

Advances in Fire Retardancy of Polymeric Nanocomposites and Applications

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Abstract: Emerging advancement in nanotechnology have facilitated the embedment of nanomaterials (NMs) such as graphene and derivatives, carbon nanotubes and derivatives, nanowires, and so on, within polymeric matrices to attain enhanced properties, especially fire retardancy, in polymeric nanoarchitectures (PNC) for multifarious applications. In thermal interface materials (TIM) for electronic gadgets, notable fire hazards are often ignored, whereas PNC exhibiting electromagnetic interference (EMI) shielding are frequently subjected to accidental fires. Furthermore, fire warning sensors with capability of rapidly exposing fire dangers in combustible materials plays a key role in mitigating or entirely eliminating fire disasters in most scenarios. Moreover, the escalating evolution of electronic gadgets in the fifth-generation (5G) era has made superlative fire safety, thermal stability and high-performance of PNC highly imperative. Nanowires are one-dimensional (1-D) nanostructures possessing a high length to diameter aspect ratios, unique flame retardant (FR), mechanical, electrical, thermal, and optical properties. The inclusion of different forms of nanowires within polymeric matrices has tremendously enhanced the flame retardancy (F-R) of nanowire@polymeric nanoarchitectures (N-PNC) thereby enlarging their scope of applications. Therefore, this paper presents advances in flame retardancy of nanowire polymeric nanoarchitectures.

Keywords: Flame retardancy; Nanowires; Nanowire@polymeric nanoarchitectures, Multifarious applications.

1. INTRODUCTION

Nowadays, fire hazards, heat-shock and thermal deterioration caused by slow heat diffusion within microelectronic gadgets have made it critically imperative for these materials to exhibit highly efficient thermal control system for highly performing electronic packaging materials. The integration of high F-R and outstanding electromagnetic interference (EMI) shielding into PNC has become critically imperative. Furthermore, with the broadening application of thermally conductive PNC in the aviation, automobile, maritime, oil and gas segments, and so on, not only elevated in-plane thermal conductivity (TC), mechanical and electrically insulative features are essential, but thermal stability and F-R have become critically imperative for these NMs [1].

Although possessing exceptional features such as low weight, outstanding flexibility with processability, inherently poor flammability as well as elevated temperature deterioration is deficiencies for most polymeric composites, and these flaws have restricted their scope of application in a versatile range of segments. In the construction sector, FR wallpapers with multifunctional features (F-R and an automatic alarm in fire disasters), have become attractive for

interior decoration of houses [2]. Furthermore, organically affiliated heat insulative materials exhibiting poor density and low heat dissipation have undergone wide utilization in construction and domestic gadgets. Nevertheless, their elevated flammability and inferior flexibility have hindered the versatility of their application in certain segments. In order to mitigate or completely eliminate aforementioned challenges, due to their peculiar advantages over conventional FRs, nanoparticulates (nanoclays, carbon derivatives, nanowires and so on) have been incorporated within polymeric matrices to enhance their FR as well as other features [3].

Nanowires (NWs) are 1-D nanostructures expressing a wide length to diameter aspect ratios and exhibiting peculiar mechanically, electrically, thermally, and optically affiliated features, fabricated via top-down or bottom-up strategies based on the NWs features (type of material and geometry). A NW is a nanostructure, having the appearance of a wire exhibiting diameter in the order of a nanometric (10^{-9} metre) [4]. Generally, NWs are known as architectures with thickness or diameter restrained to tens of nanometers or less and an unrestrained length. Relative to these nanometric scales, then quantum mechanically inclined effects become essential—referred as "quantum wires". Differing types of nanowires are prevalent, including superconducting NWs (YBCO NWs), metallic NWs (NiNWs, Pt, AuNWs, AgNWs), semiconducting (silicon NWs (SiNWs), InP, GaN) and insulating NWs (SiO₂NWs, TiO₂NWs) [5-7].

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Molecularly, NWs are made up of repeating molecularly units in either organic form (DNA) or inorganically ($\text{Mo}_6\text{S}_9\text{-xlx}$). Peculiarly, NWs display aspect ratio (length-to-width ratio) of 1000 or more [8]. Relative to NWs@PNC, for instance, metallic NWs are constructed utilizing AC electro-deposition on PAO templates, with subsequent surface functionalization of NWs and direct mixing within polymeric solutions [9].

Alternatively, the can undergo drying and mixture with polymeric melts. In this instance, copper nanowires (CuNWs) underwent mixing with polymeric solutions directly utilizing a miscible solvent mixture to fabricate NW architectures appearing segregated via miscible solvent mixing and precipitation (MSMP) [9]. The fabrication procedure of NWs@PNC is depicted in Figure 1a, whereas Figure 1b present SEM image of

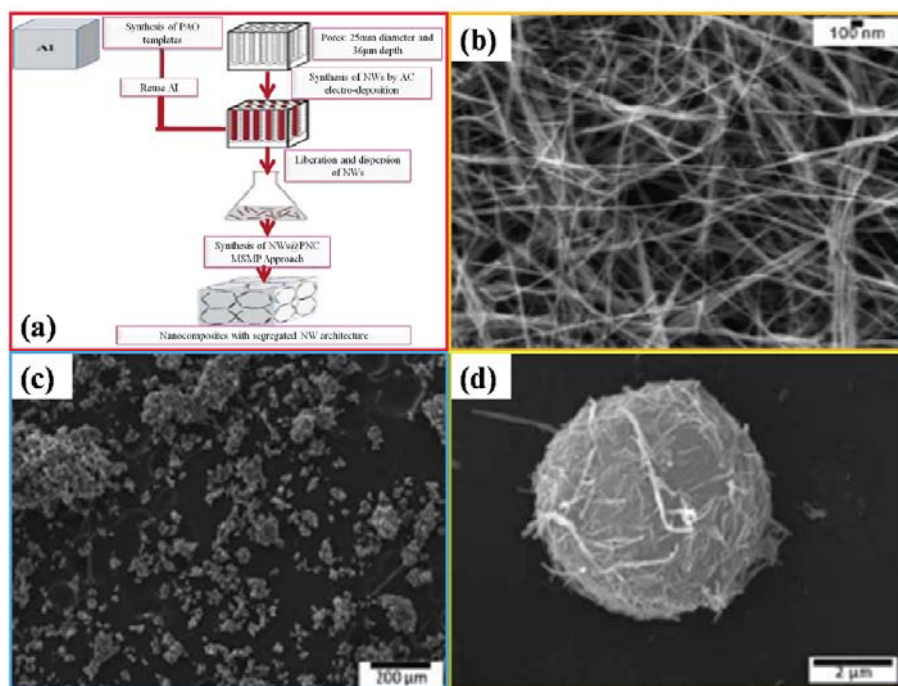


Figure 1: Schematic elucidation of the fabrication route of metallic NWs@polymeric nanoarchitectures (a). SEM image of CuNWs constructed via PAO templates (b). Low and elevated magnification SEM images of CuNW@PS nanoarchitecture respectively (c, d) [9].

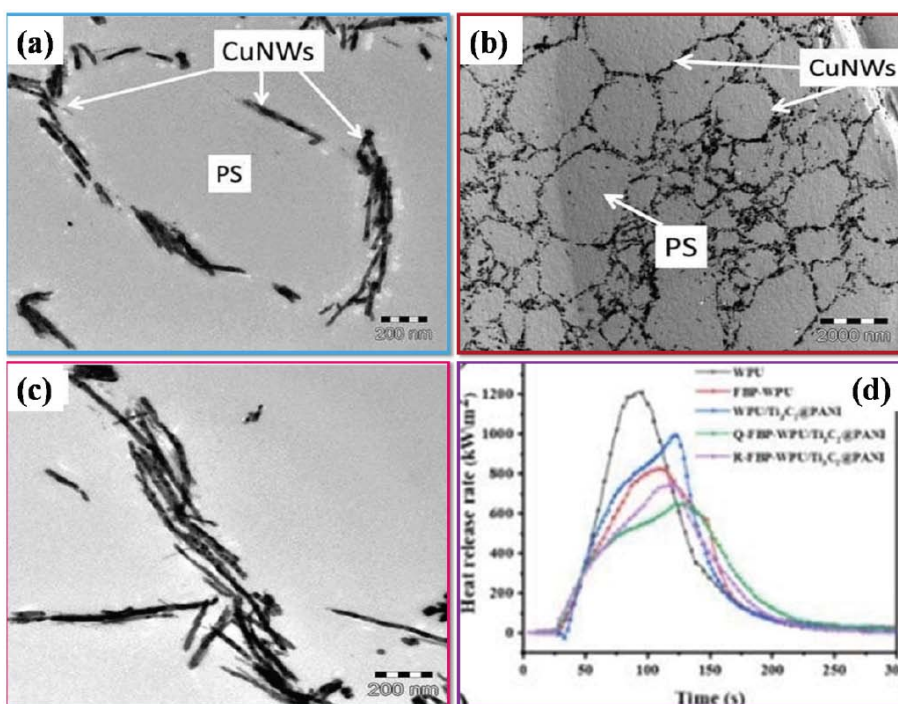


Figure 2: TEM image of ultra-microtome portions of CuNW@PS nanoarchitecture constructed via MSMP technique (a). Low and high magnification TEM of ultra-microtome section of heat pressed CuNW@PS nanoarchitecture (b, c) [9]. Typical FR heat release rate (HRR) of NWs@PNC [10].

CuNWs constructed via PAO templates. Figures 1c, 1d depicts low magnification and elevated magnification SEM images of CuNW@PS nanoarchitecture respectively, garnered via MSMP technique, a typical NWs@PS nanoarchitecture [9]. Clusters and single NWs of several microns (length) can be typically observed in 1b.

Furthermore, transmission electron microscopic (TEM) images of CuNWs@PS nanoarchitectures are presented in Figure 2a-c [9], while a typical FR curve of a NW@PNC is presented in Figure 2d [10].

Hence, NWs as NMs are FR at minimal inclusion within polymeric matrices and form NW_s@PNC with enhanced properties (mechanical, electrical, thermal, and optical), especially improved flame retardant features [1-10]. Therefore, this paper presents the flame retardant mechanism of nanowires polymeric nanoarchitectures and multifacet applications.

2. FR OF HYDROXYAPATITE NANOWIRES (HNS) AND GRAPHENE OXIDE POLYDOPAMINE NANOPAPER

Smart FR and fire alarm wallpaper (FAW) will be outstanding if it can simultaneously hinder fire from spreading while sending out alerts during fire mishap. Hence, the FAW require an ideal FR paper capable of maintaining its structural integrity during fire, in synergy with a thermos-sensitive sensor capable of rapidly responding to elevated fire temperature. Commercially available wallpaper from plant cellulosic fibers (CWP) or synthetic polymeric exhibit low-weight, flexibility, and inexpensiveness, as good interior decor for homes, but with the pertinent challenge of high

flammability and promotion of fire spread during fire disaster. In order to mitigate this challenge, there is need to enhance the FR of the substrate. Ultra-long hydroxyapatite nanowires (HNWs) with ultrahigh aspect ratios possesses elevated flexibility and capable of mitigating these challenges. Hence, in a work, an intelligent FAW was constructed using fire-resisting HN@GF inorganic paper as a substrate and GO (or PGO) as a thermos-sensitive sensor, capable of simultaneously preventing fire spreading and sending out alarms to warn people of occurrence of fire disaster [11].

The outstanding thermal stability and FR of the substrate depicts the exceptional-performance of FAW. The synergy is maintained between the substrate and thermos-sensitive sensor enabled FAW efficiency and durability in real life fire scenario [11]. The pristine commercial CWP derived from plant cellulose fibers exhibited elevated combustibility and inferior thermal stability. Results garnered from the TG curve of the CWP reveals that the weight loss is as elevated as 93.41%@1000 °C in air (Figure 3a). Contrastingly, both HNs and GFs display elevated inherent heat stability, while TG curves reveal that HNs and GFs weight loss is only 2.90 and 0.33%, respectively (Figure 3a) [11].

The vertical combustibility technique was utilized in testing the FR of the HN@GF inorganic paper and commercial wallpaper. Results show that HN@GF inorganic paper displayed outstanding FR, as the HN@GF paper are FR for prolonged duration of time (Figure 3c. Contrastingly, CWP burnt easily in very brief time (within 10 s) (Figure 3d) [11].

