

Architecture of E-Textiles

Subjects: [Materials Science](#), [Textiles](#)

Contributor: Mohammad Shak Sadi , Eglé Kumpikaitė

E-textiles are the traditional textiles of different hierarchies embedded with multifunctional nanomaterials to be utilized in different areas, for instance, human motion monitoring, i.e., joints bending, walking, running, facial expression, vocal vibration, pulse, breathing, laughing, etc., healthcare applications, i.e., EMG, ECG, EEG, sleep monitoring, drug delivery, cell culture, etc., thermal heating, electromagnetic shielding, antimicrobial protection, self-cleaning, energy storage/harvesting, fire alarm, electronic display, color-changing, etc. with a wide spectrum of functions by mitigating the wear complexities associated with non-flexible and bulky wearable electronics.

e-textiles

architecture

stability

washability

1. Fiber Shaped Durable E-Textiles

Fiber is the first phase of the textile hierarchy which serves as the basic construction block of e-textiles, conductivity at the fiber level facilitates seamless integration of electronic function for the next generation of miniature devices. Nanomaterials with fiber components are expected to exhibit strong adhesion at the molecular level with improved electrical properties, mechanical properties (strength, flexibility, stretchability), durability (stability, washability), comfort, etc. Fiber materials can be made of natural (cellulose, protein) or synthetic resources. Synthetic fibers (the filament, i.e., continuous fibrous strand or nanofiber) are manufactured from polymer solution following different electrospinning processes. Traditional cellulosic textile fiber can be functionalized in the typical yarn manufacturing phase (sliver/roving) and subsequently spun into yarn.

Yang et al. demonstrated that the incorporation of nanomaterials at the roving level gives the ring-spun yarn improved stability and washability compared to the cotton yarn coated with carbon nanotube (CNT) via the dip-coating technique. The roving modified ring-spun yarn can withstand repeated bending (180°) of 100 cycles with nominal resistance change ($<10\%$), optimum stability for abrasion (up to 400 cycles), and displayed washability with minimal changes ($R/R_0 < 1.3$) in resistance for 8 consecutive wash cycles while the CNT-coated cotton yarn was vulnerable and could barely satisfy such circumstances [\[1\]](#). Alternatively, Jia et al. constructed a conductive core yarn wrapped with cotton fiber (roving) where a CNT yarn was introduced prior to the twisting zone. The multifunctional cotton fiber-wrapped CNT yarn retained its electrical properties without change in subsequent folding-releasing (~ 100 cycles) and washing (~ 5 cycles) [\[2\]](#).

The functional protein fibers (i.e., silk) are mostly produced by electrospinning (dry/wet/bio-mimetic) processes, which are accused of damaging the micro and nanostructures of the fiber. Thus, directly modified silkworm spinning is admired for keeping the inherent properties of the fiber intact. Wang et al. developed a functional native

silk fiber via the continuous force-reeling and dip-coating technique (with CNT, Ag, and thermochromic paint) directly from *Antheraea pernyi* (*A. pernyi*) silkworms (known as Chinese Oak Tussah silkworms and having a similar primary structure to spider silk [3]). The functional fiber was highly stable and could withstand 48 h of washing without affecting the surface morphology [4]. Natural fiber in the form of liquid suspension is often prepared and utilized for improved electrochemical performance. Zhang et al. developed a thermally reduced graphene oxide (GO) cellulose composite paper-based pressure sensor (TRG-PS) from cotton pulp dispersion which displayed great cyclic stability (~8% changes in resistance for 300 bending-releasing) and washability up to 20 washing cycles with minimal resistance changes [5].

