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Densifying Conduction Network in the Skeleton of non-Conducting Natural Feathers for Developing Flexible Conductive Composite

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Abstract

Electrical and thermal conducting flexible composite materials are in demand for next-generation electronics. Devices like biomedical instruments, conducting textiles, low-power sources, electronic skin, and flexible displays require stretchable conductors possessing high electrical conductivity under excessive strain and deformation. In this respect, renewable, sustainable materials and/or their biomimicry could help to generate a three-dimensional, highly dense structure. We in this study have hence used the naturally occurring, densified non-conducting feather skeleton to develop three-dimensional conducting films. Herein, the natural feathers were treated with polydopamine solution to create a coating layer with dual action, as a linker for conductive filler as well as for self-adherence of feathers. The optimized amount of feathers and polydopamine is adsorbed with modified carbon nanotubes. Two simple laboratory methods of dip coating and freeze-drying process for the adsorption of conducting material, were optimized. The feathers themselves and polydopamine-coated feathers showed nil electrical conductivity, while different concentrations of filler-containing films showed electrical resistance from 5 to 1 kilo ohm. The film showed similar resistance after bending (50%), stretching (50%), compressing, and even breaking the film and reforming it 10 times exhibited similar trends. The high conductivity, electromechanical stability, and easy production methods make such nano-bio composites as renewable substrates for next-generation electronic devices.

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Introduction

With the fast growth of flexible electronic devices, energy conversion, storage, dissipation and protection from electromagnetic energy need development of novel conductive composite materials[1]. The rate of flow of electrons for electric conduction vis a vis of phonon for thermal conduction depends upon the conduction pathway attained three

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dimensionally in composite networks. Hence the performance of flexible and stretchable conductors depends on two major factor one being the material and other their layout in definite structures[2].

Densified networks engineering leading filler alignment is an influential emerging method for creation of continuous conductive pathways[3,4]. The strategy of pre-constructing three-dimensional network followed by functionalization and filler loading has been employed for development of high-performance conductive composites. Such pre-defined networks offer structural controllability of filler and allow high customizability considering conducting attribute. The process of constructing three-dimensional network structure has thus attracted researcher's interest for achieving higher stability with flexibility. Three dimension (3D) densified network designed through various chemical and physical method has been reported in literature. Likewise, chemically functionalized surface of polyurethane sponge was utilized as 3D skeleton for constructing conductive network through dip coating or electro-less deposition of metal layers[5,6].

Continuous arrangement of carbon fiber could enhance contact area by reducing interfacial thermal resistance which could increase thermal conduction of carbon fiber loaded composite[7]. It has been reported that secondary networks made by graphene incorporation within carbon fibers array could not only form a more densified seamless interconnects between carbon fiber but additionally introduces thermal conduction paths leading to low thermal contact resistance of 865 K W-1 and hence significantly enhance in plane thermal conduction[4]. Another study utilized nature inspired 3D assembly structure of wood for fabrication of conductive film with Mxene and hemicellulose networks via simple self-assembly process. Abundant oxygen containing functional groups of hemicellulose allowed embedding of Mxene sheets tethering together adjacent nanosheets through hydrogen bonding forming 'reinforced concrete' like structure[8]. Inspired by such structures naturally occurring fibers and feathers act as another 3D scaffolds for creating hierarchical arrangement. Bamboo fiber had been used with Ni-Fe-P alloy electroless plating for creating energy conversion composites which could be utilized as solar heater, joule heater and even as electromagnetic shielding[9].

In similar fashion another natural feather which holds utmost importance due to its tiered structure are keratin based down fibres[10]. Down fibers are well known thermal insulators and attains its richness due to its fluffy nature as well as abundant reserves because of its structure[11]. Twinning between down fibres could infact result in 3D network structure which could be well exploited as densely interconnected skeleton for fabrication of flexible conductors. Utilizing such network a study is reported in literature where silver nanowires were arranged on surface of modified down feathers to form binary networks for flexible conductors. The study attained higher conductivity and stability to bending as well as stretchability showing its high-class performance for constructing flexible film like conductors[12]. Inspired from such study we here have utilized modified carbon nanotubes as conducting base material and natural feathers as 3D skeleton structure for fabrication of conducting flexible film like structure. Carbon nanotubes (CNTs) hold its own importance being a less expensive, biocompatible, resistant to oxidation and highly conductive nanomaterial. Being one dimension nanomaterial compared to other 2D materials like graphene and Mxene CNTs also allow high thermal conduction through effective phonon conduction pathways[13]. Hence, we have tried to form conductive network with natural feathers and non-covalently modified CNTs via dip coating and freeze-drying method. Freeze drying method holds its own uniqueness in providing and conserving the structural integrity which could further enhance the overall property of composites. The key point of study reveals the utilization of non-covalently modified CNTs utilization to form better interaction between modified natural feather skeleton. The two methods are compared in terms of their response to conduction of electrons. Also, electro-mechanical ability of films is monitored after bending, stretching as well as reforming to develop a sustainable flexible form of conductor for future electronics.

