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CARBON NANO-ONIONS AND RELATED MULTIFUNCTIONAL HYBRIDS—RADIATION SHIELDING, TRIBOLOGICAL AND ANTICORROSION POTENTIALS

ABSTRACT

Over recent decades, carbon nano-onions and related nanomaterials have attained considerable research interests for wide ranging industrial purposes. In view of that, current review article is developed to highpoint three significant engineering characteristics (including radiation defense, friction/wear resistance, and corrosion resistance) of carbon nano-onions and derived multifunctional polymeric and inorganic hybrids. In all these scientifically and industrially promising fields, carbon nano-onion nanoadditives have enhanced the radiation absorption, tribological, and anticorrosion performance of the polymeric and inorganic matrices. Consequently, carbon nano-onions derived nanocomposites have fine interfacial links and percolation networks; thereby leading to efficient electron transfer and electromagnetic absorption or dissipation properties. In the case of antiscratch, antiwear, and antifriction performance, carbon nano-onions have been noted to act as microbearing between the desired metal surfaces. Furthermore, owing to the development of matrix-nanofiller interactions and electron conducting paths, carbon nano-onions and derivative multifunctional hybrids offer notable barrier effects towards the percolating corrosion species. Decisively, carbon nano-onions, modified carbon nano-onions, and derived hybrids depicted technological promise to enhance the electromagnetic, wear, and erosion resistance of space, automotive, defense, civil, medical, and other advanced structural materials. Nevertheless, limited research exertions seen up till now regarding carbon nano-onions nanocomposites in these technical areas and comprehensive future investigations may unfold their industrial potential.

Keywords: *Carbon nano-onions; hybrids; radiation shielding; tribology; antiwear; anticorrosion*

INTRODUCTION

Among carbonaceous nanoparticles, carbon nano-onions (zero dimensional tiny spherical nanoentities) have been distinctively studied for remarkable structural and physical characteristics, including electron transfer, thermo-oxidative, barrier, microbearing, and other advanced physical properties [1]. Consequently, carbon nano-onions and related nanomaterials have revealed enormous worth for radiation shielding, tribological, and corrosion protection applications [2-4]. Particularly, microstructural, magnetic, electrical conductivity features of carbon nano-onions and hybrids resulted in promising electromagnetic wave shielding competence [5, 6]. Moreover, owing to intrinsic nano- or microbearing properties of carbon nano-onions, the resulting multifunctional hybrids have been investigated for outstanding tribological potential [7]. Consequently, applying carbon nano-onions hybrids between sliding surfaces was noted to reduce the coefficient of friction, and so enhancing their antiwear attributes [8]. In terms of corrosion defiance, multifunctional carbon nano-onion based hybrids have been designed with superior electrical conductivity,

percolation, and barrier characters for corrosive ions, molecules, species [9-11]. In this concern, combination of carbon nano-onions with semiconducting matrices (like conductive polymers) have been effectively researched for corrosion protective coatings [12, 13].

In the light of present research surveys and few past reports, this state-of-the-art review discloses technical value of carbon nano-onions and multifunctional hybrids for radiation defensive, friction resistant, and corrosion resistance deployments. To the best of the literature to date, no wide-ranging review manuscript is reported so far covering significant characteristics (radiation shielding, tribology, anticorrosion) of carbon nano-onions based nanomaterials, at one place. Literature deficiency was also observed in terms of theoretical investigations and challenges of multifunctional carbon nano-onions hybrids towards microwave absorption, antifriction, and corrosion resisting potential. The real motivation behind current review centers on transitioning these nanocomposites from traditional design curiosities to functional and scalable materials for high performance engineering applications. To make this review novel and all-inclusive in every aspect, notable relevant recent research reports up to 2026 have been covered. Moreover, all literature is debated in view of research trends in fundamentals, design, and features, as well as foremost field challenges and future prospects. Henceforward, progresses in all the applied zones of carbon nano-onions and related nanomaterials strongly rely on comprehensive future experimental and theoretical research efforts of field scientists for overcoming the underlying field challenges.

