807). IEEE.
- [21] Lilja J, Salonen P, Kaija T, et.al. Design and manufacturing of robust textile antenna for harsh environments. *IEEE Transactions on Antenna and Propagation*. 2012 ;60(9):4130-40.

- [22] Hatamie A, Angizi S, Kumar S, et.al. Textile-based chemical and physical sensors for healthcare monitoring. *Journal of the Electrochemical Society*. 2020 Jan 21;167(3):037546.
- [23] Marasco I, Niro G, Lamanna L, et.al. Compact and flexible meander sensors for surface acoustic wave sensors. *Microelectronic Engineering*. 2020;227:111322.
- [24] Wagih M, Wei Y, Komolafe A, et.al. Reliable UHF long-range textile-integrated RFID tag based on a compact flexible sensors filament. *Sensors*. 2020;20(12):3435.
- [25] Ossa OD, Lopez FE. Rectangular patch sensors strain sensor with plastic substrate for curvature measurements. *IEEE Latin America Transactions*. 2018 ;16(5):1358-63.
- [26] Kim C, Kim JK, Kim KT, et.al. Micromachined wearable/foldable super wideband (SWA) monopole sensors based on a flexible liquid crystal polymer (LCP) substrate toward imaging/sensing/health monitoring systems. In 2013 IEEE 63rd Electronic Components and Technology Conference 2013 (pp. 1926-1932). IEEE.
- [27] Lin CP, Chang CH, Cheng YT, et.al. Development of a flexible SU-8/PDMS-based sensors. *IEEE Antenna and wireless propagation letters*. 2011;10:1108-11.
- [28] Sanz-Izquierdo B, Batchelor JC. WLAN jacket-mounted sensors. In 2007 International Workshop on Sensors Technology: Small and Smart Antenna Metamaterials and Applications 2007 (pp. 57-60). IEEE.
- [29] Mantash M, Tarot AC, Collardey S, et.al. Zip-based monopole sensors for wearable communication systems. In 2012 6th European Conference on Antenna and Propagation (EUCAP) 2012 (pp. 762-764). IEEE.
- [30] Bahr R, Le T, Tentzeris MM, et.al. RF characterization of 3D printed flexible materials-NinjaFlex Filaments. In 2015 European Microwave Conference (EuMC) 2015 (pp. 742-745). IEEE.
- [31] Moscato S, Bahr R, Le T, et.al. Infill-dependent 3-D-printed material based on NinjaFlex filament for sensors applications. *IEEE Antenna and Wireless Propagation Letters*. 2016;15:1506-9.
- [32] Yu ST, Liu Y, Jiang W, et.al. A novel compact UWB textile button sensors. *Progress In Electromagnetics Research C*. 2012;32:233-43.
- [33] Salman LK, Talbi L. Dual band G-shape wearable cuff button sensors for ISM bands applications. In 2010 IEEE Antenna and Propagation Society International Symposium 2010 (pp. 1-4). IEEE.
- [34] Aldrigo M, Costanzo A, Masotti D, et.al. Exploitation of a novel magneto-dielectric substrate for miniaturization of wearable UHF antenna. *Materials Letters*. 2012;87:127-30.
- [35] Sanz-Izquierdo B, Huang F, Batchelor. Small size wearable button sensors *Eur. Sp. Agency*, 2006;626:8-11.
- [36] Khaleel HR, Al-Rizzo HM, Rucker DG, et.al. Wearable Yagi microstrip sensors for telemedicine applications. In 2010 IEEE Radio and Wireless Symposium (RWS) 2010(pp. 280-283). IEEE.
- [37] Hong S, Kang SH, Kim Y, et.al. Transparent and flexible sensors for wearable glasses applications. *IEEE Transactions on Antenna and Propagation*. 2016;64(7):2797-804.
- [38] Nguyen SH, Ellis N, Amirtharajah R. Powering smart jewelry using an RF energy harvesting necklace. In 2016 IEEE MTT-S International Microwave Symposium (IMS) 2016(pp. 1-4). IEEE.