Materials and Methods

Dopamine hydrochloride (Sigma-Aldrich), phosphate (PBS) buffer, lithium hydroxide,[6] amino hexanoic acid, sodium chloride (Sinopharm) and isopropyl alcohol (Sinopharm). High-purity silver paste (SPI), multiwall carbon nanotubes (CNTs). Recycled natural feather was obtained from used winter clothing & ensembles.

Method

Preparation of Poly-Dopamine Coated Natural Feathers

The natural feathers were mixed with varied concentration of dopamine in PBS buffer at pH 9 for a period of 24 hours. The process of modification was optimized by varying different time of coating.

Preparation of Conductive Composite with Dip Coating Method and Freeze-Drying Process

The modified natural feathers were dip coated with different concentration of modified CNTs. The amount and concentration of CNTs were varied in various ratio to feather amount. The modified CNTs were sonicated in isopropanol for 30min. The dispersed solution of CNTs were used to modify the surface of feathers coated with polydopamine by dip coating and drying method until all the volume of solution got soaked and dried.

For freeze drying process the prepared polydopamine coated natural feathers were interacted with modified CNTs solution. The modified CNTs were sonicated in water for 45min. The dispersed solution of CNTs were poured directly to polydopamine coated feathers and freezed at -80^{0}C. It is -80 degree Celsius for 2h followed by lyophilization for 48hours at -40^{0}C. It is -40 degree Celsius. until completely dried.

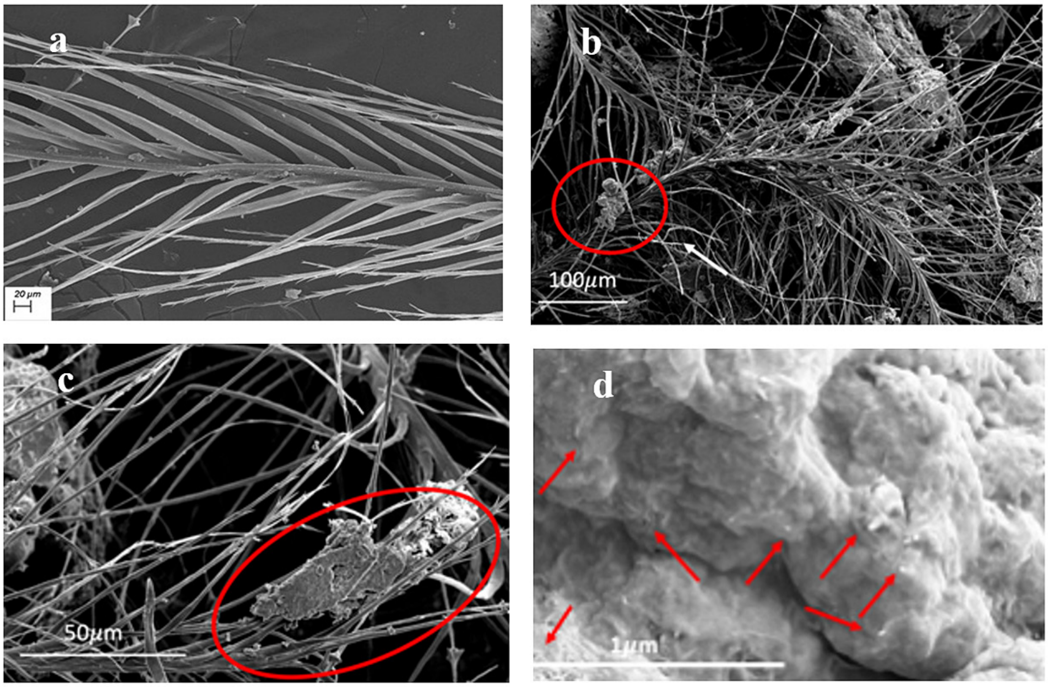

Fig. 1: SEM images showing (a) pristine feather exhibiting hierarchical fibrous structure, (b) CNT deposition over feather network at low magnification, (c) localized coating of CNTs on feather fibers, and (d) high-magnification image illustrating formation of an interconnected CNT network on the PDA-modified feather scaffold.