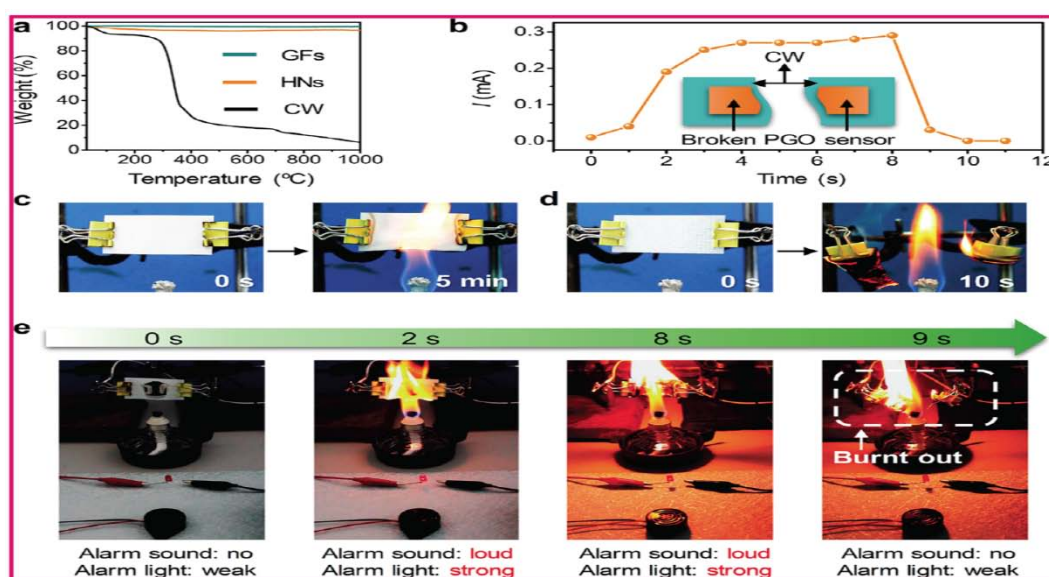


Figure 3: (a) TG trend of GFs, HNs, and CWP). (b) Electrical current (I) across PGO thermos-sensitive sensor on CWP with time in alcohol fire; schematic elucidation (inset) of damaged PGO thermos-sensitive sensor on CWP post burning procedure. (c, d) FR examination of the HN@GF inorganic paper (c) and CWP (d). (e) Actual-time monitoring of the variations posed by the alarm lamp, the alarm buzzer, and the PGO thermos-sensitive sensor on CWP during the burning step [11].

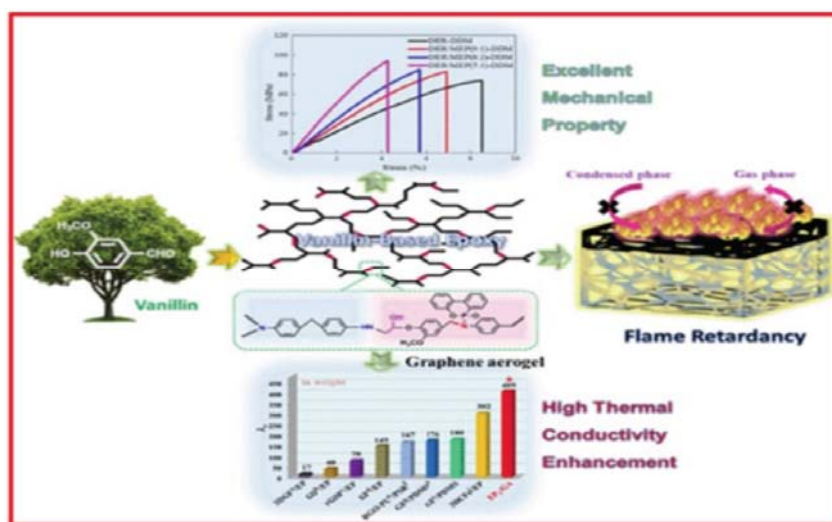


Figure 4: FR, Mechanical and thermal conductivity of nanoarchitectures [12].

3. F-R AND THERMAL CONDUCTIVITY OF VANILLIN-ORIENTED EPOXY RESIN FOR THERMALLY-CONDUCTIVE EPOXY@GRAPHENE AEROGEL NANOARCHITECTURES

Vanillin, a lignin-obtained single-aromatic entity, has garnered escalating interest attributed to inherently specific function as an intermediate entity for the fabrication of differing bio-oriented polymeric matrices. Hence, in a work, F-R and thermally-conductive vanillin-based epoxy@graphene aerogel (GA) nanoarchitectures were constructed [12]. Results revealed that the, flexural strength as well as modulus were highly improved from 72.8 MPa and 1.3 GPa to 90.3 MPa and 2.8 GPa, respectively, at 30 wt. % MEP, attributed to the rigidity of MEP as well strong intermolecular N–H hydrogen bonding interactions (Figure 4). On the other hand, the cured epoxy attained a UL-94-V0 rating at low P constituent of 1.06%. The FR vanillin-oriented epoxy was then introduced into the thermal conductive 3-D GA architectures. (Figure 4). The garnered epoxy@graphene nanoarchitecture displayed outstanding FR (Figure 4) [12].

4. FR OF $\text{Mg}_2\text{B}_2\text{O}_5\text{NW@POLY(ETHYLENE OXIDE)}$ (PEO) SOLID-STATE ELECTROLYTES (SSES)

High ionic conductivity, endows mechanical features, and versatile electrochemical opportunities are critical parameters for nanocomposite electrolytes utilized in solid-state lithium-ion batteries (SSLIBs). Premised on this perspective, a work constructed $\text{Mg}_2\text{B}_2\text{O}_5$ NWs facilitated poly(ethylene oxide) (PEO)-based solid-state electrolytes (SSEs) (Figure 5) [13]. Garnered SSEs possessed improved ionic conductivity as well as wide electrochemical spectrum. Additionally, the high ionic conductivity is ascribed to the enhanced movement of PEO chains as well as incremental Li migration at the interfacial segment between $\text{Mg}_2\text{B}_2\text{O}_5\text{@PEO-LiTFSI}$. Additionally, the

SSEs composed of $\text{Mg}_2\text{B}_2\text{O}_5\text{NWs}$ displayed improved FR and mechanical performances, when compared with virgin PEO@LiTFSI electrolyte (Figure 5) [13].

5. SYNERGISTIC INCREMENT IN FR AND THERMAL CONDUCTIVITY OF GRAPHENE@SILVERNWS@EPOXY NANOARCHITECTURES

The fire hazards incurable from polymeric oriented-thermal interface materials (TIMs) utilized in electronic gadgets are usually ignored. In addition to the elevated filler embedment causing the degradation of mechanically, thermally, and processing features hinder further usage of the conventional polymer-oriented TIMs. Hence, in a work, a ternary TIMs fabricated from epoxy resin (EP) matrix, silver nanowires (AgNWs), with small inclusion of FR modified graphene (GP-DOPO) were constructed to mitigate these challenges [14]. Summarily, a “branch-appearing” approach having a polymeric matrix as backbone and FR molecular entity was initially utilized in functionalizing reduced graphene oxide (RGO) towards incrementing the FR grafting ratio and RGO’s compatibility within the matrix, and the garnered GP@DOPO was subsequently in situ inculcated within the EP@AgNW nanoarchitectures. The inclusion of GP@DOPO (2 wt. %) is capable of incrementing the thermal conductivity to 1.413 W/(m K) at a very low AgNW increment (4 vol. %), which is 545 and 56% increments in comparison with pristine EP and EP@AgNW, respectively [14].

The garnered enhancement of thermal conductivity was put down to the synergetic effect of AgNW and GP@DOPO, relative to enhancement in distribution and bridging effect of AgNWs through inclusion of GP@DOPO. Moreover, the elevated FR grafting level and outstanding compatibility of GP@DOPO induced elevated catalytically charring influence on EP matrix.

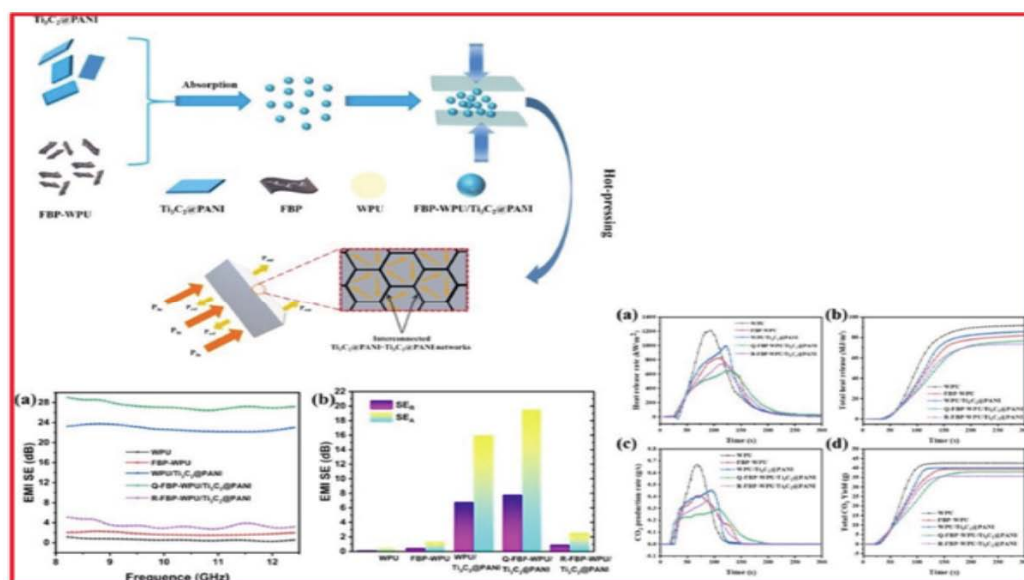


Figure 5: Construction route, FR and EMI of PEO@LiTFSI electrolyte nanoarchitectures [13].

Nevertheless, the elevated FR grafting amount and the outstanding compatibility of GP@DOPO resulted in a strong catalytic charring effect on EP matrix, which further formed a robust protective char layer through synergy of AgNW and graphene architecture. Hence, the FR of EP@AgNW was notably enhanced by inculcating GP@DOPO, i.e., the PHRR, THRR and TSP minimized by 27.0, 32.4, and 30.9% in comparison with EP@AgNW, respectively [14] (Figure 6).

6. FR OF ULTRA-LONG HYDROXYAPATITE NWS@ARAMID NANOFIBERS

Herein, elevatedly flexible, heat stable, and FR nanoarchitecture paper possessing high dielectrically breakdown strength along with mechanical strength was constructed by synergistically embedding ultra-long hydroxyapatite (HAP) nanowires combined with aramid nanofibers (ANFs) via vacuum-facilitated filtration procedure (Figure 7) [15].

The as-constructed HAP/ANF nanoarchitecture paper possesses nanowire/nanofiber networked framework as well as a layered architecture for applications in miniature and flexible electronic gadgets, elevated-voltage electrically insulating equipments, and FR and elevated-temperature segments [15].

7. FR OF UNSATURATED POLYESTER@F-HAPNW NANOHYBRIDS

Zero-toxic, minimally-smoking, elevated-efficiency and ecobenign F-R have become imperative recently. Here, polyphosphazene cross-linked with hexachlorocyclotriphosphazene (HCCP), 3-aminopropyltriethoxysilane (APTES), and dopamine (DA) was utilized in modifying hydroxyapatite nanowires (HAPNW), thereby deriving a novel ecobenign nano-hybridized architecture (f-HAPNW) [16]. Subsequently, f-HAPNW was embedded within unsaturated polyester (UPR) matrix in the presence of nanowires architecture with a high aspect ratio, in accompaniment by

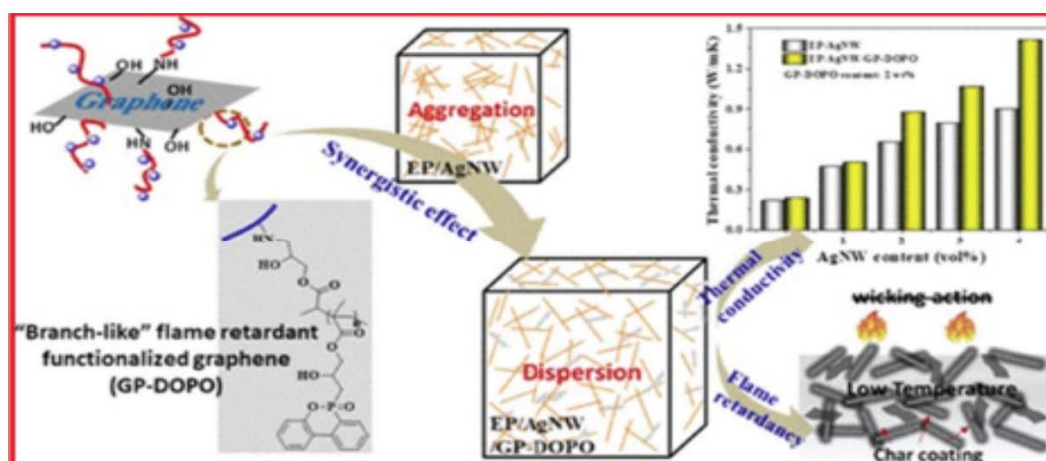


Figure 6: Synergistic enhancement in thermal conductivity and FR of epoxy@AgNWs nanoarchitectures through inclusion of "branch-appearing" FR functionalized GN [14].