- [39] Vorobyov A, Henemann C, Dallemagne P. Liquid metal based sensors for wearable electronic. In 2016 10th European Conference on Antenna and Propagation (EuCAP) 2016(pp. 1-3). IEEE.
- [40] Zhou Y, Bayram Y, Du F, et.al. Polymer-carbon nanotube sheets for conformal load-bearing antenna. *IEEE Transactions on Antenna and Propagation*. 2010;58(7):2169-75.
- [41] Graz IM, Cotton DP, Lacour SP. Extended cyclic uniaxial loading of stretchable gold thin films on elastomeric substrates. *Applied Physics Letters*. 2009;94(7):071902.
- [42] Liu Q, Ford KL, Langley R, et.al. A stretchable PIFA sensors. In 2011 Loughborough Antenna & Propagation Conference 2011(pp. 1-4). IEEE.
- [43] Rakibet OO, Rumens CV, Batchelor JC, et.al. Epidermal passive RFID strain sensor for assisted technologies. *IEEE Antenna and Wireless Propagation Letters*. 2014;13:814-7.
- [44] Amendola S, Milici S, Marrocco G. Performance of epidermal RFID dual-loop tag and on-skin retuning. *IEEE Transactions on Antenna and Propagation*. 2015;63(8):3672-80.

- [45] Lee EC, Soh PJ, Hashim NB, et.al. Design and fabrication of a flexible Minkowski fractal sensors for VHF applications. In Proceedings of the 5th European Conference on Antenna and Propagation (EUCAP) 2011(pp. 521-524). IEEE.
- [46] George G, Nagarjun R, Thiripurasundari D, et.al. Design of meander line wearable sensors. In 2013 IEEE Conference on Information & Communication Technologies 2013 (pp. 1190-1193). IEEE.
- [47] Salonen P, Rahmat-Samii Y. Textile antenna: Effects of sensors bending on input matching and impedance bandwidth. In 2006 First European Conference on Antenna and Propagation 2006 (pp. 1-5). IEEE.
- [48] Catarinucci L, Colella R, Tarricone L. Smart prototyping techniques for UHF RFID tags: electromagnetic characterization and comparison with traditional approaches. Progress in Electromagnetics Research. 2012;132:91-111.
- [49] Wang X, Lu X, Jia Z, et.al. The application of micro-milling technology in the processing of micro-strip sensors. Int. J. Materials and Product Technology. 2015;51(1).
- [50] Chahat N, Zhadobov M, Muhammad SA, et.al. 60-GHz textile sensors array for body-centric communications. IEEE Transactions on Antenna and Propagation. 2012 ;61(4):1816-24.
- [51] Trajkovikj J, Zürcher JF, Skrivervik AK. PDMS, a robust casing for flexible W-BAN antenna [EurAAP Corner]. IEEE Antenna and Propagation Magazine. 2013;55(5):287-97.
- [52] Ouyang Y, Chappell WJ. High-frequency properties of electro-textiles for wearable sensors applications. IEEE Transactions on Antenna and Propagation. 2008;56(2):381-9.
- [53] Kaufmann T, Fumeaux IM, Fumeaux C. Comparison of fabric and embroidered dipole antenna. In 2013 7th European Conference on Antenna and Propagation (EuCAP) 2013(pp. 3252-3255). IEEE.
- [54] B. Ivšić, D. Bonefačić, J. Bartolić, "Performance of embroidered conductive yarn in textile antenna and microstrip lines," *2015 9th Eur. Conf. Antenna Propagation, EuCAP 2015*, 2015.
- [55] Acti T, Zhang S, Chauraya A, et.al. High-performance flexible fabric electronics for megahertz frequency communications. In 2011 Loughborough Antenna & Propagation Conference 2011(pp. 1-4). IEEE.