CARBON NANO-ONIONS

Onion like concentric graphitic nanostructures were initially noticed by Ugarte et. al. [14]. In addition, onion like carbon nanostructures were also recognized in combustion soot produced in detonation synthesis method for nanocarbons [15]. These multilayered hollow zero dimensional nano-entities were first formed by using electron irradiation approach and had high surface/volume ratio [16]. Later, symmetrical tiny onion like carbon nanostructures (nanosizes ~ 5 -10 nm) were named as carbon nano-onions in the literature [17, 18]. Nevertheless, multilayered carbon nano-onions may have sizes of around 100 nm in diameters [19]. The overlapping multilayered concentric shells of carbon nano-onions own van der Waals forces and interdistances of ~ 0.34 nm between them [20]. Remarkable features of these carbon nanoentities can be listed as catalytic, electron/charge transfer, florescence, mechanical, thermal, dielectric, magnetic, tribological, electrochemical, chemical, and biological, to name a few [21, 22].

Since discovery, countless facile and competent synthesis methods (ion implantation, electron beam irradiation, arc discharge, plasma, chemical vapor deposition, combustion/pyrolysis, annealing, detonation, and others.) have been developed to date for carbon nano-onions [23, 24]. Herein, choice of synthesis technique, precursor, conditions, parameters, and efficiency define the quality and yield of resulting nanocarbon product [25]. Suitably, Fig. 1 shows some commonly practiced manufacturing processes and applications of carbon nano-onions.

After synthesis, advanced methods have also been applied for doping or surface modification of carbon nano-onions [26]. Consequently, applied zones of carbon nano-onions and functional carbon nano-onions have been noticed for energy production devices (photovoltaics, fuel cells) [27, 28], energy storage devices (capacitors, batteries) [29, 30], electronics (sensors, wearable smart sensors) [31], catalysis [32], engineering space/defense/civil structures [33], and medical (drug delivery, tissue scaffolds, biosensors) [34], and a lot more.