Results

Structural and Modification of Natural Feathers

Natural feathers have intensive structural aspect which was here utilized as skeleton for constructing conductive composite[14]. The branches and sub-branches of natural feathers could help in forming interconnected networks which in return could act as constructive pathway for conduction[15]. Similar hierarchical and porous structures of feather-based fibers have been reported to facilitate interconnected conductive pathways and lightweight scaffold formation for flexible electronic device.[16,17,18] The SEM images of natural feather shown in figure 1 clearly highlights the structural aspect of natural feather. This natural feather skeleton was modified with polydopamine solution. Since dopamine polymerize through free radical reaction to form its polymer polydopamine at a pH of 9 so the solution of dopamine in pH buffer solution was used for modification of natural feather surface. The amount and concentration of dopamine was optimized by visualizing the color of natural feather after modification as it turned from off white to blackish grey due to the deposition of polydopamine layer.

In figure 2. The successful adherence of polydopamine (PDA) onto the natural down fibers is confirmed by the distinct spectral changes in the FTIR analysis. The broadening and increased intensity of the peak at 3265 cm-1 indicate the overlapping of phenolic -OH and amine -NH groups from the PDA layer. Further evidence is found in the intensification of the Amide I (1624 cm-1) and Amide II (1512 cm-1) regions, attributed to the aromatic C=C stretching and indole ring formation during polymerization. Most notably, the enhanced absorption in the 1200–1300 cm-1 range represents the C-O stretching of catechol groups, providing definitive chemical proof of the coating.

The presence of polydopamine was also witnessed in SEM imaging due to presence of rough surface compared to pristine natural feather surface. Further this modified natural feather was compared with unmodified natural feather in terms of their hydrophobicity. It is known that pristine natural feather is inherently superhydrophobic in nature while the modified natural feather surface showed a small amount of adsorption of water due to presence of polydopamine layer, however the layer of polydopamine was adjusted such that the hydrophobicity aspect is rationally maintained as shown in photographic image in figure S1.

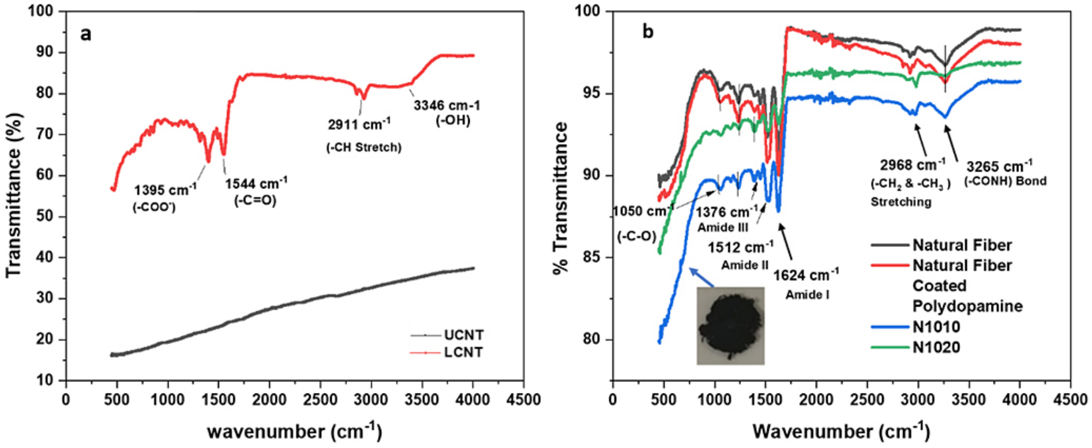

Fig. 2: FTIR spectra of (a) modified and unmodified CNTs (b) natural feather; polydopamine-coated natural feather; N1010 and N1020 composite. The inset in (b) shows the sample image of N1010