- [56] Fu YY, Chan YL, Yang MH, et.al. Experimental study on the washing durability of electro-textile UHF RFID tags. IEEE Antenna and Wireless Propagation Letters. 2014;14:466-9.
- [57] Whittow WG, Li Y, Torah R, et.al. Printed frequency selective surfaces on textiles. Electronics Letters. 2014;50(13):916-7.
- [58] Chauraya A, Seager R, Whittow W, et.al. Embroidered Frequency Selective Surfaces on textiles for wearable applications. In 2013 Loughborough Antenna & Propagation Conference (LAPC) 2013(pp. 388-391). IEEE.
- [59] Tahseen MM, Kishk AA. Flexible and portable textile-reflectarray backed by frequency selective surface. IEEE Antenna and Wireless Propagation Letters. 2017;17(1):46-9.
- [60] Ahmad S, Saidin NS, Isa CC. Development of embroidered Sierpinski carpet sensors. In 2012 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE) 2012(pp. 123-127). IEEE.
- [61] Kiourti A, Volakis JL. IEEE Antenna Wirel. Propag. Lett. 2014;13:1381.
- [62] Kiourti A, Volakis JL. Colorful textile antenna integrated into embroidered logos. Journal of Sensor and Actuator Networks. 2015;4(4):371-7.
- [63] Locher I, Klemm M, Kirstein T, et.al. Design and characterization of purely textile patch antenna. IEEE Transactions on Advanced Packaging. 2006;29(4):777-88.
- [64] Yan S, Soh PJ, Vandenbosch GA. Wearable dual-band magneto-electric dipole sensors for WBAN/WLAN applications. IEEE Transactions on Antenna and Propagation. 2015;63(9):4165-9.
- [65] Loss C, Gonçalves R, Lopes C, et.al. Smart coat with fully-embedded textile sensors for IoT applications. Sensors. 2016;16(6):938.
- [66] Tronquo A, Rogier H, Hertleer C, et.al. Applying textile materials for the design of antenna for wireless body area networks. In 2006 First European Conference on Antenna and Propagation 2006(pp. 1-5). IEEE.
- [67] Hertleer C, Tronquo A, Rogier H, et.al. The use of textile materials to design wearable microstrip patch antenna. Textile Research Journal. 2008;78(8):651-8.

- [68] Elliot PG, Rosario EN, Rao BR, et.al. E-textile microstrip patch antenna for GPS. In Proceedings of the 2012 IEEE/ION Position, Location and Navigation Symposium 2012 (pp. 66-73). IEEE.
- [69] Wang S, Chong NL, Virkki J, et.al. Towards washable electro-textile UHF RFID tags: Reliability study of epoxy-coated copper fabric antenna. *International Journal of Antenna and Propagation*. 2015.
- [70] Monti G, Corchia L, Tarricone L. Textile logo antenna. In Proceedings of 2014 Mediterranean Microwave Symposium (MMS2014) 2014(pp. 1-5). IEEE.
- [71] G. Monti, L. Corchia, E. De Benedetto, et.al, "A wearable wireless energy link for thin-film batteries charging," *Int. J. Antenna Propag.*, vol. 2016, 2016, DOI: 10.1155/2016/9365756.
- [72] Monti G, Corchia L, De Benedetto E, et.al. Wearable logo-sensors for GPS–GSM-based tracking systems. *IET Microwaves, Antenna & Propagation*. 2016;10(12):1332-8.
- [73] Corchia L, Monti G, De Benedetto E, et.al. Wearable antenna for remote health care monitoring systems. *International Journal of Antenna and Propagation*. 2017 17;2017.
- [74] Scarpello ML, Kazani I, Hertleer C, et.al. Stability and efficiency of screen-printed wearable and washable antenna. *IEEE antenna and wireless propagation letters*. 2012 ;11:838-41.
- [75] Kellomäki T, Virkki J, Merilampi S, et.al. Towards washable wearable antenna: a comparison of coating materials for screen-printed textile-based UHF RFID tags. *International Journal of Antenna and Propagation*. 2012.