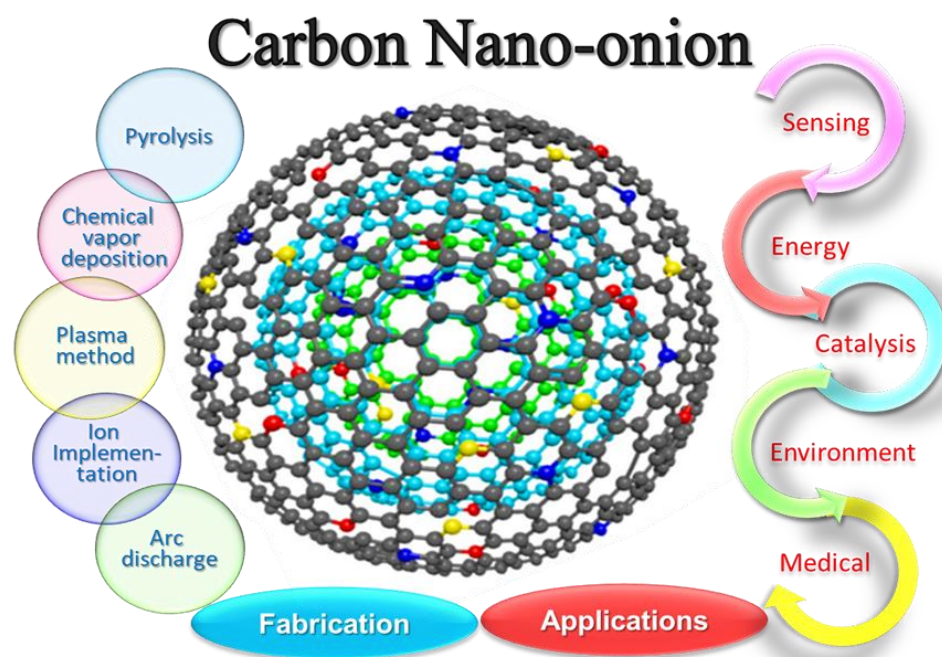


Fig. 1. Fabrication methods and applications of carbon nano-onions

MULTIFUNCTIONAL CARBON NANO-ONION HYBRIDS FOR RADIATION SHIELDING

To cope today's microwave and similar radiation linked pollution issues, uncountable types of advanced materials have been proposed and practiced up till now [35-37]. Among noticeably demarcated materials, metals [38], polymers [39], and functional hybrids [40] can be itemized for radiation defense purposes. Incidentally, scientific trends seemed to be drifting towards carbonaceous nanoparticles, such as carbon nanotube [41], graphene [42], nanodiamond [43], fullerene [44], carbon black [45], and the like [46]. Moreover, wide ranging polymeric and organic-inorganic hybrid nanostructures have been anticipated to deal with the radiation hazards to devices and living environment [47]. In this concern, carbonaceous and hybrid structures have been investigated for underlying electromagnetic interference phenomenon [48, 49]. Herein, high performance nanomaterials may reveal absorption, reflection, or internal reflection phenomena for electromagnetic shielding [50]. Particularly, magnetic, dielectric, and electron conducting properties of hybrids seemed to be beneficial for enhancing their microwave absorption potential [51]. Distinctive carbonaceous nanoparticles, like carbon nano-onions, and related multifunctional hybrids have capability to prevent harmful effects of electromagnetic interfering radiations [52-54]. Amongst preliminary efforts, Kuzhir et. al. [55] synthesized carbon nano-onions via detonation method. The as prepared carbon nano-onions based radiation defensive shields had fine conductivity and electromagnetic attenuation (26-38 GHz). In a later attempt, Su et. al. [56] developed hollow core carbon nano-onions through chemical vapor deposition procedure with methane source and iron/nickel metal catalyst. Fig. 2 A demonstrates a prototype for a hollow core carbon nano-onion. Herein, interfacial region can be seen between carbon nano-onion shell and hollow core. Thus, presence of a well defined interfacial region caused dipole separation, which was in turn useful for electromagnetic wave absorption features of these hollow nano-entities.

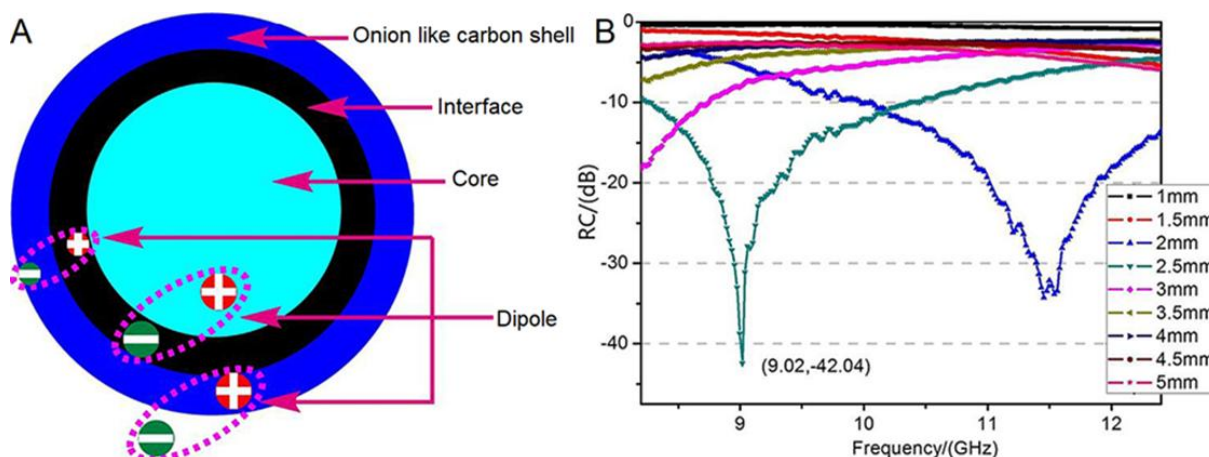


Fig. 2. (A) Illustration of a hollow core carbon nano-onion nanostructure; (B) trends of reflection coefficient vs. rising frequency (8.2-12.4 GHz) for hollow core carbon nano-onions with increasing thicknesses (1-5 mm) [56]. Reproduced with permission from Elsevier

Accordingly, Fig. 2 B shows plots of minimum reflection coefficient vs. frequency for hollow core carbon nano-onions with increasing thicknesses, in the range of 1-5 mm. Consequently, higher minimum reflection coefficient (~ 2.4 GHz) was observed at the thickness of 2.5 mm. Hence, it was observed that decreasing thickness of carbon nanomaterial resulted in enhancement of reflection coefficient values. Mechanism for minimum reflection at high thickness relies on preventing incident waves from returning to surface discontinuity. This process is generally guided by the principles of impedance matching and high attenuation loss.