Fibrous materials are highly flexible to retain any shape as desired at the pre-stage of e-textiles development. Distinctive fiber architecture often offers better performance than regular configuration. A recent study reported a 3D helical fiber-shaped sensor with improved sensing performance (<1% detection limit), superior stability (no obvious change in >20,000 stretching cycles), and washability (no decay of electrical output in ten washing cycles) than regular fiber-shaped triboelectric nanogenerators (TENG). The helical fiber was obtained from the multiaxial winding of two core-shell braided fibers (Ag core in both fibers, whereas the shells were polytetrafluoroethylene-PTFE and nylon, respectively) followed by alternative winding on a stretchable fiber substrate [6]. The Helical fiber produced in a different but facile way, that is, pre-stretched (100–400%) polyurethane (PU) fiber with adhered copper fiber wrapped with glue, also showed satisfactory durability (stable against 500 stretching cycles and 100 min ultrasonic washing [7].

Fibers of all categories in the form of aqueous suspension synchronized with nanomaterials are of great interest and are produced through electrospinning, printing, and other solution-based methods for the development of e-textiles with long-lasting stability and durability. Liao et al. developed large-scale continuous fiber (~1500 km) lithium-ion batteries using the solution-extrusion method that displayed excellent stability (withstands up to 10,000 bending cycles with negligible decay) and durability (<10% loss of capacity) against different hostile events, i.e., water immersion, heavy pressure, washing, and hammer strike [8]. Conductive fiber materials are the fundamental building block of wearable e-textiles but are usually converted into the shape of yarn (continuous length) to enhance cohesion between them and make them suitable for subsequent transformation as required.

2. Yarn Shaped Durable E-Textiles

In general, yarn is a continuous assembly of fibers or filaments twisted/bonded together for improved mechanical properties, i.e., strength, flexibility, etc. Electronically active yarn can be constructed in different ways, i.e., by converting conductive fibers/filaments into yarn, imparting functionality at the yarn stage, and synthetic spinning of polymeric solution with conductive filler. The conductive yarn plays an important role in the architecture of the wearable system by interconnecting different units within the system and facilitates the fabrication of mass-scale electronic devices in the form of fabric or garments. The conductive yarn must be robust enough to withstand different physical, chemical, mechanical, and other hostile stimuli involved in daily use. The combination of nanomaterials at the yarn level expedites functionality-induced performance enhancement because of the increased contact surface area.

Gunawardhana et al. developed wearable triboelectric nanogenerators (TENGs) made of textiles (fabric made of Ag-coated nylon yarn) with differently coated triboelectric material (Polydimethylsiloxane-PDMS). It was observed that yarn-coated TENG outperforms other TENGs (i.e., screen printed and dip-coated fabric made of the same conductive yarn) in output due to higher triboelectric contact surface area. The electrical output of the yarn-coated TENG (i.e., open circuit voltage (V_{OC}) \sim 34.5 V, short circuit current (I_{SC}) \sim 60 nA, short circuit charge (Q_{SC}) \sim 12 nC) was superior to that of other TENGs (screen printed; V_{OC} \sim 17.3 V, I_{SC} \sim 43 nA, Q_{SC} \sim 5 nC and dip-coated; V_{OC} \sim 4.9 V, I_{SC} \sim 11 nA, Q_{SC} \sim 2 nC) and showed better cyclic stability up to 3000 contact separation cycles [9]. Xiao et al. developed cotton yarn-based sweat-activated batteries (CYSAB) by drop coating black carbon (cathode, 4 cm), a bare portion (salt bridge, 0.5 cm), and subsequently wrapped with Zn foil (anode, 1.0 cm) of the same pristine cotton yarn. The device could withstand 2000 bending cycles and 16 washing cycles of 10 min each without a significant change in voltage output of the battery activated with 100 mL of salt solution (NaCl). The higher durability of the device was further verified by the unaffected surface morphology of the cathode portion against washing [10]. Electroactive regenerated cellulose yarn produced via roll-to-roll coating with poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT: PSS)/Ethylene glycol (EG) showed high conductivity (36 Scm^{-1}) and durability. A thermoelectric energy harvester was designed by sewing the electronic yarn into a multilayered fabric. No resistance changes were observed for the device after repeated bending (1000 cycles) and machine washing (insignificant changes in the first five cycles, while further washing (<10) leads to notable changes) [11].