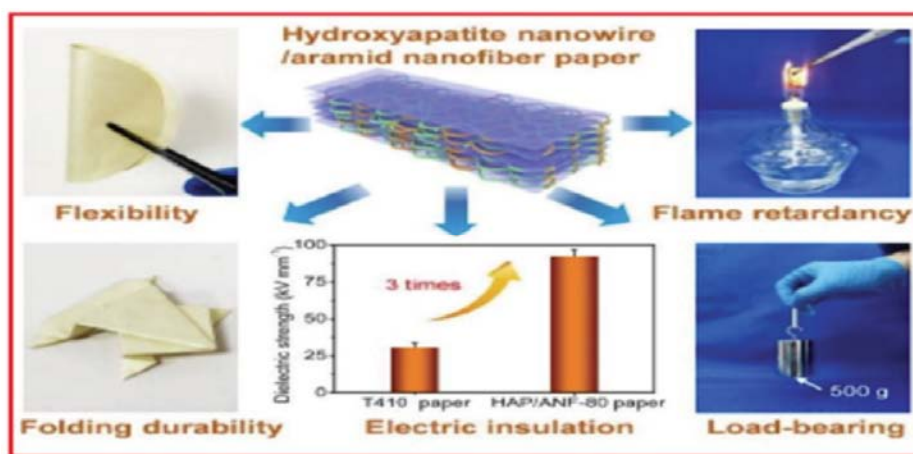


Figure 7: FR of ultra-long HAP NWs@aramid nanofibers [15].

outstanding interfacially inclined compatibility. Hence, the embedment of a small levels of f-HAPNW attained a complete enhancement in the F-R and mechanical features of UPR nanoarchitectures, including 23% decrement in total heat release rate (THR), 25.7% and 29.5% minimization in total smoke production (TSP) and the peak of CO production rate (PCOP) on inclusion of 2 wt.% content Figure 8 [16].

Generally, this work constructed ecobenign hierarchical f-HAPNW architecture, and attained a total enhancement in UPR nanocomposites performance, offering an anchor for designing highly performing UPR nanoarchitectures [16].

8. FR AND SMOKE SUPPRESSION OF PP@ZINC OXIDE NWS

In order to effectively improve the FR of epoxy resin (EP), a new core-shell organic-inorganic hybridized NWs relying on copper aromatic-sulfide and polyphosphazene hetero-architecture were constructed and synthesized using a dual-step synthesizing approach, including the synthesis of 2,4-

dichlorothiophenol-Cu (Cl-Cu) nanowires and the in-situ coating of poly(cyclotriphosphazene-co-4,4'-sulfonyldiphenol) (PZS) on Cl-Cu nanowires (Cl-Cu@PZS). On inclusion of 0.5 wt. % of Cl-Cu@PZS-2 NWs, EP limited oxide index (LOI) incremented to a maximum of 27.4 % [17]. The synergistic disposition of EP with 0.5 wt. % Cl-Cu@PZS-2 NWs studied by cone calorimeter examination revealed that the peak of heat release rate (PHRR), and total smoke production (TSP) decremented by 24.50 %, and 22.73 %, respectively, whereas the residue mass incremented by 135.82 % Figure 9 [17].

It was concluded that Cl-Cu@PZSNWs garnered notable synergistic impact on the F-R enhancement, smoke suppression and mechanical strength [17]

In a similar work, Polyethylenimine/phytic acid (PEI/PA) layer and silver nanowires (AgNWs) conductive networks were constructed on cotton fibers surface via layer-by-layer assemblage technology along with dip-coating strategy, attributable to elevatable electrostatic interactivity as well as bonding effect. Specifically, cotton fabric with 24.2 wt. % of

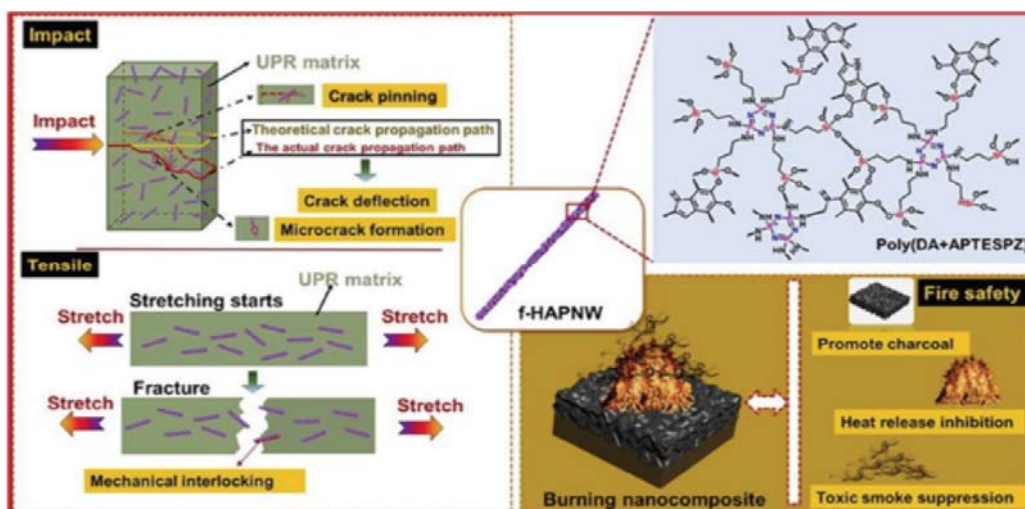


Figure 8: FR of silicon-oriented polyphosphazene-functionalized hydroxyapatite nanowires [16].

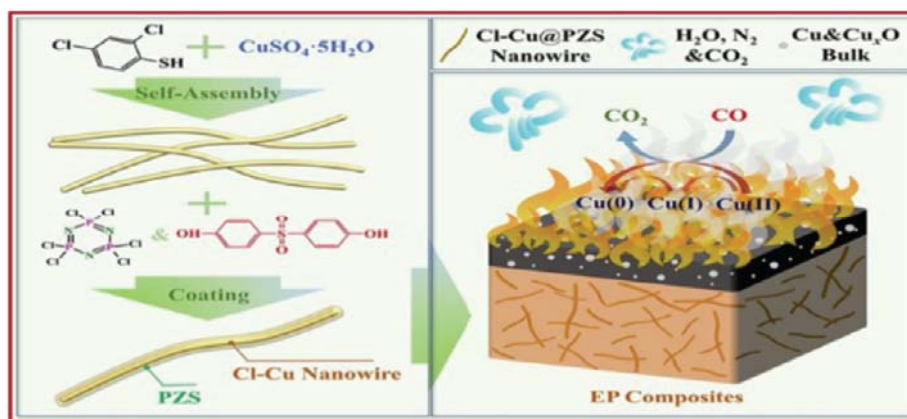


Figure 9: FR and smoke suppression of PP@zinc oxide NWs [17].

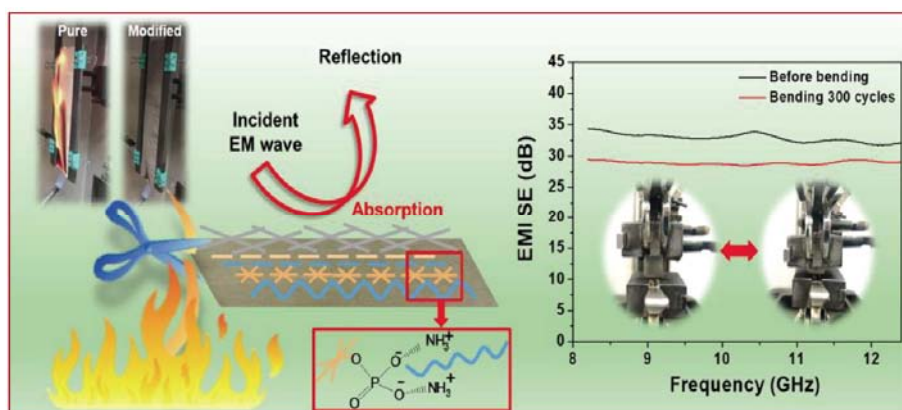


Figure 10: Eco-friendly flame retardant and electromagnetic interference shielding cotton fabrics with multi-layered coatings [17].

PEI/PA layering and 7.5 wt. % of AgNWs network possessed effectual self-extinguishment while minimizing the PHRR value to about 58.59% of pure cotton fabric (Figure 10) [17].

9. FR OF HAP@SILICA AEROGEL NANOARCHITECTURE

Organic heat insulating materials exhibiting low density and low thermal conductivity with FR have undergone vast usage in building and domestic appliances [18]. Nevertheless, their elevatedly flammable and inferior flexibility features hamper their usage on subjection to certain situation. Thus, in a work, novel nanoarchitecture paper exhibiting low thermal conductivity, FR and good mechanical features was fabricated by utilizing ultra-long hydroxyapatite (HAP) NWs as scaffolds for silica aerogels (Figure 11) [18].

On the other hand, the garnered paper exhibited notable FR with peak heat release rate (HRR) of only 33.1 W/g on inclusion of silica aerogel of 50 wt.%, thereby presenting the as-constructed HAP/silica aerogel nanoarchitecture for applications in protecting insulation materials, FR wallpapers, specialty fire clothing, and so on [18].

10. FR $\text{Ti}_3\text{C}_2\text{Tx}$ MXENE ARCHITECTURE FOR RAPID, RE-APPLICABLE AND WEATHER-PROTECTION FIRE WARNING

In this work, biomimetic polyethylene glycol or polyvinyl pyrrolidone polymer in decoration with $\text{Ti}_3\text{C}_2\text{Tx}$ MXene architecture having outstanding FR and specific fire cyclic warning disposition was constructed [19]. Fire warning sensors constructed relying on as-fabricated FR MXene architectures display very rapid fire warning signal and recovery time (~ 1.8 s and ~ 1.0 s), resistance switching disposition with >4 orders of magnitude, and stabilized fire cyclic signaling capability for 100 cycles. Structural observation and analysis show that, during fire, polymeric molecules heat pyrolysis enable the oxidation of MXene sheets thereby forming a miniature fish scale-like C/N doped titania architecture, which triggers its electron excitation thereby generating a sensitive resistance transition to initiate ultra-fast fire cyclic warning signal (Figure 12) [19].

11. ENHANCED FR OF GRAPHENE@ HEXAGONAL BORN NITRIDE NWS@EPOXY NANOARCHITECTURE

The heat aging, thermal shock and fire hazard caused by delayed heat diffusion within

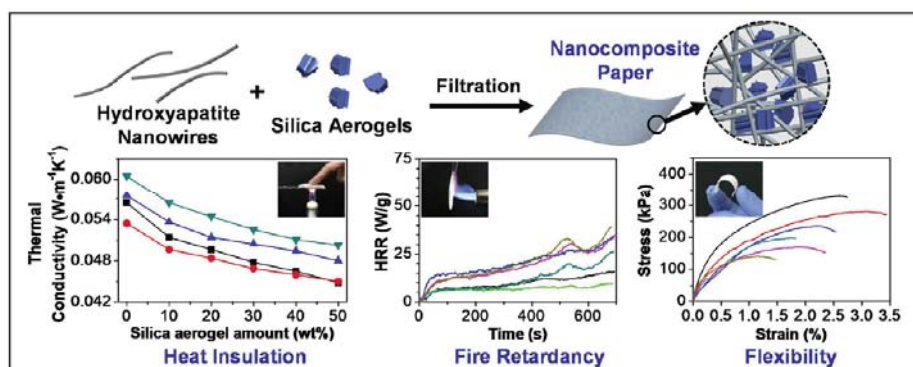


Figure 11: FR of HAP@silica aerogel nanoarchitecture [18].

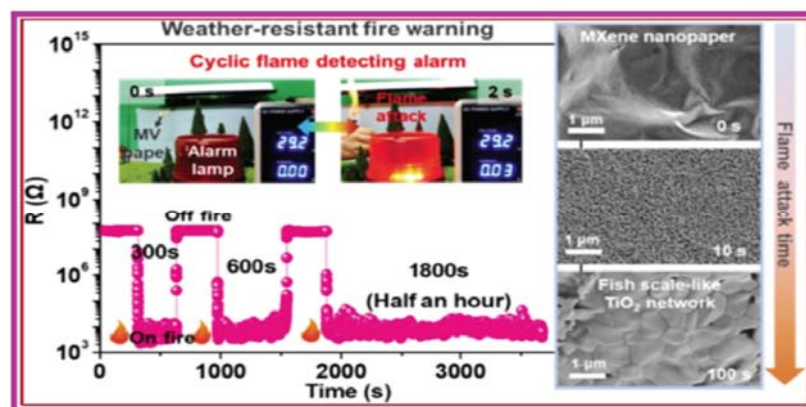


Figure 12: MXenemechanisms of fire cyclic warning sensors for fire safety and prevention [19].

microelectronic gadgets need a highly-efficient heat management system exhibiting elevated-performance electronic packaging materials. Hence, in a work, notable heat conductivity and FR of polymeric-oriented heat conductive composites (PTCs) are mitigated via several synergistic effects of hexagonal born nitride (hBN) and few FR modified graphene [20]. Summarily, a multifunctionalized hydrophilic graphene-oriented hybrid composed of $\text{Ni}(\text{OH})_2$ nanoribbons and reduced graphene oxide (rGO) underwent synthesization via dual-step hydrothermal procedure. The resultant $\text{rGO}@\text{Ni}(\text{OH})_2$ hybrid and hBN sheets (lateral size of $4.37 \pm 1.68 \mu\text{m}$ and thickness of $80 \pm 21 \text{ nm}$) utilized as synergistic and reinforcements, respectively, was

simultaneously embedded within EP matrix [20]. Results exposed that the binary reinforcement displayed several synergisms for enhancement of heat conductivity and FR of composites (Figure 13) [20].