Among inorganic nanocomposites, Xu et. al. [57] presented designs of carbon nano-onions and nickel oxide nanoparticles derived hybrids, obtained by atomic layer deposition practice. The resulting carbon nano-onions/nickel oxide nanoparticles based shield of 2.5 mm thickness depicted minimum reflection loss around -46 dB. Similarly, Pan et. al. [58] formed carbon nano-onions and nickel nanoparticles derived nanocomposites via layer by layer assembly method. The resulting carbon nano-onions/nickel oxide nanoparticles revealed high electrical conductivity of up to 125 S m^{-1} . Moreover, the multifunctional shield of 2.5 mm thickness depicted minimum reflection loss around -51 dB and optimal electromagnetic interference shielding effectiveness of about 67 dB. The remarkable radiation shielding performance seemed to be caused by mutual associations among nano-onions and inorganic metal nanoparticles due to the development of compatible multilayered interfaces. A very recent attempt by Shoaib et. al. [59] disclosed carbon nano-onions/titania/silica nanocomposite designs formed by flame pyrolysis, chemical vapor deposition, and sol gel processes (Fig. 3 A). Fig. 3 B shows microwave absorption mechanism of these multifunctional hybrids. Accordingly, carbon nano-onions/titania/silica nanomaterials were found capable of displaying superior minimum reflection loss (-54.4 dB) property at maximum effective absorption of 5.5 GHz (Fig. 3 C). It seems that microwave absorption efficiency and dielectric characteristics of multifunctional hybrids were due to nanolevel synergies of carbon nano-onions with titania and silica nanoparticles. Subsequently, radiation absorption occurs due to interfacial polarization and high dielectric loss caused by high surface area and spherical multi-shell nanostructure of carbon nanoonions.