The core-sheath yarn structure holds great promise toward durability by combining nanoparticles in the core securely and preventing it from decay. Zeng et al. developed a highly durable wearable strain sensor based on a spandex dip-coated CNT core and cotton fiber sheath yarn. The sensor showed promising stability under 20% cyclic stress and ultrasonic washability ($<5\%$ deviation in resistance, five cycles) against water, acid, and alkali solution [12]. The self-powered sensor made of commercially available nylon/spandex yarn dip-coated with multi-walled carbon nanotubes (MWCNT) followed by spray coating with silver nanoflakes (AgNFs) and covered with silicone rubber showed good durability ($\sim 10,000$ cycles of repeated operations) and washability (no significant decrease in performance against five repeated washing cycles) [13]. Zhou et al. demonstrated a polyester yarn twisted around a steel rod (10 μm dia.) covered with ultrathin silicon and weaved into a back textile substrate with the serpentine structure for sleep monitoring. The substrate was consistent under the repetitive pressure test up to 20,000 cycles and with insignificant variation in the electrical output after 8 weeks (20 min per week) of repetitive washing [14]. In the case of core-sheath yarn, where the conductive fiber is wrapped around a textile core, the twist count (number of twists per inch/cm) also plays an important role in enhancing conductivity and robustness. Higher twist counts (over twisting) tend to exert more stability in larger deformation and repeated washing actions [15].

Pre-stretching of the yarn (in case of stretchable substrate) prior to nanomaterial incorporation leads to the formation of a wrinkled surface, which allows the electroconductive properties to be more stable against mechanical deformation by a gradual release of the surface wrinkles upon stretching. Zhang et al. developed an underwater wireless charging patch made of pre-stretched polyurethane filament spray-coated with multi-walled carbon nanotubes (MWCNT), silver nanowire (AgNW), and styrene-(ethylene-butylene)-styrene (SEB),

respectively. The device could withstand more than 100,000 stretching cycles under 50% strain and displayed good washability (up to ten cycles without significant resistance change) [16].

Electrospinning is widely being used for yarn-based washable e-textile development, which enables nanomaterial integration at the molecular level in the form of polymeric suspension (which contains both substrate and nanoparticles) spun into a continuous filament directly or the spinning of functional nanofiber around a conductive filament. A unique triboelectric yarn was manufactured via electrospinning of Poly(vinylidene fluoride) (PVDF) nanofiber around a CNT filament. The device showed phenomenal stability (~200,000 fatigue cycles) without a decrease in RMS (root mean square) power output; instead, a 33% increase in energy harvesting capability was observed with a peak power density of $20.7 \mu\text{W cm}^{-2}$. Furthermore, the yarn could withstand ten repeated washing cycles without a significant change in RMS power output. The slight resistance change observed in between five and ten washing cycles may be due to the small amount of water residue inside or slight damage due to washing. However, the morphological analysis of the yarn after repeated tapping and washing showed no significant damage, apart from slight tearing of the PVDF fiber surface while the core was completely intact [17]. Medeiros et al. developed omniphobic silk-based coils (OSCs) made of electrospun yarn composed of silk fibroin, multi-walled carbon nanotubes (MWCNTs), and chitin carbon (ChCs) to power the wearable electronics remotely via magnetic resonance coupling. The device possessed great stability upon the repeated strain of 100% for 2500 cycles without a significant drop in performance. Furthermore, no performance degradation was observed even after 50 washing cycles [18].

Different yarn-shaped e-textiles and their endurance properties are presented in **Table 1**.

Table 1. Summary of different yarn-shaped durable wearable electronic textiles.