- [76] Pflug HW, Visser HJ, Keyrouz S. Practical applications of radiative wireless power transfer. In 2015 IEEE Wireless Power Transfer Conference (WPTC) 2015(pp. 1-4). IEEE.
- [77] Kazani I, Declercq F, Scarpello ML, et.al. Performance study of screen-printed textile antenna after repeated washing. *Autex Research Journal*. 2014;14(2):47-54.
- [78] Whittow WG, Chauraya A, Vardaxoglou JC, et.al. Inkjet-printed microstrip patch antenna realized on textile for wearable applications. *IEEE Antenna and Wireless Propagation Letters*. 2014;13:71-4.
- [79] Li Y, Torah R, Beeby SP, et.al. Inkjet-printed flexible sensors on textile for wearable applications.
- [80] Kim Y, Kim H, Yoo HJ. Electrical characterization of screen-printed circuits on the fabric. *IEEE transactions on advanced packaging*. 2009;33(1):196-205.
- [81] Björninen T, Virkki J, Sydänheimo L, et.al. Manufacturing of antenna for passive UHF RFID tags by direct write dispensing of copper and silver inks on textiles. In 2015 International Conference on Electromagnetics in Advanced Applications (ICEAA) 2015 (pp. 589-592). IEEE.
- [82] Akbari M, Virkki J, Sydänheimo L, et.al. Toward graphene-based passive UHF RFID textile tags: A reliability study. *IEEE Transactions on Device and Materials Reliability*. 2016 ;16(3):429-31.
- [83] Zhang S, Chauraya A, Whittow W, et.al. Embroidered wearable antenna using conductive threads with different stitch spacings. In 2012 Loughborough Antenna & Propagation Conference (LAPC) 2012(pp. 1-4). IEEE.
- [84] Monti G, Corchia L, Tarricone L. Logo sensors on textile materials. In 2014 44th European Microwave Conference 2014(pp. 516-519). IEEE.
- [85] Huang S, Liu Y, Zhao Y, et.al. Flexible electronics: stretchable electrodes and their future. *Advanced Functional Materials*. 2019;29(6):1805924.
- [86] Yan X, Yu M, Ramakrishna S, et.al. Advances in portable electrospinning devices for in situ delivery of personalized wound care. *Nanoscale*. 2019;11(41):19166-78.
- [87] Rai P, Oh S, Shyamkumar P, et.al. Nano-bio-textile sensors with mobile wireless platform for wearable health monitoring of neurological and cardiovascular disorders. *Journal of The Electrochemical Society*. 2013;161(2):B3116.
- [88] J. Jang, J. I. Han, "High-Performance Cylindrical Capacitor as a Relative Humidity Sensor for Wearable Computing Devices," *J. Electrochem. Soc.*, vol. 164, no. 4, pp. B136–B141, 2017, DOI: 10.1149/2.1121704jes.
- [89] Song Y, Min J, Gao W. Wearable and implantable electronics: moving toward precision therapy. *ACS Nano*. 2019;13(11):12280-6.
- [90] Agrawal DR, Tanabe Y, Weng D, et.al. Conformal phased surfaces for wireless powering of bioelectronic microdevices. *Nature biomedical engineering*. 2017;1(3):1-9.

- [91] Chuang MC, Windmiller JR, Santhosh P, et.al. Textile-based electrochemical sensing: effect of fabric substrate and detection of nitroaromatic explosives. *Electroanalysis*. 2010;22(21):2511-8.
- [92] Stoppa M, Chiolerio A. Wearable electronics and smart textiles: A critical review. *sensors*. 2014 ;14(7):11957-92.
- [93] Marculescu D, Marculescu R, Zamora NH, et.al. Electronic textiles: A platform for pervasive computing. *Proceedings of the IEEE*. 2003;91(12):1995-2018.