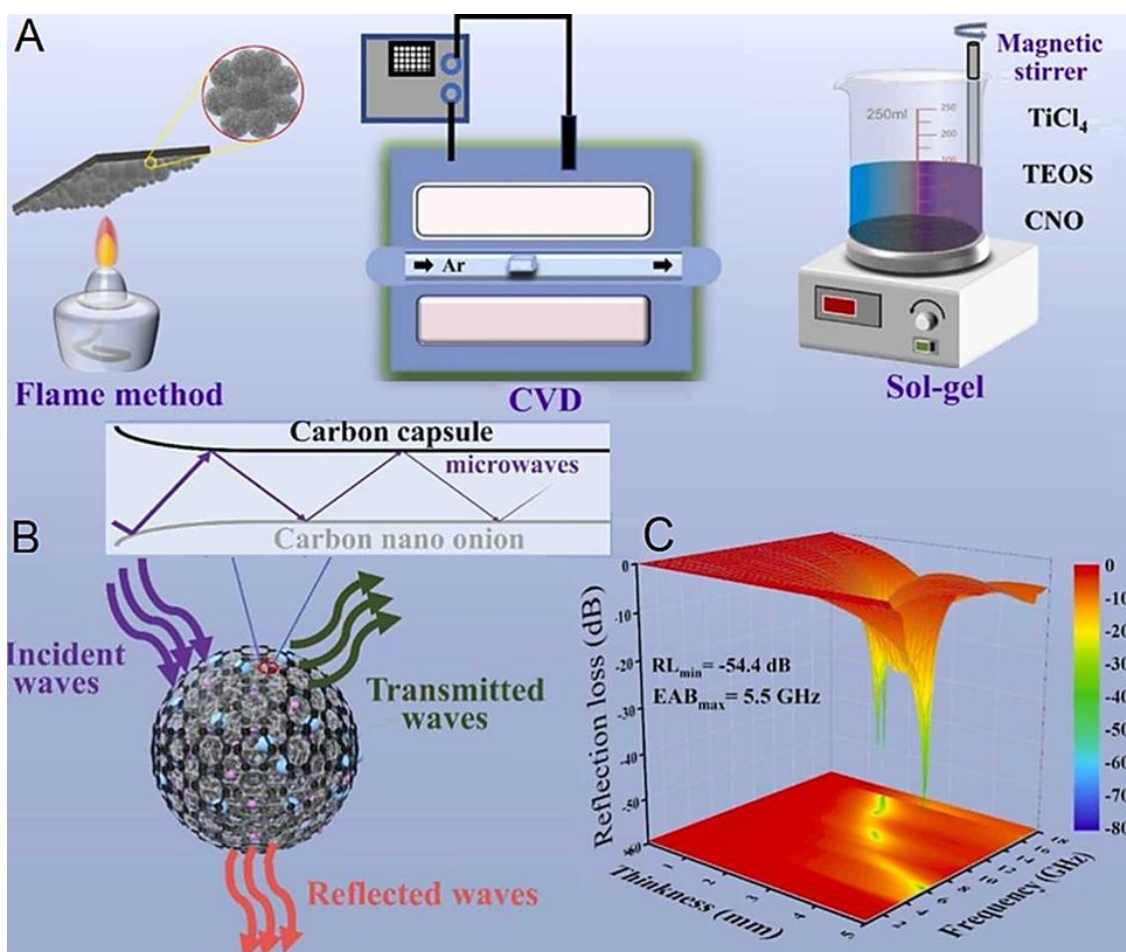


Fig. 3. (A) Manufacturing scheme for multifunctional carbon nano-onions/titania/silica hybrids via flame technique, chemical vapor deposition, and sol gel processes; (B) mechanism for microwave absorption of the nanocomposites; (C) plots for reflection loss vs. thickness of carbon nano-onions/titania/silica hybrids (minimum reflection loss (RL_{min}) = -54.4 dB; maximum effective absorption bandwidth (EAB_{max}) = 5.5 GHz [59]. CVD = chemical vapor deposition; CNO = carbon nano-onions; TEOS = tetra ethoxy silane. Reproduced with permission from Elsevier

Limited scientific attempts have been noticed so far regarding polymer/carbon nano-onions hybrids [60]. In a preliminary attempt, Kuzhir et. al. [61] reported poly(methyl methacrylate)/carbon nano-onions nanocomposites for electromagnetic interference shielding. Carbon nano-onions were produced using nanodiamond under high temperature and high pressure conditions. The as synthesized carbon nano-onions were annealed at different temperatures to study the effects on microstructural and radiation shielding properties. Later, the nanocomposites were fabricated by coagulation method in dimethylformamide/N-methylpyrrolidone solvent pair. The poly(methyl methacrylate)/carbon nano-onions nanocomposites were prepared using carbon nano-onions annealed at different temperatures, in the range of 1400-1800 K. Figs. 4 A-C show high resolution transmission electron microscopy images for carbon nano-onions produced at annealing temperatures of 1400 K, 1600 K, and 1800 K, respectively.