Substrate	Nano Materials	Fabrication	Initial Output	Durability		Application	Ref.
				Stability	Washability		
Pu/PAN core-sheath yarn	GO/CNT ink	Dip Coating	Conductivity, 14.8 S m^{-1}	~100,000 operation cycles, 99.3% capacitance retention	5 cycles, no significant deterioration of capacitance	Pressure sensor, motion sensing	[15]
Cotton/Lycra yarn	CNT	Dip coating	Resistance, $2.39 \text{ k}\Omega \text{ cm}^{-1}$	~Cyclic stretching-releasing for 2000 s, high stability	10 cycles, slight increase of resistance ($\Delta R/R_0 \sim 1.6$)	Strain sensing, thermal heating	[19]
Pu/PET braided yarn	CNT	Dip Coating	Conductivity, $0.12 \text{ k}\Omega \text{ cm}^{-1}$	~1000 stretch-release cycles, no obvious	5 cycles, slight increase ($\Delta R/R_0 \sim$	Wearable strain sensor	[20]

Substrate	Nano Materials	Fabrication	Initial Output	Durability		Application	Ref.
				Stability	Washability		
				change in resistance	10%) of resistance		
PET yarn	Cu	Electroless deposition	Resistance, $0.34 \Omega \text{ cm}^{-1}$	~1000 tapping cycles, no change of voltage output	20 cycles, negligible change ($<0.6 \Omega \text{ cm}^{-1}$) of yarn resistance	Respiratory Monitoring	[21]
SS/terylene yarn	SS filament	Spinning	Output voltage, 28 V	~100,000 loading-unloading cycles, excellent stability	40 cycles, no change of output voltage	Physiological signal monitoring	[22]
Nylon yarn	Silver	Nano coating	Resistance, $53 \Omega \text{ m}^{-1}$	-	50 cycles, notable resistance change (108%)	Biomedical textile computing	[23]
Lyocell yarn	PPy	Polymerization	Conductivity, $21.6 \Omega \text{ Sq}^{-1}$	~2000 cyclic operations, 90% capacitance retention	20 cycles, minor variations in electrical response	Wearable electronics	[24]
Cotton yarn	RGO	Dip Coating	Conductance ($2.60 \pm 0.1 \mu\text{S}$)	~1000 bending cycles, slight variation (2.42%) in conductance	5 cycles, minimal (2.96% variation) conductance change	Gas sensing	[25]
CNT yarn	CNT, PEI, FeCl_3	CVD, Doping	Conductivity, 3695 S cm^{-1}	~5000 bending cycles, retained 90% PCE	10 cycles, slight change of PCE	Solar cell	[26]
Silk yarn	PEDOT:PSS, EG	Roll to roll dyeing	Conductivity, 70 S cm^{-1}	~1000 bending cycles, stable resistance profile	15 cycles, slight change after 1st wash than resistance	Wearable keyboard	[27]

Substrate	Nano Materials	Fabrication	Initial Output	Durability		Application	Ref.
				Stability	Washability		
Cotton yarn	RGO	Dip Coating	Resistance, 42.7 kΩ cm ⁻¹	kept constant	~1000 bending and compression cycles, stable resistance variance	Temperature sensor	[28]
				10 cycles, resistance increased initially then kept constant			
Silver-plated nylon yarn	CNTs, TPU	Electrospinning	Sensitivity, 84.5 N ⁻¹	~5000 pressure (5 N) cycles, stable current signal obtained	2.5 h of washing, constant order of magnitude (only 1.4% variation)	Pressure sensor	[29]

Functionalization of Natural Silks through Continuous Force-Reeling Technique. *Chem. Eng. J.* 2022, 435, 134901.

Abbreviation: PU—Polyurethane, PAN—Polyacrylonitrile, GO—Graphene oxide, RGO—Reduced graphene oxide, CNT—Carbon nanotube, PET—Polyethylene terephthalate, SS—Stainless steel, PPy—Polypyrrole, PEI—Polyethyleneimine, CVD—Chemical vapor deposition, PCE—Power conversion efficiency, PEDOT: PSS—Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, EG—Ethylene glycol, TPU—Thermoplastic polyurethane.

6. Ning, C.; Cheng, R.; Jiang, Y.; Sheng, F.; Yi, J.; Shen, S.; Zhang, Y.; Peng, X.; Dong, K.; Wang, Z.L. Helical Fiber Strain Sensors Based on Triboelectric Nanogenerators for Self-Powered Human Respiratory Monitoring. *ACS Nano* 2022, 16, 2811–2821.