- [94] Yuan L, Gong X, Liu J, et.al. Colored spun fabric texture representation and application by combining spatial features with frequency features. *Textile Research Journal*. 2021 ;91(7-8):828-38.
- [95] Schneider D, Merhof D. Blind weave detection for woven fabrics. *Pattern Analysis and Applications*. 2015;18(3):725-37.
- [96] Jing J, Xu M, Li P, et.al. Automatic classification of woven fabric structure based on texture feature and PNN. *Fibers and Polymers*. 2014;15(5):1092-8.
- [97] Salem YB, Nasri S. Automatic classification of woven fabrics using multi-class support vector machine. *Research Journal of Textile and Apparel*. 2009.
- [98] Iqbal Hussain MA, Khan B, Wang Z, et.al. Woven fabric pattern recognition and classification based on deep convolutional neural networks. *Electronics*. 2020;9(6):1048.
- [99] Ben Salem Y, Nasri S. Automatic recognition of woven fabrics based on texture and using SVM. *Signal, image, and video processing*. 2010;4(4):429-34.
- [100] Sun X, Zhou M, Sun Y. Classification of textile fabrics by use of spectroscopy-based pattern recognition methods. *Spectroscopy Letters*. 2016;49(2):96-102.
- [101] Ferrándiz M, Fages E, Rojas-Lema S, et.al. Development and characterization of weft-knitted fabrics of naturally occurring polymer fibers for sustainable and functional textiles. *Polymers*. 2021;13(4):665.
- [102] Al Faruque MA, Kiziltas A, Mielewski D, et.al. A facile approach of fabricating electrically conductive knitted fabrics using graphene oxide and textile-based waste material. *Polymers*. 2021 ;13(17):3003.
- [103] Wu J, Wang L, Xiao Z, et.al. Wool knitted fabric pilling objective evaluation based on double-branch convolutional neural network. *The Journal of The Textile Institute*. 2021 ;112(7):1037-45.
- [104] Stankovic SB, Popovic D, Poparic GB, et.al. Ultraviolet protection factor of gray-state plain cotton knitted fabrics. *Textile Research Journal*. 2009;79(11):1034-42.
- [105] Islam SR, Alassod A, Naveed T, et.al. The study of hydrophobicity and oleophilicity of 3D weft-knitted spacer fabrics integrated with silica aerogels. *Journal of Industrial Textiles*. 2022;51(5_suppl):8804S-25S.
- [106] Majumdar A, Mukhopadhyay S, Yadav R. Thermal properties of knitted fabrics made from cotton and regenerated bamboo cellulosic fibres. *International Journal of Thermal Sciences*. 2010 ;49(10):2042-8.
- [107] Salvado R, Loss C, Gonçalves R, et.al. Textile materials for the design of wearable antenna: A survey. *Sensors*. 2012;12(11):15841-57.
- [108] Tsolis A, Whittow WG, Alexandridis AA, et.al. Embroidery and related manufacturing techniques for wearable antenna: challenges and opportunities. *Electronics*. 2014 ;3(2):314-38.
- [109] Mokhena T, Mochane M, Tshwafo M, et.al. Wearable antenna for medical applications. *Intech*. 2016; 225–240.
- [110] Wang JC, Lim EG, Leach M, et.al. Review of wearable antenna for WBAN applications. *IAENG Int. J. Comput. Sci*. 2016;43(4):474-80.
- [111] Mahfuz MH, Islam MR, Park CW, et.al. Wearable Textile Patch Sensors: Challenges and Future Directions. *IEEE Access*. 2022 ;10:38406-27.
- [112] Rao S, Llombart N, Moradi E, et.al. Sensors applications corner: Miniature implantable and wearable on-body antenna: Towards the new era of wireless body-centric systems. *IEEE Antenna and Propagation Magazine*. 2014;1(56):271-91.