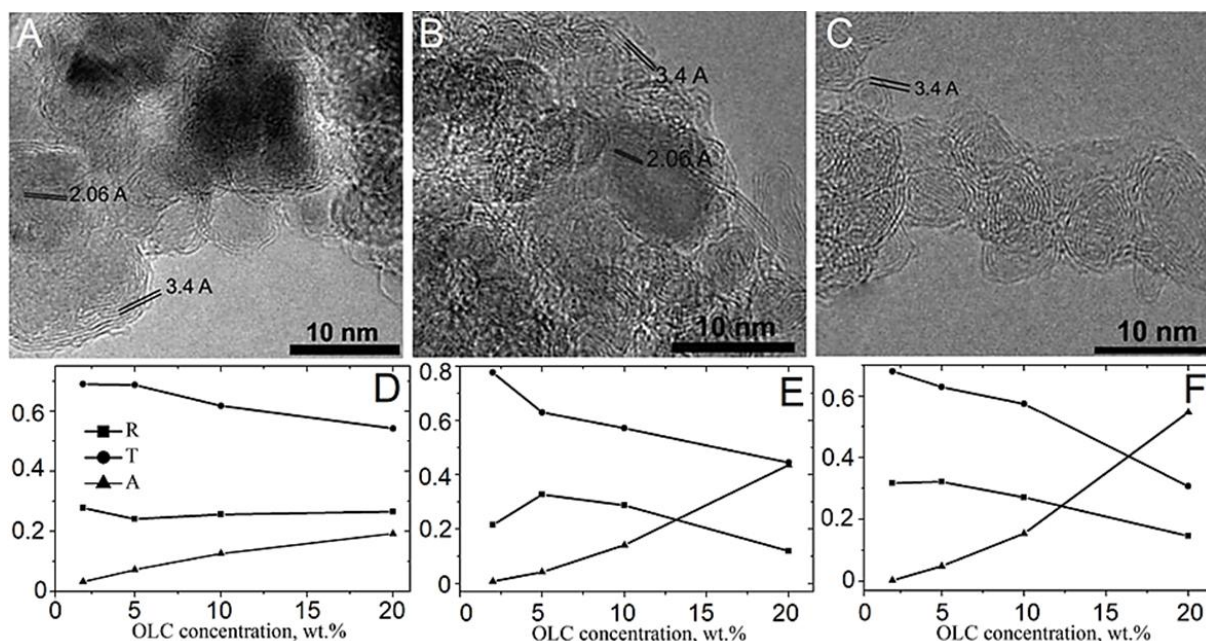


Fig. 4. High resolution transmission electron microscopy images for carbon nano-onions produced at: (A) 1400 K; (B) 1600 K; and (C) 1800 K annealing temperature; Electromagnetic absorption, reflection, and transmission of poly(methyl methacrylate)/carbon nano-onions nanocomposites (y-axis) vs. annealed carbon nano-onions contents (x-axis) at: (D) 1400; (E) 1600; and (F) 1800 K [61]. OLC = onion like carbon; A = absorption; R = reflection; T = transmission. Reproduced with permission from IEEE

As per results, rising annealing temperature formed well defined multilayered nanoentities with sizes in the range of 100-200 nm. Figs. 4 D-F depict electromagnetic absorption, reflection, and transmission trends of poly(methyl methacrylate)/carbon nano-onions nanocomposites vs. annealed carbon nano-onions contents formed at 1400 K, 1600 K, and 1800 K, respectively. According to outcomes, increasing annealing temperatures enhanced the electromagnetic absorption properties of the nanocomposites, relative to reflection or transmittance phenomenon. Herein, absorption appeared at the dominant mechanism for electromagnetic interference shielding of poly(methyl methacrylate)/carbon nano-onions nanocomposites. Besides, Li et. al. [62] used in situ polymerization practice to manufacture magnetic carbon nano-onions filled polyaniline hybrids. Figs. 5 A & B demonstrate scanning electron microscopy and transmission electron microscopy micrographs for magnetic carbon nano-onions and core shell polyaniline/magnetic carbon nano-onion nanostructures, respectively.

In the case of nanocomposite, polyaniline seemed to develop radial spikes of ~ 100 nm in length on nano-onion surfaces. This type of core shell microstructure was probably observed due to uniform in situ generation of polyaniline in the presence of core nanocarbon particles. Furthermore, Fig. 5 C scans reflection loss properties of polyaniline/magnetic carbon nano-onions with different material thicknesses. As per results, the hybrids (~ 1.5 mm thickness) revealed minimum reflection loss and electromagnetic wave absorption wavelength around -47.8 dB and 4.40 GHz, respectively. The optimal radiation shielding performance of polyaniline/magnetic carbon nano-onion hybrids can be attributed to interfacial synergies of core shell nanostructures at appropriate material thickness. Accordingly, Fig. 5 D presents a model diagram representing the core shell polyaniline/magnetic carbon nano-onions, which was used for theoretical evaluation of dielectric and permittivity properties of the nanomaterials.

Ultimately, among radiation shielding materials, carbon nano-onions and nickel nanoparticle hybrids had notable minimum reflection loss of - 47-51 dB and electromagnetic interference shielding effectiveness ~ 67 -70 dB with optimal shield thickness (~ 2 -3 mm) [57, 58]. Similar radiation shielding effectiveness was achieved with conjugated polymer and magnetic carbon nano-onions based system with relatively lesser shield thickness (~ 1.5 mm) owing to superior electrical conductivity and permittivity properties of these nanomaterials [62]. Despite, the successful efforts on carbon nano-onions based inorganic and polymeric hybrids, future endeavors must be conducted aiming optimized shield designs with > 99 % shielding efficiency and ~ 100 % reproducibility for industrial scale radiation protection deployments.