12. FR AND EMI OF TPU@PA-APP@ $\text{Ti}_3\text{C}_2\text{TX}$ -SCS NANOARCHITECTURES

Inculcating elevated FR and outstanding electromagnetic interference (EMI) shielding within polymeric materials is critically essential and even dispersion of conductive fillers within polymeric materials remains a daunting challenge due to inherent incompatibility of the interfacial polarity between

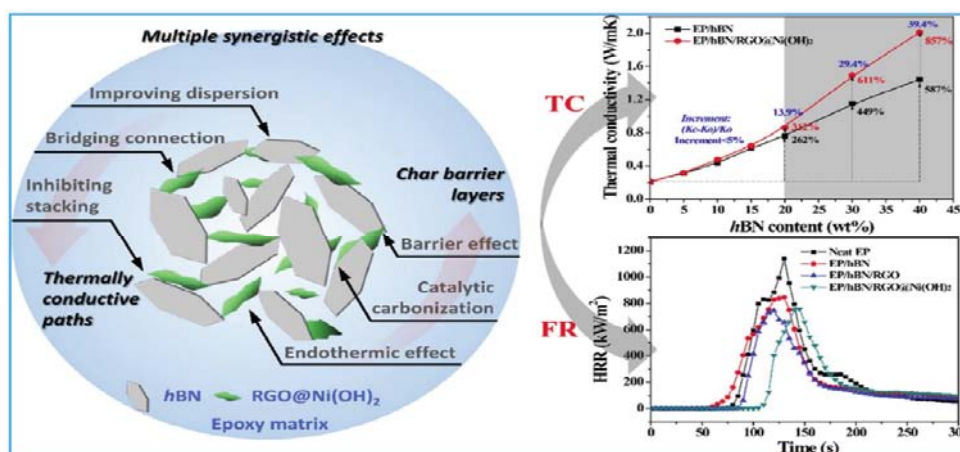


Figure 13: FR and thermal conductivity of synergistic r-GO@hBNNWs@Epoxy nanoarchitectures [20].

polymeric matrix and conductive reinforcements. Hence, in a bid to maintain integral conductive films within hot compression steps, the construction of novel EMI shielding polymeric nanoarchitectures where conductive films closely adhere to polymeric nanoarchitectural layers has garnered attention. Thus, in a work, salicylaldehyde-functionalized chitosan embedded titanium carbide nano-hybrid ($\text{Ti}_3\text{C}_2\text{Tx-SCS}$) synergized with piperazine-functionalized ammonium polyphosphate (PA-APP) for the construction of thermoplastic polyurethane (TPU) nanoarchitectures, with inclusion of reduced graphene oxide (rGO) films into $\text{TPU@PA-APP@Ti}_3\text{C}_2\text{Tx-SCS}$ nanoarchitectures through customized air facilitated hot pressing strategy [21]. The THR, TSR and total carbon monoxide yield for TPU nanoarchitecture containing 4.0 wt.% $\text{Ti}_3\text{C}_2\text{Tx-SCS}$ nano-hybrid were 58.0%, 58.4% and 75.8% reduced in comparison with pristine TPU, respectively (Figure 14) [21].

This work offers a potential technique for constructing fire safe with EMI shielding polymeric nanoarchitectures [21].

13. HYDROXYAPATITE NANOWIRES (HAPNWS)@BORON NITRIDE NANOSHEETS (BNNSS)

Due to increase in the scope of application of thermally conductive nanocomposites in the aviation segment and so on, high in-plane thermal conductivity (TC), mechanical flexibility and electrical insulation, as well as heat stability and FR are essential. Despite exceptional features (low weight, satisfactory flexibility as well as processability, the intrinsically fire and elevated temperature deficiencies of polymeric matrices are detrimental for most polymeric-oriented thermally conducting nanocomposites, thereby severely hindering their usage in extreme environments. In order to mitigate this challenge, a facile technique of fabricating a flexy inorganic based composite films instigated by emergence of inorganic

NWs in fabricating F-R paper was construed. Here, 1-D hydroxyapatite nanowires (HAPNWs) garnered through solvo-thermal approach and 2-D boron nitride nanosheets (BNNSSs) constructed via liquid phase exfoliation underwent inculcation utilizing vacuum-facilitated filtration in forming layer-architecture composite films, where HAPNWs offered flexibility and BNNSSs provided directional heat conductive routes [22]. On inclusion of 30 wt. % BNNSSs, the in-plane TC value of garnered composite film attained $6.4 \text{ W m}^{-1} \text{ K}^{-1}$ at 25°C and maintained at $5.5 \text{ W m}^{-1} \text{ K}^{-1}$ under 100°C (Figure 15) [22].

Hence, the all-inorganic films demonstrated outstanding flexibility, fire retardant ability and low coefficient of thermal expansion, thereby exhibiting great prospects as thermally conducting materials utilized in harsh environment [22].

14. FR OF AGNWS@PANI@PU FOAMS NANOARCHITECTURES

Due to ultra-fast evolvement of 5G technology, modified coatings possessing both elevated F-R effectiveness and EMI have become critically essential, while conventionally ineffective strategies have garnered challenges. Thus, in a work, an ecobenign and multifunctionalized nanometric/micrometric decoration made by bio-substrate phytic acid (PA) induced polymerization and self-assembly of polyaniline (PANI) nanoparticulates and dip-decoration of silver microwires (AgNWs) [23]. Here, FR efficiency is induced into PANI to attain PA F-R while simultaneously enhancing PANI electrical conductivity. Subsequently, decorated PU foam display elevated F-R because PA synergism garnered from PA@PANI , with capability of self-extinguishing immediately after ignition during the UL-94 vertical burning test, demonstrates elevated limiting oxygen index (LOI) value of 34.8%, while exhibiting a 50.7% minimal pHRR in comparison with pristine PU foam (Figure 16) [23].

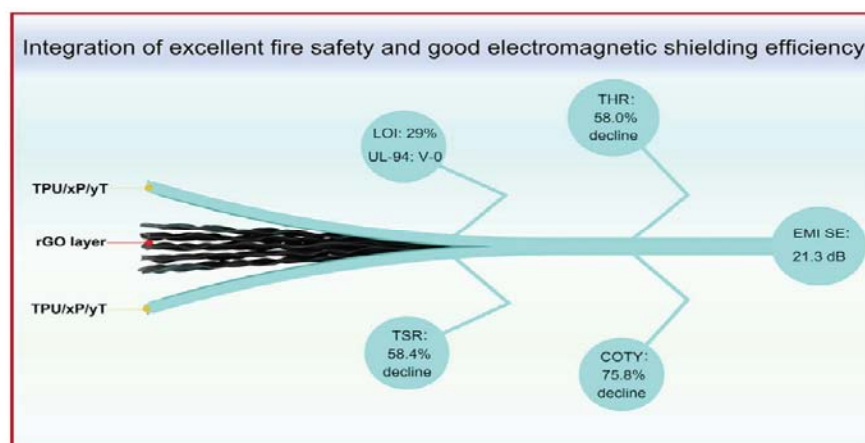


Figure 14: FR and EMI feature of $\text{TPU@PA-APP@Ti}_3\text{C}_2\text{Tx-SCS}$ nanoarchitectures [21].

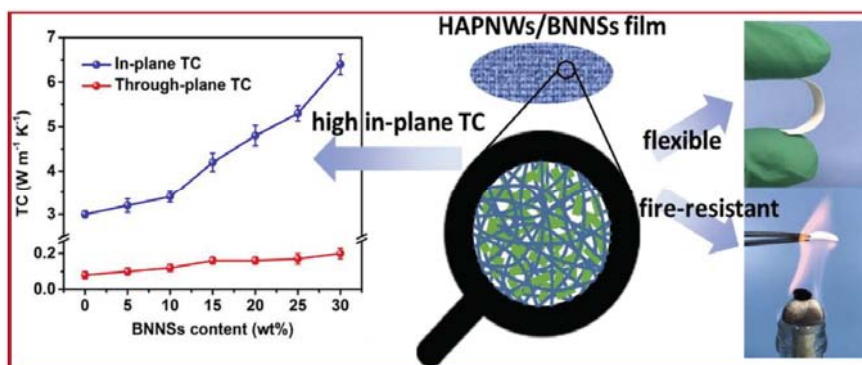


Figure 15: FR and TC of HAPNWs offered flexibility using BNNs [22].

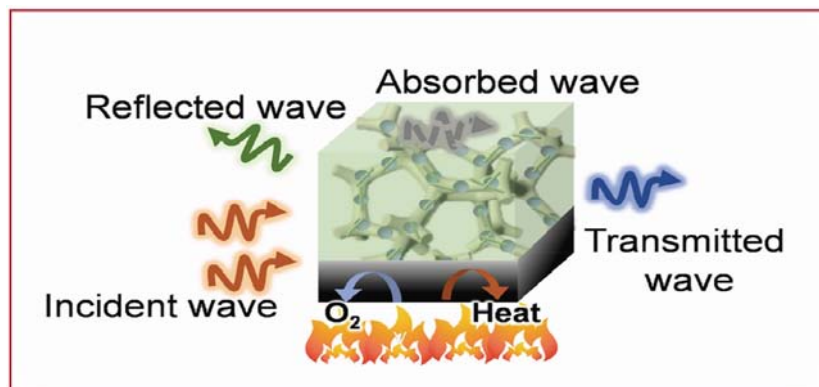


Figure 16: FR of AgNWs@PANI@PU foams nanoarchitectures [23].

15. FR OF SMPU@MXENE NWS NANOARCHITECTURE

Conventional fire warning sensors are sensitive to fire incident or elevated temperature while ignoring electrical safety. Hence, it is essential to fabricate an effective instantaneous fire warning sensor possessing circuit safety on exposure to fire scenario. Thus, in a work, a FR paper possessing thermos-sensitive fire-alarm responses as well as self-cutting performance is postulated [24]. Here, shape memory thermoplastic polyurethane (SMPU) and MXene is fabricated through facile electro-spinning along with vacuum filtering steps, capable of been utilized as early fire alarm induced by the shape memory disposition of SMPU [24]. Results showed that SMPU@MXene paper

offered a stabilized detecting signal and automatic early fire warning sensitivity when the ambient temperature is beyond transition temperature of SMPU. In comparison with SMPU paper, SMPU@MXene paper exhibited superior F-R with a fast self-extinguishing behavior, along with 66.0% and 49.8% minimization in pHRR and THR, respectively. Therefore, this work offers a new pathway for construction of early detection fire-alarm sensors and fire-protection applications [24].

16. PEO@LITFSI@LLTO-NWS POLYMERIC NANO-ARCHITECTURAL ELECTROLYTES

Herein, rapid ionic conductor $\text{Li}_{0.33}\text{La}_{0.557}\text{TiO}_3$ (LLTO) nanowires having elevated ionic conductivity

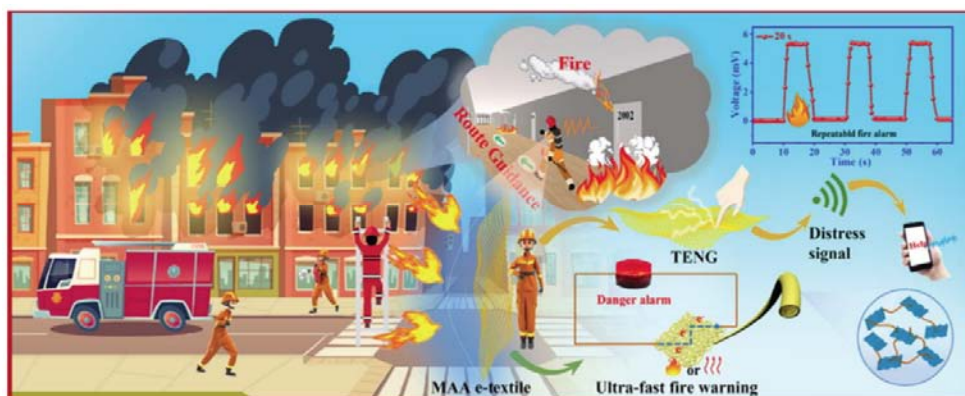


Figure 17: FR of $\text{Ti}_3\text{C}_2\text{Tx}$ MXene@AgNWs@ANFs [28].

were constructed via electro-spinning with subsequent elevated temperature calcination. LLTO NWs was used in filling poly (ethylene oxide) (PEO) matrix as reinforcement and the novel PEO@LiTFSI@LLTO-NWs polymeric nanoarchitectural electrolytes were constructed via inexpensive solution casting technique [25]. The results revealed that LLTO NWs inclusion could effectively enhance the ionic conductivity, electrochemical stability window, transference number, and compatibility with lithium metal of polymeric nanoarchitecture electrolytes. The maximum ionic conductivities of nanocomposite electrolytes reinforced with 5 wt.% LLTO NWs at ambient temperature and 60 °C were $5.53 \times 10^{-5} \text{ S cm}^{-1}$ and $3.63 \times 10^{-4} \text{ S cm}^{-1}$, respectively. FR of the materials was achieved. [25].