- [113] Nepa P, Rogier H. Wearable Antenna for Off-Body Radio Links at VHF and UHF Bands: Challenges, the state of the art, and future trends below 1 GHz. *IEEE Antenna and Propagation Magazine*. 2015;57(5):30-52.

- [114] Aun NF, Soh PJ, Al-Hadi AA, et.al. Revolutionizing wearables for 5G: 5G technologies: Recent developments and future perspectives for wearable devices and antenna. *IEEE Microwave Magazine*. 2017;18(3):108-24.
- [115] Jia W, Zhang Q, Cheng Y, et.al. A Flexible Capacitive Paper-Based Pressure Sensor Fabricated Using 3D Printing. *Chemosensors*. 2022;10(10):432.
- [116] Chohan JS, Singh R, Boparai KS. Mathematical modelling of surface roughness for vapour processing of ABS parts fabricated with fused deposition modelling. *Journal of Manufacturing Processes*. 2016;24:161-9.
- [117] Kumar R, Singh R, Ahuja IP. Mechanical, thermal, and micrographic investigations of friction stir welded: 3D printed melt flow compatible dissimilar thermoplastics. *Journal of Manufacturing Processes*. 2019 Feb 1;38:387-95.
- [118] Singh T, Kumar S, Sehgal S. 3D printing of engineering materials: A state of the art review. *Materials today: proceedings*. 2020; 28:1927-31.
- [119] Kumar R, Singh R, Ahuja IP. Mechanical, thermal, and micrographic investigations of friction stir welded: 3D printed melt flow compatible dissimilar thermoplastics. *Journal of Manufacturing Processes*. 2019; 38:387-95.
- [120] Singh D, Singh R, Boparai KS. Development and surface improvement of FDM pattern based investment casting of biomedical implants: A state of art review. *Journal of Manufacturing Processes*. 2018; 31:80-95.
- [121] Kumar P, Ahuja IS, Singh R. Experimental investigations on hardness of the biomedical implants prepared by hybrid investment casting. *Journal of Manufacturing Processes*. 2016; 21:160-71.
- [122] Karakurt I, Lin L. 3D printing technologies: techniques, materials, and post-processing. *Current Opinion in Chemical Engineering*. 2020; 28:134-43.
- [123] Singh R, Kumar S, Singh AP, et.al. On comparison of recycled LDPE and LDPE–bakelite composite based 3D printed patch sensors. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. 2022;236(4):842-56.
- [124] Akbar I, El Hadrouz M, El Mansori M, et.al. Continuum and subcontinuum simulation of FDM process for 4D printed shape memory polymers. *Journal of Manufacturing Processes*. 2022;76:335-48.
- [125] Rizwan M, Khan MW, Sydänheimo L, et.al. Flexible and stretchable brush-painted wearable sensors on a three-dimensional (3-D) printed substrate. *IEEE Antenna and wireless propagation letters*. 2017;16:3108-12.
- [126] Tomassoni C, Bozzi M. Substrate Integrated Waveguide Cavity Filters: Miniaturization and New Materials for IoT Applications. *Radioengineering*. 2017;26(3).
- [127] MacDonald E, Espalin D, Doyle D, et.al. Fabricating patch antenna within complex dielectric structures through multi-process 3D printing. *Journal of Manufacturing Processes*. 2018 ;34:197-203.
- [128] Kumar R, Singh R, Singh M, et.al. On ZnO nanoparticle reinforced PVDF composite materials for 3D printing of biomedical sensors. *Journal of Manufacturing Processes*. 2020 ;60:268-82.
- [129] Liu C, Huang N, Xu F, et.al. 3D printing technologies for flexible tactile sensors toward wearable electronics and electronic skin. *Polymers*. 2018 ;10(6):629.
- [130] Kalkal A, Kumar S, Kumar P, et.al. Recent advances in 3D printing technologies for wearable (bio) sensors. *Additive Manufacturing*. 2021;46:102088.