3. Fabric Shaped Durable E-Textiles

Yang, Z.; Zhai, Z.; Song, Z.; Wu, Y.; Jiang, J.; Shan, Y. Conductive and Elastic 3D Helical Fibers by either using a Washable and Wearable Electronic Activ. *Mater* 2020, 32, 1907495.

Washable electronic fabrics can be obtained in many ways, such as by knitting or weaving the electroconductive yarn, by electrospinning an electronic nanofiber mat/film (nonwoven), or by direct incorporation of nanomaterials with them, etc. Satharasinghe et al. revealed that the washability assessment of photodiode-embedded yarns in both the e-yarn and the fabric form showed distinctive performance. For the e-yarn, the first failure was observed after 5 washing cycles and only 20% of them survived 25 washing cycles, while the fabric remained unaffected up to 15 cycles and 60% of them fully functioned after 25 cycles.

9. Gunawardhana, K.R.S.; Wanasekara, N.D.; Wiyanantha, K.G.; Dharmasena, P.D. Scalable Textile Manufacturing Methods for Fabricating Triboelectric Nanogenerators with Balanced Electrical and Wearable Properties. *ACS Appl. Electron Mater* 2022, 4, 678–688.

10. Xiao, G.; Ju, J.; Lu, H.; Shi, X.; Wang, X.; Wang, W.; Xia, Q.; Zhou, G.; Sun, W.; Li, C.M.; et al. A Weavable and Scalable Cotton-Yarn-Based Battery Activated by Human Sweat for Textile Electronics. *Adv. Sci.* 2022, 9, 2103822.

11. Darabi, S.; Hummel, M.; Rantasalo, S.; Rissanen, M.; Öberg Månsson, I.; Hilke, H.; Hwang, B.; Skrifvars, M.; Hamed, M.M.; Sixta, H.; et al. Green Conducting Cellulose Yarns for Machine-Sewn Electronic Textiles. *ACS Appl. Mater. Interfaces* 2020, 12, 56403–56412.