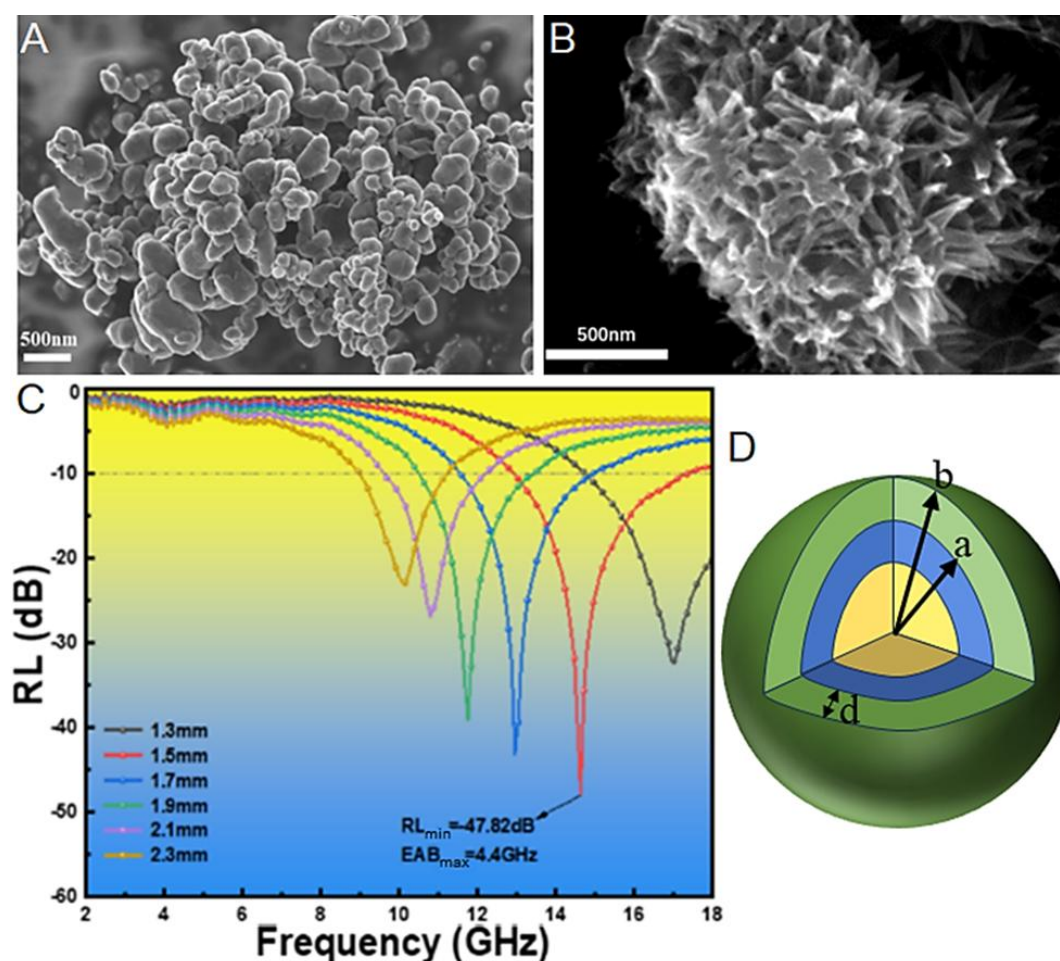


Fig. 5. (A) Scanning electron microscopy image of magnetic carbon nano-onions; (B) transmission electron microscopy micrograph of polyaniline/magnetic carbon nano-onions hybrid; (C) reflection loss curves for polyaniline/magnetic carbon nano-onions hybrid; (D) a representative model diagram of polyaniline/magnetic carbon nano-onions hybrid, where a = dielectric constant; b = average inner radius, d = shell thickness [62]. RL_{min} = minimum reflection loss; EAB_{max} = electromagnetic wave absorption wavelength. Reproduced with permission from ACS