- [131] Tekcin M, Paker S, Bahadır SK. UHF-RFID enabled wearable flexible printed sensor with sensors performance. *AEU-International Journal of Electronics and Communications*. 2022 ;157:154410.
- [132] Nate K, Tentzeris MM. A novel 3-D printed loop sensors using flexible NinjaFlex material for wearable and IoT applications. In 2015 IEEE 24th Electrical Performance of Electronic Packaging and Systems (EPEPS) 2015 (pp. 171-174). IEEE.
- [133] Moscato S, Bahr R, Le T, et.al. Infill-dependent 3-D-printed material based on NinjaFlex filament for sensors applications. *IEEE Antenna and Wireless Propagation Letters*. 2016;15:1506-9.
- [134] Yang H, Leow WR, Wang T, et.al. 3D printed photoresponsive devices based on shape memory composites. *Advanced Materials*. 2017 ;29(33):1701627

- [135] Seo M, Hwang S, Hwang T, et.al. Fabrication of soft sensor using laser processing techniques: for the alternative 3D printing process. *Materials*. 2019;12(18):2955.
- [136] Eijking B, Sanders R, Krijnen G. Development of whisker inspired 3D multi-material printed flexible tactile sensors. In 2017 IEEE SENSORS 2017 (pp. 1-3). IEEE.
- [137] Li B, Zhang S, Zhang L, et.al. Strain sensing behavior of FDM 3D printed carbon black filled TPU with periodic configurations and flexible substrates. *Journal of Manufacturing Processes*. 2022;74:283-95.
- [138] Rizwan M, Khan MW, He H, et.al. Flexible and stretchable 3D printed passive UHF RFID tag. *Electronics Letters*. 2017;53(15):1054-6.
- [139] Ramadan M, Dahle R. A flexible 2.4 GHz microstrip patch sensors using a 3-D printed tile array design. In 2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP) 2017 (pp. 1-3). IEEE.
- [140] Tariq F, Amjad Q, Kamran A, et.al. A flexible sensors on cost-effective PEN substrate for sub-6 GHz 5G wireless transceivers. In 2019 International Conference on Frontiers of Information Technology (FIT) 2019 (pp. 89-895). IEEE.
- [141] Li J, Jiang Y, Zhao X. Circularly polarized wearable sensors based on NinjaFlex-embedded conductive fabric. *International Journal of Antenna and Propagation*. 2019.
- [142] Mukai Y, Li S, Suh M. 3D-printed thermoplastic polyurethane for wearable breast hyperthermia. *Fashion and Textiles*. 2021;8(1):1-2.
- [143] Fawaz M, Jun S, Oakey WB, et.al. 3D printed patch Sensors for millimeter wave 5G wearable applications.
- [144] Su Z, Klionovski K, Liao H, et.al. A Fully-Printed 3D Sensors with 92% Quasi-Isotropic and 85% CP Coverage. *IEEE Transactions on Antenna and Propagation*. 2022
- [145] Njogu P, Sanz-Izquierdo B, Jun S, et.al. 3D Printed Millimeter-wave Sensors Integrated into a Ring for 5G Applications. In 2022 Microwave Mediterranean Symposium (MMS) 2022(pp. 1-5). IEEE.
- [146] Rahman T, Renaud L, Heo D, et.al. Aerosol-based direct-write micro-additive fabrication method for sub-mm 3D metal-dielectric structures. *Journal of Micromechanics and Microengineering*. 2015;25(10):107002.
- [147] Chauraya A, Whittow WG, Vardaxoglou JY, et.al. Inkjet printed dipole antenna on textiles for wearable communications. *IET Microwaves, Antenna & Propagation*. 2013;7(9):760-7.
- [148] Ahmed S, Tahir FA, Shamim A, et.al. A compact Kapton-based inkjet-printed multiband sensors for flexible wireless devices. *IEEE Antennas and Wireless Propagation Letters*. 2015;14:1802-5.
- [149] Krykpayev B, Farooqui MF, Bilal RM, et.al. A wearable tracking device inkjet-printed on textile. *Microelectronics Journal*. 2017; 65:40-8.