12. Zeng, Z.; Hao, B.; Li, D.; Cheng, D.; Cai, G.; Wang, X.; et al. Large-Scale Production of Washable, Dyeable, and Durable Spandex/CNT/Cotton Core-Sheath Yarn for Wearable Strain Sensors. *Compos. Part B Appl. Sci. Manuf.* 2021, 149, 106520. When coated with silver ink through the inkjet printing process, the woven fabric showed superior wash durability (insignificant resistance change after 15 machine washing cycles), while the knit fabric's resistance doubled (>1 k Ω) after the same amount of wash cycles and 50 times higher resistance (2.3 Ω to >100 Ω) was observed for the nonwoven fabric only after a single wash. The poor resistance to washing of the nonwoven fabric may be ascribed to the looseness of the structure. Compact nonporous fabric structures (i.e., woven and knit) ensured better integration of conductive ink in the inkjet printing process, leading to better durability [31].
13. Ginnaram, S.; Chen, Y.T.; Lai, Y.C. Solid-State Intrinsically-Superstretchable Multifunctional Nanogenerator Fiber for Biomechanical and Ambient Electromagnetic Energy Harvesting and Self-Powered Sensing. *Nano Energy* 2022, 95, 107035.
14. Zhou, Z.; Padgett, S.; Cai, Z.; Costa, G.; Wu, Y.; He, Q.; Zhang, S.; Sun, C.; Liu, J.; Fan, F.; et al. Single-Layered Ultra-Soft Washable Smart Textiles for All-around Ballistocardiograph, Respiration, and Posture Monitoring during Sleep. *Biosens. Bioelectron.* 2020, 155, 112064.
15. Ma, Y.; Ouyang, J.; Raza, T.; Li, P.; Jian, A.; Li, Z.; Liu, H.; Chen, M.; Zhang, X.; Qu, L.; et al. Flexible All-Textile Dual Tactile-Tension Sensors for Monitoring Athletic Motion during Taekwondo. *Nano Energy* 2021, 85, 105941.
16. Zhang, Y.; Zhang, W.; Ye, G.; Tan, Q.; Zhao, Y.; Qiu, J.; Qi, S.; Du, X.; Chen, T.; Liu, N. Core-Sheath Stretchable Conductive Fibers for Safe Underwater Wearable Electronics. *Adv. Mater. Technol.* 2020, 5, 1900880.
17. Busolo, T.; Szewczyk, P.K.; Nair, M.; Stachewicz, U.; Kar-Narayan, S. Triboelectric Yarns with Electrospun Functional Polymer Coatings for Highly Durable and Washable Smart Textile Applications. *ACS Appl. Mater. Interfaces* 2021, 13, 16876–16886.
18. Sala de Medeiros, M.; Goswami, D.; Chanci, D.; Moreno, C.; Martinez, R.V. Washable, Breathable, and Stretchable e-Textiles Wirelessly Powered by Omnipophobic Silk-Based Coils. *Nano Energy* 2021, 87, 106155.
19. Cai, G.; Song, W.; Pan, J.; Cheng, D.; Wang, X.; Zhang, X.; et al. Large-Scale Production of Highly Stretchable CNT/Cotton Spandex Composite Yarn for Wearable Applications. *ACS Appl. Mater. Interfaces* 2018, 10, 32726–32735.
20. Pan, J.; Hao, B.; Song, W.; Chen, S.; Li, D.; Luo, L.; Xia, Z.; Cheng, D.; Xu, A.; Cai, G.; et al. Highly Sensitive and Durable Wearable Strain Sensors from a Core-Sheath Nanocomposite Yarn. *Compos. Part B Eng.* 2020, 183, 107683.
21. Zhao, Z.; Van Noers, Z.; Fesides, P.; Peng, L.; Han, Y. The Electrical Machine-Washable Textile Triboelectric Nanogenerators for Effective Wearable Respiration Monitoring through Polyaniline (PANI) nanofiber yarns. *Adv. Mater.* 2016, 28, 10267–10274.
22. Fan, W.; He, Q.; Meng, K.; Tan, X.; Zhou, Z.; Zhang, G.; Yang, J.; Wang, Z.L. Machine-Knitted Washable Sensor Array Textile for Precise Epidermal Physiological Signal Monitoring. *Sci. Adv.* 2020, 6, eaay2840.
23. Eskandarian, L.; Lam, F.; Ruppow, C.; Meghbrazi, M.A.; Naguib, H.F. Robust and Multifunctional Conductive Yarns for Biomedical Textile Computing. *ACS Appl. Electron. Mater.* 2020, 2, 1554–