17. SILICIOUS NWS FACILITATED DENDRITES REPRESSION AND FR FOR ADVANCED LITHIUM METAL ANODES

The ultrahigh-energy-density lithium (Li) metallic anodes have garnered incremental interests for the fabrication of next-generation Li batteries, however, the safety concern and interior cycling stability originating from intrinsically dendritic Li plating, have highly hindered their scope of applications. Thus, in a work, 3-D architectural assembled form the mineral xonotlite ($\text{Ca}_6\text{Si}_6\text{O}_{17}(\text{OH})_2$) NWs (XNs) elevated high specific surface area, strongly electrolyte affinity and F-R features are fabricated for homogenizing the Li^+ flux while alleviating the dendrite-induced safety hazards [26]. This strategy offer insight into rational designing of highly safe long-cycling Li metal batteries [26].

18. FR OF CUNWS@GO NANOARCHITECTURES

In a work, surfacial functionalization of polydopamine (PDA), composites films constituting of graphene oxide (GO) and differing mass ratio (5, 15, 25, 35 wt. %) of copper nanowires (CuNWs) were fabricated via a solvent-induced assemblage technique. PDA inclusion not only minimized GO, CuNWs were additionally protected from oxidation [27]. 1-D CuNWs, as heat-bridge underwent inculcation within 2-D GO nanosheets to fabricate interconnected thermal conduction architecture. This architecture can offer an effectual heat conductive pathway. The CuNWs@GO-PDA film as a result of char forming capability of PDA, and GO architecture, demonstrated outstanding F-R. Micro combustion calorimeter tests reveal drastic minimization of 80.9% PHRR rate in comparison with pristine GO [27].

19. FR OF ARAMID NANOFIBERS/MXENE/SILVER NANOWIRES AEROGEL FIBER

Fire combative fabrics are critical equipments capable of offering safety personnel from all manner of

heat hazards while preventing burn induced injuries for firefighting personnel. Nevertheless, it remains challenging to construct elevated fire fighting clothing exhibiting automatic fire alarm responsivity prior protective clothing malfunctioning in extreme fire situations. Hence, in a work, a self-propelled wearable automatic fire warning e-textile (MAA e-textile) facilitated by $\text{Ti}_3\text{C}_2\text{Tx}$ MXene@silver nanowires (AgNWs)@aramid nanofibers (ANFs) aerogel fiber ($\text{Ti}_3\text{C}_2\text{Tx}$ MXene@AgNWs@ANFs), was constructed via wet spinning approach [28]. The garnered self-powered fire warning MAA e-textile was integrated within firefighting fabric to attain a vast temperature range sensing at 100–400 °C relying on a linear relationship between thermoelectric voltage as well as temperature because of thermoelectric feature of MXene, capable of alerting firefighters for timely evacuation prior damage of the protective clothing (Figure 17) [28].

20. FR OF GRAPHENE@SILVERNWS@PDMS NANOARCHITECTURES

The backfilling of polymeric matrices within preformed three-dimensional (3-D) conducting filler architecture is a herculean approach for the development of highly conductive polymeric composites (CPCs). Therefore, in a work, the selection of complementary graphene oxides (GOs), good water dispersibility ($\sim 15 \text{ mg/mL}$) and silver nanowires (AgNWs), outstanding conductivity ($\sim 106 \text{ S/cm}$) as fundamental blocks, highly conductive (12.1 S/cm) and robust 3-D reduced GOs (r-GOs)@AgNWs bi-continuous conductive skeletons (GACSSs) underwent successful construction via freezing of partially r-GOs@AgNWs hydrogel strategy capable of pore size increment, pore-wall thickness and homogeneity of GACSSs. The emergent PDMS@r-GOs@AgNWs composite (PGAC) possessing low filler inclusion of 0.76 wt.% demonstrated superior conductivity of 10.6 S/cm , absorption-dominated electromagnetic interference shielding efficiency (EMI SE, 34.1 dB) and high-level specific SE (SSE, total SE divided by filler loading and thickness) up to 22.43 dB/unit wt.%/mm (most common values of 0.66–12.5 dB/unit wt. %/mm). At same vein, PGACs demonstrated outstanding compression feature, thermal stability and F-R (Figure 18) [29].

21. SUPERIOR F-R POLYPHOSPHATE (MPP) NWS/POLY (ETHYLENE TEREPHTHALATE) (PET) NANOARCHITECTURES

A novel approach has been innovated for fabricating melamine polyphosphate (MPP) NWs to attain superior FR poly (ethylene-terephthalate) (PET), attributable to the well-constructed nanoarchitecture, which enabled the MPP nanowires demonstrate

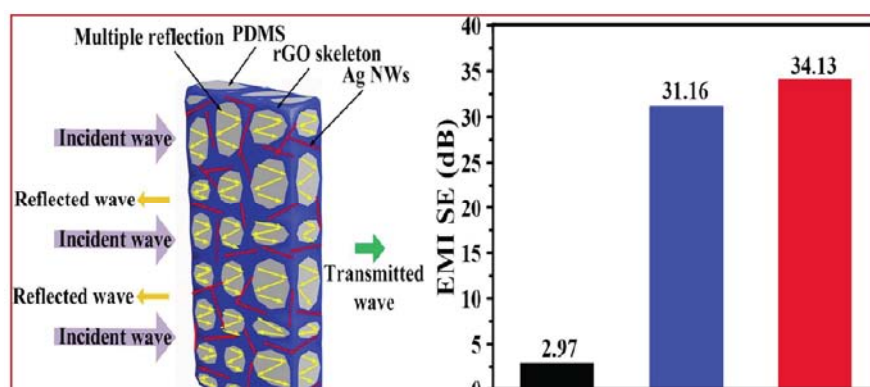


Figure 18: Features of PDMS@r-GOs@AgNWs composite (PGAC) [29].

elevated thermal stability and FR. Hence, with the inclusion of 1 wt. % MPP NWs (PET@FR1 nanoarchitecture), the LOI value sharply incremented to 29.4% from 20.5%, thereby demonstrating self-extinguishing disposition [30]. Furthermore, PET@FR1 nanoarchitecture passed V-0 UL-94 rating in the vertical combustion examination. Nevertheless, PET constituting of 5-wt. % commercial MPP powder (PET@FRC5.0) demonstrated a LOI of 27.9% and initiated the ignition of the absorbent cotton with fire prone melt-droplets. Results from cone tests also revealed that inclusion of 1-wt. % MPP nanowires minimized PET fire hazards, for instance, 11.1% and 7.7% optimal minimization in HRR and THR ascribed to the synergistic dilutional effect within the gaseous phase as well as the catalytic carbonization effect in condensed phase [30].

22. POTENTIAL APPLICATION PROSPECTS OF NANOWIRES@POLYMERIC NANOARCHITECTURES

Pristine polymeric matrices have often released elevated levels of toxic gases during combustion and

this poses a great hazard to human lives. Hence, the effectual minimization of toxic gases as well as smoke during the process of polymeric combustion is essentially critical to minimizing fire casualties during real time fire scenario. Thus, a large level of investigations have revealed that nanowire polymeric nanoarchitectures composed of various types of nanowires can repress the smoke released and enhancing flame retardancy during the polymeric nanoarchitectures combustion [32-35].

These have largely expanded their scope of applications in segments where fire safety, thermal stability and conductivity and so on are imperative such as the automobile, aerospace, construction, maritime, rail, electronics, and oil and gas industries and so on as depicted in Figure 19 [36-148].

23. CHALLENGES AND FUTURE PERSPECTIVES

Polymeric nanoarchitectures (PNC) fabricated using metallic NWs as reinforcement is being studied because of their improved fire retardant, optical, electromagnetic, electrical, mechanical and thermal

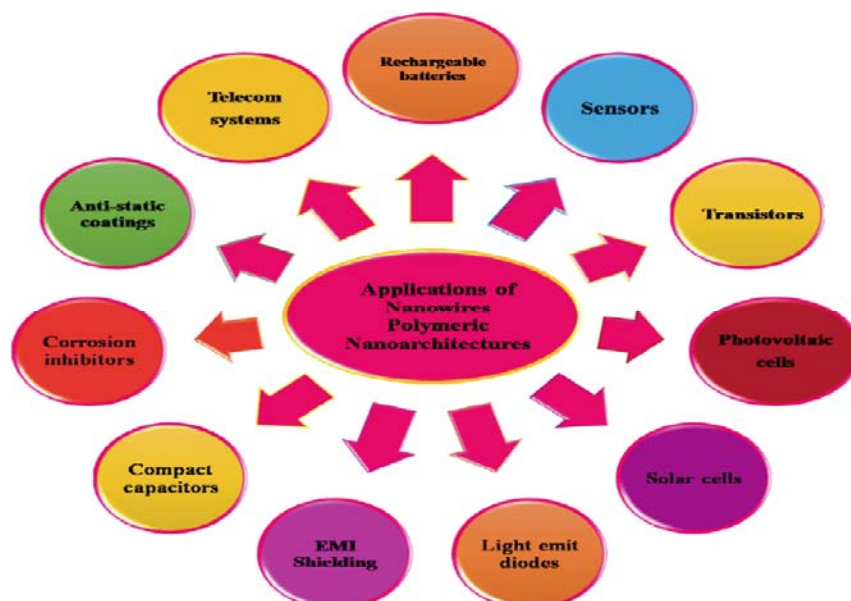


Figure 19: Prospective application segments of nanowires@polymeric nanoarchitectures.

features. As a result of high aspect-ratio of metallic NWs, the inclusion of miniature levels of NWs can sharply improve the physical features of polymeric matrices (electromagnetic shielding, conductivity, dielectric constant, thermal conductivity, and so on. Other essential physical features (transparency, stretchability, and flexibility), remained almost constant. This facilitates the development of novel materials with synergistic physical features for usage as transparent electrodes for solar cells, flexy electrodes for wearable electronics, along with elevated dielectric constant stretchable dielectrics for elevatedly sensitive pressure sensors. NWs nanoarchitectures are, also, printable with solution processability. The macroscopic physical features of metallic NW nanoarchitectures are function of the NWs dimension (diameter and length), concentration (in % weight of the composite) as well as their spatial distribution within polymeric matrices.

24. CONCLUSION

Fire hazards induced by thermal-shock and heat deterioration initiated by gradual thermal diffusion within microelectronic gadgets have made it critically imperative for these materials to display highly effective FR and thermal insulation for multifacet applications. Hence, the possession of elevated F-R and outstanding electromagnetic interference (EMI) shielding for PNC has become essential. Furthermore, the escalated use of heat conductive PNCs composed of nanowires in the aviation, automobile, maritime, oil and gas segments, and so on, has made F-R of nanowires@PNC highly imperative. In order to mitigate or completely eliminate inherent challenges prevalent in pristine polymeric materials attributable to their chemical composition, nanoparticulates including nanowires, nanoclays, carbon derivatives, and so on, have been incorporated within polymeric matrices to enhance their features especially FR [31-127]. Despite, the possession of properties such as low weight, outstanding flexibility and processability, the inherently poor flammability, as well as, elevated temperature deterioration pose challenges to most polymeric composites, and these flaws have restricted their scope of application in a versatile range of segments. Specifically, present investigation has revealed that the inclusion of various forms of nanowires within pristine polymeric materials has fabricated fire safety nanowire@PNC, thereby enlarging their scope of prospective applications for the future.

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AUTHORS CONTRIBUTION

A.C.E. wrote the manuscript, C.I. edited and revised the manuscript, W.K.K. and E.R.S. supervised and reviewed the manuscript.

CONFLICT OF INTEREST

No conflict is declared.

DATA AVAILABILITY

Data is available on request.

SUPPLEMENTARY INFORMATION

Not applicable.

ETHICAL APPROVAL

Not applicable.