Coating of Modified Natural Feather with Conducting Carbon Nanotubes

The interaction of carbon nanotubes requires presence of functional group on its surface[19]. Since the concept of sustainability was base of the work so the modification of CNTs were done in all aqueous solution via a simple noncovalent modifier lithium salt of 6-aminohexanoic acid[20]. Non-covalent functionalization is advantageous as it improves CNT dispersibility while preserving the intrinsic electrical properties and graphitic structure of CNTs, unlike harsh covalent oxidation treatments. Such aqueous-based surface modification strategies have been widely reported as environmentally favorable approaches for developing conductive nanocomposites and also in other studies[21, 22,23].The

CNTs were modified as described in other works and characterized by FT-IR as shown in figure 2 for the presence of functional group[10]. The additional advantage of same modifier on CNTs surface holds that an optimized ratio of modifier allows to attain pH 9 on being dispersed. Hence this ability of modified CNTs were additionally useful here as it allows further proper interaction of feather with conducting materials since dopamine polymerize to form polydopamine at pH 9.

Modified CNTs were tried to interact with natural feather surface through two processes. The first being the simple dip coating method where modified CNTs in different concentration and volume was interacted with modified natural feather surface by dipping and drying process. The other method utilized was freeze drying method where the natural feather, polydopamine and CNTs were mixed in aqueous solution, freeze and lyophilized at -40° degree Celsius . write degree for two days. The difference between both process was assessed through water absorption ability of conducting composite designated as N1010 and N1010L for one of the concentrations of dip coated and lyophilized sample respectively. It was observed that lyophilized samples showed higher hydrophobic aspect compared to its dip coated counter sample. Hydrophobicity behavior of the composites was evaluated (Figure S1), showing reduced water absorption in freeze-dried samples compared to dip-coated counterparts.

Conductivity Aspect of Composite

The CNTs modified composites with different composition was tested for their resistance and hence conductivity aspect. With the change of ratio of amount of natural feathers and CNTs the resistance aspect varied as shown in figure 3. The composites N1010 and N1020 with the compositional ratio of 1:1 and 1:2 w.r.t. feather and CNTs showed better conductivity range compared to other composites. N1020L corresponds to the lyophilized sample of N1020. This optimized ratio of composites was prepared with both dip coating and freeze-drying method. The conductivity of composite could be tuned by varying the concentration of conducting material however after a certain concentration there appears saturation which could be possibly due to improper dispersion of modified CNTs at higher concentration.

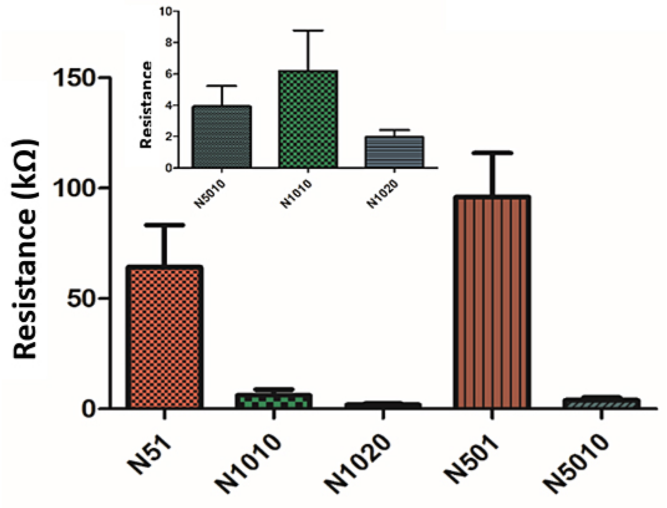

Fig. 3: Resistance measurements of varied composites. The inset shows the optimized composites N5010, N1010 and N1020

The optimized composite was further evaluated for their varied voltage to current response. The voltage was varied from 10V to 20V, and the composite was kept at a particular voltage for a period of 30min. The average value at different voltages were plotted for comparing the performance of dip coated and freeze-dried sample as shown in figure 4. It was observed that the freeze-dried sample showed a higher current attainment compared to its dip coated counter partner. This attainment of higher current in case of freeze-dried sample shows that the process method plays important role in maintaining the internal structure of composite. The 3D structure attained through dip coated sample compared to freeze dried sample attains less interconnected network leading to attainment of lower current value.