- utilized 1566 efficiency. The fabric was highly washable (100 hand wash cycles) and could withstand different harsh environments for a longer period (3 weeks) [38]
24. Lv, J.; Dai, Y.; Xu, H.; Zhong, Y.; Zhang, L.; Chen, Z.; Sui, X.; Feng, X.; Wang, B.; Mao, Z. Transforming Commercial Regenerated Cellulose Yarns into Multifunctional Wearable Electronic Textiles. *J. Mater. Chem. C* 2020, 8, 1309–1318.
 25. Lee, S.W.; Jung, H.G.; Kim, I.; Lee, D.; Kim, W.; Kim, S.H.; Lee, J.H.; Park, J.; Lee, J.H.; Lee, G.; et al. Highly Conductive and Flexible Dopamine-Graphene Hybrid Electronic Textile Yarn for Sensitive and Selective NO₂ Detection. *ACS Appl. Mater. Interfaces* 2020, 12, 46629–46638.
 26. Kim, J.H.; Koo, S.J.; Cheon, J.Y.; Jung, Y.; Cho, S.; Lee, D.; Choi, J.W.; Kim, T.; Song, M. Self-Powered and Flexible Integrated Solid-State Fiber-Shaped Energy Conversion and Storage Based on CNT Yarn with Efficiency of 5.5%. *Nano Energy* 2022, 96, 107054.
 27. Lund, A.; Darabi, S.; Hultmark, S.; Ryan, J.D.; Andersson, B.; Ström, A.; Müller, C. Roll-to-Roll Dyed Conducting Silk Yarns: A Versatile Material for E-Textile Devices. *Adv. Mater. Technol.* 2018, 3, 1800251.
 28. Afroj, S.; Karim, N.; Wang, Z.; Tan, S.; He, P.; Holwill, M.; Ghazaryan, D.; Fernando, A.; Novoselov, K.S. Engineering Graphene Flakes for Wearable Textile Sensors via Highly Scalable and Ultrafast Yarn Dyeing Technique. *ACS Nano* 2019, 13, 3847–3857.
 29. Zhong, W.; Ming, X.; Jiang, H.; Ke, Y.; Ding, X.; Li, M.; Jia, K.; Wang, D. Full-Textile Human Motion Detection Systems Integrated by Facile Weaving with Hierarchical Core-Shell Piezoresistive Yarns. *ACS Appl. Mater. Interfaces* 2021, 13, 52901–52911.
 30. Satharasinghe, A.; Hughes-Riley, T.; Dias, T. Photodiodes Embedded within Electronic Textiles. *Sci. Rep.* 2018, 8, 16205.
 31. Salavagione, H.J.; Shuttleworth, P.S.; Fernández-Blázquez, J.P.; Ellis, G.J.; Gómez-Fatou, M.A. Scalable Graphene-Based Nanocomposite Coatings for Flexible and Washable Conductive Textiles. *Carbon* 2020, 167, 495–503.
 32. Shahariar, H.; Kim, I.; Soewardiman, H.; Jur, J.S. Inkjet Printing of Reactive Silver Ink on Textiles. *ACS Appl. Mater. Interfaces* 2019, 11, 6208–6216.
 33. Kim, T.; Park, C.; Samuel, E.P.; An, S.; Aldalbahi, A.; Alotaibi, F.; Yarin, A.L.; Yoon, S.S. Supersonically Sprayed Washable, Wearable, Stretchable, Hydrophobic, and Antibacterial RGO/AgNW Fabric for Multifunctional Sensors and Supercapacitors. *ACS Appl. Mater. Interfaces* 2021, 13, 10013–10025.
 34. Feng, M.; Wu, Y.; Feng, Y.; Dong, Y.; Liu, Y.; Peng, J.; Wang, N.; Xu, S.; Wang, D. Highly Wearable, Machine-Washable, and Self-Cleaning Fabric-Based Triboelectric Nanogenerator for Wireless Drowning Sensors. *Nano Energy* 2022, 93, 106835.

35. He, C.L.; Liang, F.C.; Veeramuthu, L.; Cho, C.J.; Benas, J.S.; Tzeng, Y.R.; Tseng, Y.L.; Chen, W.C.; Rwei, A.; Kuo, C.C. Super Tough and Spontaneous Water-Assisted Autonomous Self-Healing Elastomer for Underwater Wearable Electronics. *Adv. Sci.* 2021, 8, 2102275.
36. Qi, K.; Zhou, Y.; Ou, K.; Dai, Y.; You, X.; Wang, H.; He, J.; Qin, X.; Wang, R. Weavable and Stretchable Piezoresistive Carbon Nanotubes-Embedded Nanofiber Sensing Yarns for Highly Sensitive and Multimodal Wearable Textile Sensor. *Carbon* 2020, 170, 464–476.
37. Zhang, Z.; Wang, G.H.; Gu, W.; Zhao, Y.; Tang, S.; Ji, G. A Breathable and Flexible Fiber Cloth Based on Cellulose/Polyaniline Cellular Membrane for Microwave Shielding and Absorbing Applications. *J. Colloid Interface Sci.* 2022, 605, 193–203.
38. Jin, Y.; Chang, J.; Shi, Y.; Shi, L.; Hong, S.; Wang, P. A Highly Flexible and Washable Nonwoven Photothermal Cloth for Efficient and Practical Solar Steam Generation. *J. Mater. Chem. A* 2018, 6, 7942–7949.

Retrieved from <https://encyclopedia.pub/entry/history/show/59369>