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REFERENCES

- [1] Dong LY, Zhu YJ, Wu J. Wet End Chemical Properties of a New Kind of Fire-Resistant Paper Pulp Based on Ultralong Hydroxyapatite Nanowires. *Molecules* 2022; 27(20): 6808. <https://doi.org/10.3390/molecules27206808>
- [2] Sheng O, Jin C, Luo J, Yuan H, Huang H, Gan Y, *et al.* Mg₂B₂O₅ nanowire enabled multifunctional solid-state electrolytes with high ionic conductivity, excellent mechanical properties, and flame-retardant performance. *Nano letters* 2018; 18(5): 3104-3112. <https://doi.org/10.1021/acs.nanolett.8b00659>
- [3] Ma Y, Lou Y, Zhang H, Yang L, Yang D, Xu J, Ma H. Construction of transition metal aromatic-sulfide polyphosphazeneheterostructured nanowires for synergistic flame retardancy and smoke suppression. *Chemical Engineering Journal* 2023; 452: 139564. <https://doi.org/10.1016/j.cej.2022.139564>
- [4] Chen F, Zhu YJ. Large-Scale Automated Production of Highly Ordered Ultralong Hydroxyapatite Nanowires and Construction of Various Fire-Resistant Flexible Ordered Architectures. *ACS Nano* 2016; 10: 11483-11495. <https://doi.org/10.1021/acs.nano.6b07239>
- [5] Xie H, Li K, Nian J, Zheng J, Lai X, Wu W, *et al.* A flexible thermoelectric nanocoating with layered bridged heterostructure for sensitive thermosensation and high fire safety. *Composites Part A: Applied Science and Manufacturing* 2023; 166: 107385. <https://doi.org/10.1016/j.compositesa.2022.107385>
- [6] Li H, Zhu YJ, Jiang YY, Yu YD, Chen F, Dong LY, Wu J. Hierarchical Assembly of Monodisperse Hydroxyapatite Nanowires and Construction of High-Strength Fire-Resistant Inorganic Paper with High-Temperature Flexibility. *ChemNanoMat* 2017; 3: 259-268. <https://doi.org/10.1002/cnma.201700027>
- [7] Chen FF, Zhu YJ, Xiong ZC, Sun TW, Shen YQ, Yang RL. Inorganic Nanowires-Assembled Layered Paper as the Valve for Controlling Water Transportation. *ACS Appl. Mater. Interfaces* 2017; 3: 11045-11053. <https://doi.org/10.1021/acsami.7b01326>
- [8] Li H, Wu DB, Wu J, Dong LY, Zhu YJ, Hu XL. Flexible, High-Wettability and Fire-Resistant Separators Based on Hydroxyapatite Nanowires for Advanced Lithium-Ion Batteries. *Adv. Mater* 2017; 29: 1703548. <https://doi.org/10.1002/adma.201703548>

- [9] Gelves G, Al-Saleh M, Sundararaj U. Highly electrically conductive and high performance EMI shielding nanowire/polymer nanocomposites by miscible mixing and precipitation. *Journal of Materials Chemistry* 2011. <https://doi.org/10.1039/C0JM02546A>
- [10] Wang X, Hu W, Hu Y. Enhanced flame retardancy of poly (vinyl alcohol) with zinc oxide nanoparticles decorated boron nitride nanosheets. *Mater. Express* 2020; 10.
- [11] Chen F, Zhu Y, Chen F, Dong Y, Yang R, Xiong Z. Fire Alarm Wallpaper Based on Fire-Resistant Hydroxyapatite Nanowire Inorganic Paper and Graphene Oxide Thermosensitive Sensor. *ACS Nano* 2018; 12: 3159-3171. <https://doi.org/10.1021/acs.nano.8b00047>
- [12] Yang W, Ding H, Liu T, Ou R, Lin J, Puglia D, et al. Design of intrinsically flame-retardant vanillin-based epoxy resin for thermal-conductive epoxy/graphene aerogel composites. *ACS Applied Materials & Interfaces* 2021; 13(49): 59341-59351. <https://doi.org/10.1021/acsami.1c19727>
- [13] Shi HG, Zhao HB, Liu BW, Wang YZ. Multifunctional flame-retardant melamine-based hybrid foam for infrared stealth, thermal insulation, and electromagnetic interference shielding. *ACS Applied Materials & Interfaces* 2021; 13(22): 26505-26514. <https://doi.org/10.1021/acsami.1c07363>
- [14] Feng Y, Li X, Zhao X, Ye Y, Zhou X, Liu H, et al. Synergetic improvement in thermal conductivity and flame retardancy of epoxy/silver nanowires composites by incorporating "branch-like" flame-retardant functionalized graphene. *ACS applied materials & interfaces* 2018; 10(25): 21628-21641. <https://doi.org/10.1021/acsami.8b05221>
- [15] Wang ZY, Zhu YJ, Chen YQ, Yu HP, Xiong ZC. Flexible nanocomposite paper with superior fire retardance, mechanical properties and electrical insulation by engineering ultralong hydroxyapatite nanowires and aramid nanofibers. *Chemical Engineering Journal* 2022; 444: 136470. <https://doi.org/10.1016/j.cej.2022.136470>
- [16] Zhou Y, Qiu S, Ding L, Chu F, Liu W, Yang W, et al. Innovative design of environmentally friendly silicon-based polyphosphazene-functionalized hydroxyapatite nanowires: An efficient enhancement strategy for the fire safety and mechanical properties of unsaturated polyester. *Chemical Engineering Journal* 2022; 437: 135489. <https://doi.org/10.1016/j.cej.2022.135489>
- [17] Guo J, Liu G, Guo Y, Tian L, Bao X, Zhang X, et al. Enhanced flame retardancy and smoke suppression of polypropylene by incorporating zinc oxide nanowires. *Journal of Polymer Research* 2019; 26: 1-11. <https://doi.org/10.1007/s10965-018-1680-6>
- [18] Chen F, Zhang J, Li N, Zhang C, Ji B, Hu L, et al. Heat insulating, fire retardant and flexible inorganic nanocomposite paper. *Materials & Design* 2018; 144: 281-289. <https://doi.org/10.1016/j.matdes.2018.02.039>
- [19] Mao M, Yu KX, Cao CF, Gong LX, Zhang GD, Zhao L, et al. Facile and green fabrication of flame-retardant Ti3C2Tx MXene networks for ultrafast, reusable and weather-resistant fire warning. *Chemical Engineering Journal* 2022; 427: 131615. <https://doi.org/10.1016/j.cej.2021.131615>
- [20] Feng Y, Han G, Wang B, Zhou X, Ma J, Ye Y, et al. Multiple synergistic effects of graphene-based hybrid and hexagonal boron nitride in enhancing thermal conductivity and flame retardancy of epoxy. *Chemical Engineering Journal* 2020; 379: 122402. <https://doi.org/10.1016/j.cej.2019.122402>
- [21] Shi Y, Yao A, Han J, Wang H, Feng Y, Fu L, et al. Architecting fire safe hierarchical polymer nanocomposite films with excellent electromagnetic interference shielding via interface engineering. *Journal of Colloid and Interface Science* 2023; 640: 179-191. <https://doi.org/10.1016/j.jcis.2023.02.085>
- [22] Cheng L, Feng J. Flexible and fire-resistant all-inorganic composite film with high in-plane thermal conductivity. *Chemical Engineering Journal* 2020; 398: 125633. <https://doi.org/10.1016/j.cej.2020.125633>
- [23] Majumdar D. Role of MXenes/Polyaniline Nanocomposites in Fabricating Innovative Supercapacitor Technology. *Advanced Energy Conversion Materials* 2022: 30-53. <https://doi.org/10.37256/aecm.3120221148>
- [24] Zhang L, Huang Y, Dong H, Xu R, Jiang S. Flame-retardant shape memory polyurethane/MXene paper and the application for early fire alarm sensor. *Composites Part B: Engineering* 2021; 223: 109149. <https://doi.org/10.1016/j.compositesb.2021.109149>
- [25] Zhu L, Zhu P, Fang Q, Jing M, Shen X, Yang L. A novel solid PEO/LLTO-nanowires polymer composite electrolyte for solid-state lithium-ion battery. *Electrochimica Acta* 2018; 292: 718-726. <https://doi.org/10.1016/j.electacta.2018.10.005>
- [26] Liu Y, Wu Y, Zheng J, Wang Y, Ju Z, Lu G, et al. Silicious nanowires enabled dendrites suppression and flame retardancy for advanced lithium metal anodes. *Nano Energy* 2021; 82: 105723. <https://doi.org/10.1016/j.nanoen.2020.105723>
- [27] Nan B, Wu K, Liu Y, Xiao L, Chen W, Jiao E, et al. Nacre-inspired copper nanowires/graphene oxide films with excellent thermal conductivity, flame retardancy and electrical performance. *Journal of Materials Science: Materials in Electronics* 2019; 30: 19928-19939. <https://doi.org/10.1007/s10854-019-02359-w>
- [28] He H, Qin Y, Liu J, Wang Y, Wang J, Zhao Y, et al. A wearable self-powered fire warning e-textile enabled by aramid nanofibers/MXene/silver nanowires aerogel fiber for fire protection used in firefighting clothing. *Chemical Engineering Journal* 2023; 460: 141661. <https://doi.org/10.1016/j.cej.2023.141661>
- [29] Li Y, Li C, Zhao S, Cui J, Zhang G, Gao A, Yan Y. Facile fabrication of highly conductive and robust three-dimensional graphene/silver nanowires bicontinuous skeletons for electromagnetic interference shielding silicone rubber nanocomposites. *Composites Part A: Applied Science and Manufacturing* 2019; 119: 101-110. <https://doi.org/10.1016/j.compositesa.2019.01.025>
- [30] Li T, Li S, Ma T, Zhong Y, Zhang L, Xu H, et al. Flame-retardant poly (ethylene terephthalate) enabled by a novel melamine polyphosphate nanowire. *Polymers for Advanced Technologies* 2020; 31(4): 795-806. <https://doi.org/10.1002/pat.4815>
- [31] Idumah CI, Nwuzor IC, Odera SR, Timothy UJ, Ngenegbo UJ, Tanjung FA. A recent advances in polymeric hydrogel nanoarchitectures for drug delivery applications. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2024; 73(1): 1-32. <https://doi.org/10.1080/00914037.2022.2120875>
- [32] Idumah C. Recent Advancements in Polymer MXenes Nanoarchitectures and Applications. *Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology*, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024. <https://doi.org/10.1201/9780367694265-EPPMPT57-1>
- [33] Idumah C, Nwuzor I, Ezeani E, Nwogu N, Ugwu S, Okpechi V, Onyeoka H, Ibenta M, Odera S, Hassan A. Advancements in Biomolecules Immobilization on Natural Fiber Polymeric Nanobiocomposites for Biomedical Applications. *Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology*, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [34] Idumah C, Ezika A, Ezeani E, Obele C. Natural Plant Fiber Polymer Biocomposites and its Applications. *Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology*, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024. <https://doi.org/10.1201/9780367694265-EPPMPT64-1>
- [35] Idumah C, Nwuzor I, Ezika A, Nwogu N, Ugwu S, Okpechi U, Oyeoka H, Ibenta M, Odera S, Ukeme T. Poly (Lactic) Acid Hybrid Hybrid Bionanocomposites and Applications. *Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology*, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.