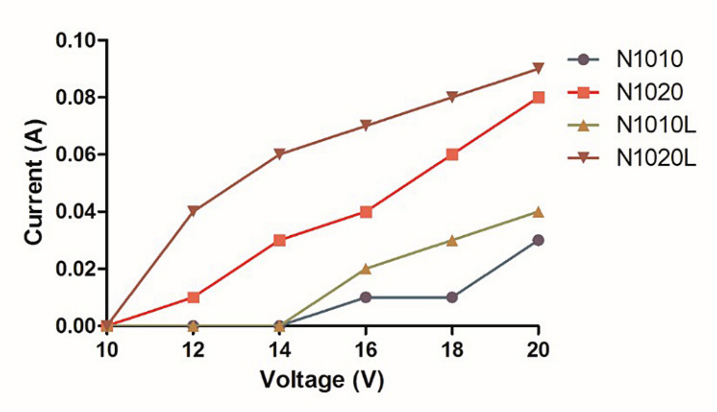

Fig. 4: Voltage–current characteristics of conductive composites (N1010, N1020, N1010L, and N1020L), showing enhanced current response in freeze-dried samples.

Freeze-dried composites exhibited improved conductivity and hydrophobicity due to better preservation of the interconnected 3D structure. The composites maintained nearly constant resistance under bending, stretching, and repeated reformation cycles, indicating good electromechanical stability. However, further improvements in conductivity and mechanical performance are required for practical electronic applications.

Discussion

The present work demonstrates that the intrinsic hierarchical architecture of natural feathers can be effectively utilized as a three-dimensional scaffold for conductive composites. Surface functionalization of natural feathers is required due to their insulating nature. Polydopamine coating enhances interfacial adhesion and enables uniform anchoring of carbon nanotubes[24]. PDA has been widely utilized as a universal bioinspired adhesive layer for improving interfacial interactions between carbon nanomaterials and bio-based substrates through catechol and amine functionalities[25,26]. Since CNTs are highly aggolomerated nanoforms so their modifications improve dispersion and so facilitates stable conductive network formation[27].

Processing methodology plays a critical role in determining composite performance where freeze-dried samples exhibited improved conductivity and network continuity compared to normal dip coated air-dried samples. This occurs as freeze-drying process allow direct sublimation process where ice the solid state converts directly to gaseous form and hence allow better preservation of the three-dimensional structure[28,29,30]. Freeze-drying has been reported to preserve porous three-dimensional conductive architectures by minimizing structural collapse during solvent removal, thereby improving conductive pathway continuity and electrical transport[31,32]. The electrical behavior follows a percolation trend, with optimal conductivity observed at intermediate CNT loadings, while excessive loading leads to aggregation and limited improvement. The composites exhibited stable electromechanical performance under bending, stretching, and repeated reformation steps, indicating robust structural integrity. Overall, the results highlight that structural preservation, interfacial engineering, and processing strategy are key factors in designing sustainable bio-based conductive composites. Further enhancements may be achieved through filler alignment and hybrid conductive systems.

Conclusion

In this study, natural feather networks were explored as a lightweight three-dimensional scaffold for developing conductive composites using non-covalently modified carbon nanotubes. Polydopamine coating facilitated the interaction between the feather surface and CNTs, enabling the formation of interconnected conductive pathways. Among the processing methods investigated, freeze-dried composites exhibited comparatively improved conductivity and structural preservation relative to dip-coated samples, due to better retention of the porous network architecture. The prepared composites also retained measurable conductivity under bending, stretching, compression, and reformation conditions, indicating electromechanical stability. Overall, the work demonstrates the feasibility of utilizing renewable feather-based structures for conductive composite fabrication through simple processing methods. Further optimization of filler dispersion, directional alignment , enhanced conductivity, and mechanical durability may expand the applicability of such materials for flexible and sustainable electronic system.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research doesn't involve human participants, animal subjects, or any material that require ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to reproduce material from other sources

Not Applicable

Author Contributions

- **Ayushi Singh:** Data Collection, Manuscript Writing.
- **Neha Agrawal:** Supervision, Conceptualization, Review & Editing, Finalization, Validation, Analysis.
- **Savita Gaur:** Reviewing.

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