- [150] He H, Chen X, Ukkonen L, et.al. Textile-integrated three-dimensional printed and embroidered structures for wearable wireless platforms. *Textile Research Journal*. 2019 ;89(4):541-50.
- [151] Amendola S, Palombi A, Marrocco G. Inkjet printing of epidermal RFID antennas by self-sintering conductive ink. *IEEE Transactions on Microwave Theory and Techniques*. 2017 ;66(3):1561-9.
- [152] Su W, Zhu J, Liao H, et.al. Wearable antennas for cross-body communication and human activity recognition. *IEEE Access*. 2020;8:58575-84.
- [153] Marasco I, Niro G, Mastronardi VM, et.al. A compact evolved sensors for 5G communications. *Scientific reports*. 2022;12(1):1-1.
- [154] Stempien Z, Rybicki E, Rybicki T, et.al. Inkjet-printing deposition of silver electro-conductive layers on textile substrates at low sintering temperature by using an aqueous silver ions-containing ink for textronic applications. *Sensors and Actuators B: Chemical*. 2016 ;224:714-25.
- [155] Akbari M, Khan MW, Hasani M, et.al. Fabrication and characterization of graphene sensors for low-cost and environmentally friendly RFID tags. *IEEE Antennas and Wireless Propagation Letters*. 2015;15:1569-72.
- [156] Eutonnat-Diffo PA, Chen Y, Guan J, et.al. Stress, strain and deformation of poly-lactic acid filament deposited onto polyethylene terephthalate woven fabric through 3D printing process. *Scientific reports*. 2019;9(1):1-8.

- [157] Chakraborty S, Biswas MC. 3D printing technology of polymer-fiber composites in textile and fashion industry: A potential roadmap of concept to consumer. *Composite Structures*. 2020;248:112562.
- [158] Sanatgar RH, Campagne C, Nierstrasz V. Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: Effect of FDM printing process parameters. *Applied Surface Science*. 2017; 403:551-63.
- [159] Spahiu T, Al-Arabiyyat M, Martens Y, et.al. Adhesion of 3D printing polymers on textile fabrics for garment production. In *IOP Conference Series: Materials Science and Engineering 2018*(Vol. 459, No. 1, p. 012065). IOP Publishing.
- [160] Melnikova R, Ehrmann A, Finsterbusch K. 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials. In *IOP conference series: materials science and engineering 2014*(Vol. 62, No. 1, p. 012018). IOP publishing.
- [161] Rivera ML, Moukperian M, Ashbrook D, et.al. Stretching the bounds of 3D printing with embedded textiles. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems 2017*(pp. 497-508).
- [162] Buckley J, O'Flynn B, Barton J, et.al. A highly miniaturized wireless inertial sensor using a novel 3D flexible circuit. *Microelectronics international*. 2009.
- [163] Singh R, Singh BP, Singh AP, et.al. Effect of infill density on the performance of recycled PET-based 3D printed microstrip sensors. *National Academy Science Letters*. 2022; 1-5.
- [164] Kumar S, Singh R, Singh AP, et.al. Case Study for the Development of a Hybrid Composite Structure of Thermosetting and Thermoplastics. In *Additive Manufacturing for Plastic Recycling 2022* (pp. 141-157). CRC Press.
- [165] Singh R, Singh G, Anand, A. On 3D printed intelligent diaphragmatic hernia sensor. *Rapid Prototyping Journal*. 2023; <https://doi.org/10.1108/RPJ-05-2023-0179>.
- [166] Yun Shao, Kaiyi Dong, Xinyu Lu, Bingbing Gao, Bingfang He. Bioinspired 3D-Printed MXene and Spidroin-Based Near-Infrared Light-Responsive Microneedle Scaffolds for Efficient Wound Management. *ACS Applied Materials & Interfaces* 2022 14 (51), 56525-56534.