- [36] Idumah C. Recent Advancements in Flame Retardancy of Polymer Nanocomposites. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [37] Idumah C. Bioactive Glass Polymer Nanocomposite Architectures for Biomedical Applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [38] Idumah C. Recent Advancements in Polymer Aerogel Nanocomposite Architectures and Applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [39] Idumah C. Recent Advancements in Polymer MXenes Nanoarchitectures and Applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [40] Idumah C. Current Trends in Natural Fibers Polymer Biocomposites, Hybrid Nano-biocomposites and Applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [41] Idumah C. Recent advancements in polymeric magnetic nanocomposites and applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [42] Idumah C. Recently Emerging Trends in Additive Manufacturing of PLA Nanocomposites applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [43] Idumah C. Recently Emerging Trends in Additive Manufacturing of PLA Nano-composites applications. Routledge Resources Online: Polymers, Polymeric Materials, and Polymer Technology, Routledge, Encyclopedia of Polymers, Polymeric Materials, and Polymer Technology 2024.
- [44] Idumah CI. Phosphorene hybrid on energy storage applications. Journal of Energy Storage 2023; 69: 107940. <https://doi.org/10.1016/j.est.2023.107940>
- [45] Idumah CI, Odera RS, Ezeani EO, Low JH, Tanjung FA, Damiri F, Wong SL. Construction, characterization, properties and multifunctional applications of stimuli-responsive shape memory polymeric nanoarchitectures: a review. Polymer-Plastics Technology and Materials 2023; 62(10): 1247-1272. <https://doi.org/10.1080/25740881.2023.2204936>
- [46] Idumah CI. Design, fabrication, characterization and properties of metallic and conductive smart polymeric textiles for multifunctional applications. Nano-Structures & Nano-Objects 2023; 35: 100982. <https://doi.org/10.1016/j.nanoso.2023.100982>
- [47] Idumah CI. Thermal expansivity of polymer nanocomposites and applications. Polymer-Plastics Technology and Materials 2023; 62(9): 1178-1203. <https://doi.org/10.1080/25740881.2023.2204952>
- [48] Idumah CI. Borophene hybrid nanoarchitecture and applications: A review. Polymer-Plastics Technology and Materials 2023; 62(12): 1560-1575. <https://doi.org/10.1080/25740881.2023.2222798>
- [49] Idumah CI, Obumneme EE. Novel trends in phosphorene and phosphorene@ polymeric nanoarchitectures and applications. Emergent Materials 2023; 1-22. <https://doi.org/10.1007/s42247-023-00507-x>
- [50] Idumah CI. Novel advancements in xerogel polymeric nanoarchitectures and multifunctional applications. Journal of Porous Materials 2023; 1-19. <https://doi.org/10.1007/s10934-023-01446-y>
- [51] Idumah CI. Design, development, and drug delivery applications of graphene polymeric nanocomposites and bionanocomposites. Emergent Materials 2023; 1-31. <https://doi.org/10.1007/s42247-024-00933-5>
- [52] Ng QY, Low JH, Pang MM, Idumah CI. Properties enhancement of waterborne polyurethane bio-composite films with 3-aminopropyltriethoxy silane functionalized lignin. Journal of Polymers and the Environment 2023; 31(2): 688-697. <https://doi.org/10.1007/s10924-022-02595-y>
- [53] Idumah CI. Recently Emerging Trends in Flame Retardancy of Phosphorene Polymeric Nanocomposites and Applications. Journal of Analytical and Applied Pyrolysis 2023; 105855. <https://doi.org/10.1016/j.jaap.2022.105855>
- [54] Idumah CI. Recent advancements in electromagnetic interference shielding of polymer and MXene nanocomposites. Polymer-Plastics Technology and Materials 2023; 62(1): 19-53. <https://doi.org/10.1080/25740881.2022.2089581>
- [55] Idumah CI, Ezeani O, Okonkwo UC, Nwuzor IC, Odera SR. Novel trends in MXene/conducting polymeric hybrid nanoclusters. Journal of Cluster Science 2023; 34(1): 45-76. <https://doi.org/10.1007/s10876-022-02243-4>
- [56] Idumah CI. Phosphorene polymeric nanocomposites for biomedical applications: a review. International Journal of Polymeric Materials and Polymeric Biomaterials 2022; 1-18. <https://doi.org/10.1080/00914037.2022.2158333>
- [57] Idumah CI. Emerging advancements in xerogel polymeric bionanoarchitectures and applications. JCIS Open 2022; 100073. <https://doi.org/10.1016/j.jciso.2022.100073>
- [58] Idumah CI. Novel advancements in xerogel polymeric nanoarchitectures and multifunctional applications. Journal of Porous Materials 2023; 1-19. <https://doi.org/10.1007/s10934-023-01446-y>
- [59] Idumah CI. Design, development, and drug delivery applications of graphene polymeric nanocomposites and bionanocomposites. Emergent Materials 2023; 1-31. <https://doi.org/10.1007/s42247-024-00933-5>
- [60] Ng Q, Low JH, Pang MM, Idumah CI. Properties enhancement of waterborne polyurethane bio-composite films with 3-aminopropyltriethoxy silane functionalized lignin. Journal of Polymers and the Environment 2023; 31(2): 688-697. <https://doi.org/10.1007/s10924-022-02595-y>
- [61] Idumah CI. Recently Emerging Trends in Flame Retardancy of Phosphorene Polymeric Nanocomposites and Applications. Journal of Analytical and Applied Pyrolysis 2023; 105855. <https://doi.org/10.1016/j.jaap.2022.105855>
- [62] Idumah CI. Recent advancements in electromagnetic interference shielding of polymer and MXene nanocomposites. Polymer-Plastics Technology and Materials 2023; 62(1): 19-53. <https://doi.org/10.1080/25740881.2022.2089581>
- [63] Idumah CI, Ezeani O, Okonkwo UC, Nwuzor IC, Odera SR. Novel trends in MXene/conducting polymeric hybrid nanoclusters. Journal of Cluster Science 2023; 34(1): 45-76. <https://doi.org/10.1007/s10876-022-02243-4>
- [64] Idumah CI. Phosphorene polymeric nanocomposites for biomedical applications: a review. International Journal of Polymeric Materials and Polymeric Biomaterials 2022; 1-18. <https://doi.org/10.1080/00914037.2022.2158333>
- [65] Idumah CI. Emerging advancements in xerogel polymeric bionanoarchitectures and applications.
- [66] Idumah CI, Low JH, Emmanuel EO. Recently emerging trends in xerogel polymeric nanoarchitectures and multifunctional applications. Polymer Bulletin 2022; 1-31. <https://doi.org/10.1007/s00289-022-04625-0>
- [67] Idumah CI. Emerging advancements in flame retardancy of polypropylene nanocomposites. Journal of Thermoplastic Composite Materials 2022; 35(12): 2665-2704. <https://doi.org/10.1177/0892705720930782>

- [68] Idumah CI. Recent advances on graphene polymeric bionanoarchitectures for biomedical. *JCIS Open* 2022; 100070.
<https://doi.org/10.1016/j.jciso.2022.100070>
- [69] Idumah CI. A review on polyaniline and graphene nanocomposites for supercapacitors. *Polymer-Plastics Technology and Materials* 2021; 61(17): 1871-1907.
<https://doi.org/10.1080/25740881.2022.2086810>
- [70] Idumah CI, Ezika AC. Recent advancements in hybridized polymer nano-biocomposites for tissue engineering. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2022; 71.
<https://doi.org/10.1080/00914037.2021.1960344>
- [71] Idumah CI. Recently emerging advancements in polymeric nanogel nanoarchitectures for drug delivery applications. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2022; 1-13.
<https://doi.org/10.1080/00914037.2022.2120875>
- [72] Idumah CI. Recently emerging advancements in thermal conductivity and flame retardancy of MXene polymeric nanoarchitectures. *Polymer-Plastics Technology and Materials* 2022; 1-37.
<https://doi.org/10.1080/25740881.2022.2121220>
- [73] Idumah CI, Ezika AC, Enwerem UE. A review on biomolecular immobilization of polymeric textile biocomposites, bionanocomposites, and nano-biocomposites. *The Journal of The Textile Institute* 2022; 113(9): 2016-2032.
<https://doi.org/10.1080/00405000.2021.1957277>
- [74] Idumah CI. MXene polymeric nanoarchitectures mechanical, deformation, and failure mechanism: a review. *Polymer-Plastics Technology and Materials* 2022; 1-24.
<https://doi.org/10.1080/25740881.2022.2114365>
- [75] Idumah CI. On MXene Conducting Polymer Nanocomposites Micro-Supercapacitors and Applications 2022.
<https://doi.org/10.21203/rs.3.rs-1871184/v1>
- [76] Idumah CI. Influence of morphology and architecture on properties and applications of MXene polymeric nanocomposites. *Journal of Thermoplastic Composite Materials* 2022; 08927057221122096.
<https://doi.org/10.1177/08927057221122096>
- [77] Idumah CI. Characterization and Fabrication of Xerogel Polymeric Nanocomposites and Multifunctional Applications 2022.
<https://doi.org/10.21203/rs.3.rs-1961392/v1>
- [78] Okonkwo UC, Idumah CI, Okafor CE, Ohagwu CC, Aronu ME. Development, characterization, and properties of polymeric nanoarchitectures for radiation attenuation. *Journal of Inorganic and Organometallic Polymers and Materials* 2022; 1-21.
<https://doi.org/10.1007/s10904-022-02420-y>
- [79] Idumah CI. Influence of surfaces and interfaces on MXene and MXene hybrid polymeric nanoarchitectures, properties, and applications. *Journal of Materials Science* 2022; 57(31): 14579-14619.
<https://doi.org/10.1007/s10853-022-07526-9>
- [80] Idumah CI. Recently emerging advancements in polymeric cryogel nanostructures and biomedical applications. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2022; 1-21.
<https://doi.org/10.1080/00914037.2022.2097678>
- [81] Idumah CI. Recently emerging advancements in MXene polysaccharide bionanoarchitectures and biomedical applications. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2022; 1-22.
<https://doi.org/10.1080/00914037.2022.2098297>
- [82] Idumah CI. Recently emerging trends in magnetic polymer hydrogel nanoarchitectures. *Polymer-Plastics Technology and Materials* 2022; 61(10): 1039-1070.
<https://doi.org/10.1080/25740881.2022.2033769>
- [83] Idumah CI. Emerging trends in poly (lactic-co-glycolic) acid bionanoarchitectures and applications. *Cleaner Materials* 2022; 100102.
<https://doi.org/10.1016/j.clema.2022.100102>
- [84] Idumah CI. Recent trends in MXene polymeric hydrogel bionanoarchitectures and applications. *Cleaner Materials* 2022; 100103.
<https://doi.org/10.1016/j.clema.2022.100103>
- [85] Okonkwo UC, Ohagwu C, Aronu ME, Okafor CE, Idumah CI. Ionizing radiation protection and the linear No-threshold controversy: Extent of support or counter to the prevailing paradigm. *Journal of Environmental Radioactivity* 2022; 253: 106984.
<https://doi.org/10.1016/j.jenvrad.2022.106984>
- [86] Ezika AC, Sadiku ER, Idumah CI, Ray SS, Adekoya GJ, Odera RS. Recently emerging trends in MXene hybrid conductive polymer energy storage nanoarchitectures. *Polymer-Plastics Technology and Materials* 2022; 61(8): 861-887.
<https://doi.org/10.1080/25740881.2022.2029888>
- [87] Idumah CI. Recent advancements in conducting polymer bionanocomposites and hydrogels for biomedical applications. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2022; 71.
<https://doi.org/10.1080/00914037.2021.1960344>
- [88] Idumah CI, Okonkwo UC, Obele CM. Recently emerging advancements in montmorillonite polymeric nanoarchitectures and applications. *Cleaner Materials* 2022; 100071.
<https://doi.org/10.1016/j.clema.2022.100071>
- [89] Tanjung FA, Kuswardani RA, Idumah CI, Siregar JP, Karim A. Characterization of mechanical and thermal properties of esterified lignin modified polypropylene composites filled with chitosan fibers. *Polymers and Polymer Composites* 2022; 30: 09673911221082482.
<https://doi.org/10.1177/09673911221082482>
- [90] Ezika AC, Sadiku ER, Idumah CI, Ray SS, Hamam Y. On energy storage capacity of conductive MXene hybrid nanoarchitectures. *Journal of Energy Storage* 2022; 45: 103686.
<https://doi.org/10.1016/j.est.2021.103686>
- [91] Idumah CI, Nwabanne JT, Tanjung FA. Novel trends in poly (lactic) acid hybrid bionanocomposites. *Cleaner Materials* 2021; 2: 100022.
<https://doi.org/10.1016/j.clema.2021.100022>
- [92] Idumah CI. Influence of nanotechnology in polymeric textiles, applications, and fight against COVID-19. *The Journal of the Textile Institute* 2021; 112(12): 2056-2076.
<https://doi.org/10.1080/00405000.2020.1858600>
- [93] Idumah CI, Ezeani EO, Ezika AC, Timothy UJ. Recent advancements in flame retardancy of MXene polymer nanoarchitectures. *Safety in Extreme Environments* 2021; 3(3): 253-273.
<https://doi.org/10.1007/s42797-021-00046-w>
- [94] Idumah CI. Novel trends in polymer aerogel nanocomposites. *Polymer-Plastics Technology and Materials* 2021; 60(14): 1519-1531.
<https://doi.org/10.1080/25740881.2021.1912092>
- [95] Idumah CI, Nwuzor I, Odera SR. Recent advancements in self-healing polymeric hydrogels, shape memory, and stretchable materials. *International Journal of Polymeric Materials and Polymeric Biomaterials* 2021; 70.
<https://doi.org/10.1080/00914037.2020.1767615>
- [96] Idumah CI, Ezika AC, Okpechi VU. Emerging trends in polymer aerogel nanoarchitectures, surfaces, interfaces and applications. *Surfaces and Interfaces* 2021; 25: 101258.
<https://doi.org/10.1016/j.surfin.2021.101258>
- [97] Idumah CI. Progress in polymer nanocomposites for bone regeneration and engineering. *Polymers and Polymer Composites* 2021; 29(5): 509-527.
<https://doi.org/10.1177/0967391120913658>
- [98] Idumah CI. Novel trends in self-healable polymer nanocomposites. *Journal of Thermoplastic Composite Materials* 2021; 34(6): 834-858.
<https://doi.org/10.1177/0892705719847247>
- [99] Idumah CI. Novel trends in magnetic polymeric nanoarchitectures. *Polymer-Plastics Technology and Materials* 2021; 60(8): 830-848.
<https://doi.org/10.1080/25740881.2020.1869780>

- [100] Idumah CI, Ezeani EO, Nwuzor IC. A review on advancements in conductive polymers nanocomposites. *Polymer-Plastics Technology and Materials* 2021; 60(7): 756-783. <https://doi.org/10.1080/25740881.2020.1850783>
- [101] Idumah CI. Recent advancements in self-healing polymers, polymer blends, and nanocomposites. *Polymers and Polymer Composites* 2021; 29(4): 246-258. <https://doi.org/10.1177/0967391120910882>
- [102] Nwuzor IC, Idumah CI, Nwanonenyi SC, Ezeani OE. Emerging trends in self-polishing anti-fouling coatings for marine environment. *Safety in Extreme Environments* 2021; 3: 9-25. <https://doi.org/10.1007/s42797-021-00031-3>
- [103] Idumah CI. Novel trends in conductive polymeric nanocomposites, and bionanocomposites. *Synthetic Metals* 2021; 273: 116674. <https://doi.org/10.1016/j.synthmet.2020.116674>
- [104] Idumah CI, Obele CM. Understanding interfacial influence on properties of polymer nanocomposites. *Surfaces and Interfaces* 2021; 22: 100879. <https://doi.org/10.1016/j.surfin.2020.100879>
- [105] Idumah CI. Novel advancements in green and sustainable polymeric nanocomposites coatings. *Current Research in Green and Sustainable Chemistry* 2021; 4: 100173. <https://doi.org/10.1016/j.crgsc.2021.100173>
- [106] Idumah CI, Nwuzor IC, Odera RS. Recent advances in polymer hydrogel nanoarchitectures and applications. *Current Research in Green and Sustainable Chemistry* 2021; 4: 100143. <https://doi.org/10.1016/j.crgsc.2021.100143>
- [107] Idumah CI, Nwuzor IC, Odera RS. Recent advances in polymer hydrogel nanoarchitectures and applications. *Current Research in Green and Sustainable Chemistry* 2021. <https://doi.org/10.1016/j.crgsc.2021.100143>
- [108] Idumah CI, Obele CM, Enwerem UE. On interfacial and surface behavior of polymeric MXenes nanoarchitectures and applications. *Current Research in Green and Sustainable Chemistry* 2021; 4: 100104. <https://doi.org/10.1016/j.crgsc.2021.100104>
- [109] Idumah CI. Recent advancements in thermolysis of plastic solid wastes to liquid fuel. *Journal of Thermal Analysis and Calorimetry* 2021; 1-14. <https://doi.org/10.1007/s10973-021-10776-5>
- [110] Idumah CI, Obele CM, Ezeani EO, Hassan A. Recently Emerging Nanotechnological Advancements in Polymer Nanocomposite Coatings for Anti-corrosion, Anti-fouling and Self-healing. *Surfaces and Interfaces* 2020. <https://doi.org/10.1016/j.surfin.2020.100734>
- [111] Idumah CI, Obele CM, Ezeani EO. Understanding interfacial dispersions in ecobonign polymer nano-biocomposites. *Journal Polymer-Plastics Technology and Materials* 2020. <https://doi.org/10.1080/25740881.2020.1811312>
- [112] Idumah CI, Odera SR. Recent advancement in self-healing graphene polymer nanocomposites, shape memory, and coating materials. *Polymer-Plastics Technology and Materials* 2020; 59(11): 1167-1190. <https://doi.org/10.1080/25740881.2020.1725816>
- [113] Idumah CI, Hassan A, Ogbu JE, Ndem JU, Oti W, Obiana V. Electrical, thermal and flammability properties of conductive filler kenaf-reinforced polymer nanocomposites. *Journal of Thermoplastic Composite Materials* 2020; 33(4): 516-540. <https://doi.org/10.1177/0892705718807957>
- [114] Idumah CI, Zurina M, Ogbu J, Ndem JU, Igba EC. A review on innovations in polymeric nanocomposite packaging materials and electrical sensors for food and agriculture. *Composite Interfaces* 2020; 27(1): 1-72. <https://doi.org/10.1080/09276440.2019.1600972>
- [115] Idumah CI, Nwuzor IC. Novel trends in plastic waste management. *SN Applied Sciences* 2019; 1: 1-14. <https://doi.org/10.1007/s42452-019-1468-2>
- [116] Idumah CI, Ogbu JE, Ndem JU, Obiana V. Influence of chemical modification of kenaf fiber on xGNP-PP nano-biocomposites. *SN Applied Sciences* 2019; 1: 1-11. <https://doi.org/10.1007/s42452-019-1319-1>
- [117] Idumah CI, Hassan A, Ogbu J, Ndem JU, Nwuzor IC. Recently emerging advancements in halloysite nanotubes polymer nanocomposites. *Composite Interfaces* 2019; 26(9): 751-824. <https://doi.org/10.1080/09276440.2018.1534475>
- [118] Idumah CI, Hassan A, Ihuoma DE. Recently emerging trends in polymer nanocomposites packaging materials. *Polymer-Plastics Technology and Materials* 2019; 58(10): 1054-1109. <https://doi.org/10.1080/03602559.2018.1542718>
- [119] Idumah CI, Zurina M, Hassan A, Orhayani O, Shuhadah I. Recently emerging trends in bone replacement polymer nanocomposites. *Nanostructured Polymer Composites for Biomedical Applications* 2019; 139-166. <https://doi.org/10.1016/B978-0-12-816771-7.00008-9>
- [120] Akubue BN, Idumah CI, David E. Challenges of Teaching and Learning Clothing and Textiles for Entrepreneurship: Case Study of Ebonyi State University, Abakaliki. *JHER* 2018; 25(2).
- [121] Idumah CI, Hassan A, Bourbigot S. Synergistic effect of exfoliated graphene nanoplatelets and non-halogen flame retardants on flame retardancy and thermal properties of kenaf flour-PP nanocomposites. *Journal of Thermal Analysis and Calorimetry* 2018; 134: 1681-1703. <https://doi.org/10.1007/s10973-018-7833-3>
- [122] Idumah CI, Hassan A. Hibiscus cannabinus fiber/PP based nano-biocomposites reinforced with graphene nanoplatelets. *Journal of natural fibers* 2017; 14(5): 691-706. <https://doi.org/10.1080/15440478.2016.1277817>
- [123] Idumah CI, Hassan A, Bourbigot S. Influence of exfoliated graphene nanoplatelets on flame retardancy of kenaf flour polypropylene hybrid nanocomposites. *Journal of Analytical and Applied Pyrolysis* 2017; 123: 65-72. <https://doi.org/10.1016/j.jaap.2017.01.006>
- [124] Idumah CI, Hassan A. Effect of exfoliated graphite nanoplatelets on thermal and heat deflection properties of kenaf polypropylene hybrid nanocomposites. *Journal of Polymer Engineering* 2016; 36(9): 877-889. <https://doi.org/10.1515/polyeng-2015-0445>
- [125] Idumah CI, Hassan A. Recently emerging trends in thermal conductivity of polymer nanocomposites. *Reviews in Chemical Engineering* 2016; 32(4): 413-457. <https://doi.org/10.1515/revce-2016-0004>
- [126] Idumah CI. Emerging trends in eco-compliant, synergistic, and hybrid assembling of multifunctional polymeric bionanocomposites. *Reviews in Chemical Engineering* 2016; 32(3): 305-361. <https://doi.org/10.1515/revce-2015-0046>
- [127] Idumah CI, Hassan A. Emerging trends in graphene carbon based polymer nanocomposites and applications. *Reviews in Chemical Engineering* 2016; 32(2): 223-264. <https://doi.org/10.1515/revce-2015-0038>
- [128] Idumah CI, Hassan A. Characterization and preparation of conductive exfoliated graphene nanoplatelets kenaf fibre hybrid polypropylene composites. *Synthetic Metals* 2016; 212: 91-104. <https://doi.org/10.1016/j.synthmet.2015.12.011>
- [129] Idumah CI, Hassan A. Emerging trends in flame retardancy of biofibers, biopolymers, biocomposites, and bionanocomposites. *Reviews in Chemical Engineering* 2016; 2(1): 115-148. <https://doi.org/10.1515/revce-2015-0017>
- [130] Idumah CI, Hassan A, Affam AC. A review of recent developments in flammability of polymer nanocomposites. *Reviews in Chemical Engineering* 2015; 31(2): 149-177. <https://doi.org/10.1515/revce-2014-0038>
- [131] Idumah CI. Comparative Evaluation of the Effects of Time of Heat Setting and Wet Processing on Shearing Properties of Knitted Ingeo™ Poly (Lactic Acid) (PLA) and Polyethyleneterephthalate. *American Journal of Materials Engineering and Technology* 2014; 2(1): 1-6.
- [132] Idumah CI, Nwachukwu A. Comparative analysis of the effect of heatsetting and wet processing on the tensile properties of Poly Lactic Acid (PLA) and Poly Ethylene

- Terephthalate (PET) knitted fabrics. *International Journal of Materials, Methods and Technologies* 2013; 1(4): 45-64.
- [133] Idumah CI, Nwachukwu AN. Effects of time of heatsetting on the tensile properties of ingeo™ poly (lactic acid) (PLA) fabric. *Journal homepage: www. IJEE. IEE Foundation org* 2013; 4(5): 797-806.
- [134] Idumah CI. Effects of Time of Heat Setting and Wet Processes on Tensile properties of Griego Knitted Ingeo™ Poly Lactic Acid (PLA) Fabric. *J Textile Sci Eng* 2013; 3:137.
- [135] Idumah CI. Comparative Analysis of the Effects of Time of Heat Setting and Wet Processing on Tensile Properties of Treated and Untreated Knitted PLA Fabric. *American Journal of Materials Science and Engineering* 2013; 1(3): 40-45.
- [136] Idumah CI. A Study of the Effects of Time of Heat Setting and Wet Processing on Shearing (Gf/Cm) Properties of Treated and Untreated Griego Knitted Ingeo™ Poly (Lactic Acid) (Pla) and *J Textile Sci Eng* 4:148.
- [137] Idumah CI, Nwachukwu AN. Effects of time of heat setting on the tensile properties of ingeo poly (lactic acid) (PLA) fabric. *Int. J. Energy Environ.* 2013; 4: 797-806. <https://doi.org/10.4172/2165-8064.1000137>
- [138] Okonkwo CU, Idumah CI, Okafor CE, Ezeani EO. Construction of radiation attenuating polymer nanocomposites and multifacet applications: A Review. *Polymer-Plastics Technology and Materials* 2023. <https://doi.org/10.1080/25740881.2023.2227251>
- [139] Idumah CI, Iwuchukwu FU, Okoye I, Ogbu JE. Construction, Characterization, Properties and Electromagnetic Interference Applications of MXene Polymeric nanoarchitectures. *Polymer-Plastics Technology and Materials* 2023. <https://doi.org/10.1080/25740881.2023.2267097>
- [140] Idumah CI, Iwuchukwu FU, Okoye I, Ogbu JE. Flame Retardant mechanisms of Metal organic Frameworks (MOFs) Polymeric nanoarchitectures. *Polymer-Plastics Technology and Materials* 2023; 1-27. <https://doi.org/10.1080/25740881.2023.2280600>
- [141] Idumah CI, Iwuchukwu FU, Okoye I, Ogbu JE. Construction, Characterization, Properties and Electromagnetic Interference Applications of MXene Polymeric nanoarchitectures. *Polymer-Plastics Technology and Materials* 2023; 1-22. <https://doi.org/10.1080/25740881.2023.2267097>
- [142] Idumah CI, Iwuchukwu FU, Ogbu JE. Progress in multifunctional properties of phosphorene polymeric nanocomposites: a review. *Inorganic Chemistry Communications* 2023; 111640. <https://doi.org/10.1016/j.inoche.2023.111640>
- [143] Idumah CI. Halloysite nanotubes assisted design of polymeric nanoarchitectures for multifarious applications: a review. *Polymer-Plastics Technology and Materials* 2023; 62(15): 2043-2062. <https://doi.org/10.1080/25740881.2023.2251562>
- [144] Shi Y, Wang Z, Liu C, Wang H, Guo J, Fu L, Feng Y, Liu M. Engineering titanium carbide ultra-thin nanosheets for enhanced fire safety of intumescent flame retardant polylactic acid. *Composites Part B: Engineering* 2022; 236: 109792. <https://doi.org/10.1016/j.compositesb.2022.109792>
- [145] Chen K, Liu M, Shi Y, Wang H, Fu L, Feng Y, Song P. Multi-hierarchical flexible composites towards superior fire safety and electromagnetic interference shielding. *Nano Research* 2022; 15(10): 9531-9543. <https://doi.org/10.1007/s12274-022-4883-6>
- [146] Liu L, Feng J, Xue Y, Chevali V, Zhang Y, Shi Y, Tang LC, Song P. 2D MXenes for fire retardancy and fire-warning applications: promises and prospects. *Advanced Functional Materials* 2023; 33(9): 2212124. <https://doi.org/10.1002/adfm.202212124>
- [147] Wang H, Chen K, Shi Y, Zhu Y, Jiang S, Liu Y, Wu S, et al. Flame retardant and multifunctional BC/MXene/MSiCnw/FRTPU aerogel composites with superior electromagnetic interference shielding via "Consolidating" method. *Chemical Engineering Journal* 2023; 474: 145904. <https://doi.org/10.1016/j.cej.2023.145904>
- [148] Liu M, Chen K, Shi Y, Wang H, Wu S, Huang R, Feng Y, Tang L, Liu X, Song P. High-performance flexible nanocomposites with superior fire safety and ultra-efficient electromagnetic interference shielding. *Journal of Materials Science & Technology* 2023. <https://doi.org/10.1016/j.jmst.2023.05.017>

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