TRIBOLOGY OF CARBON NANO-ONION AND RELATED NANOCOMPOSITES

Tribology is principally a science related to movements of surfaces in contact, which may cause substantial friction, wear, and lubrication phenomenon [63]. Owing to the significance of tribological properties in engineering structures, different types of organic (nanocarbons,

nanopolymers) [64-66] and inorganic (metal, metal oxides) [67, 68] materials, nanomaterials, or hybrids have been investigated. Amid carbonaceous nanoparticles, most prominent contenders to enhance the tribological competence include graphene [69], carbon nanotube [70], nanodiamonds [71], fullerene [72], and others. Likewise, zero dimensional multilayered carbon nano-onion nanostructures have attained topical research curiosities for distinct lubrication characteristics [73]. In this concern, adding carbon nano-onions to traditional lubricant oils have been observed for reducing the friction and wear resistance of sliding surfaces, even at high temperatures [74]. Noteworthy mechanisms behind tribological efficiency of carbon nano-onions reinforced lubricants may involve filling, rolling, polishing, or film forming phenomenon (Fig. 6). Consequently, mostly experimental and few theoretical or computational literature reports seen up till now regarding carbon nano-onions based lubricants [75].

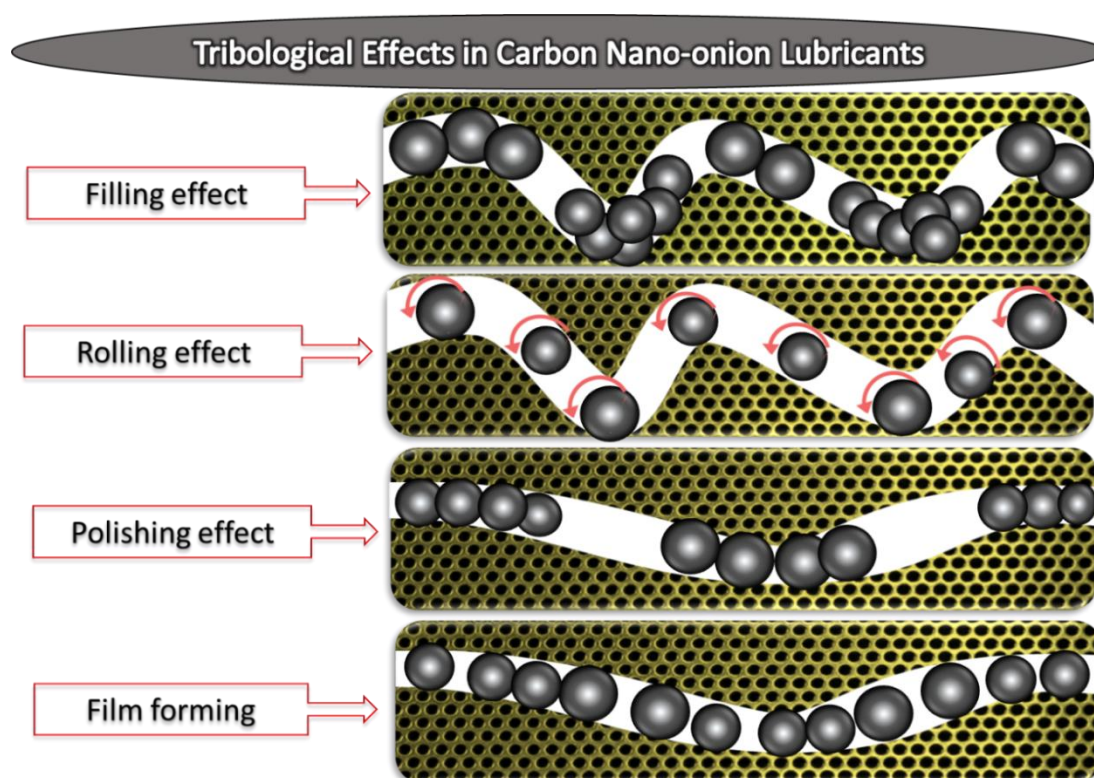


Fig. 6. Tribological effects in carbon nano-onions containing lubricants.

Particularly, molecular dynamics simulation practices have been applied to unfold the frictional properties of carbon nano-onions between the in contact surfaces [76]. Mainly, rolling or sliding movements of carbon nanoparticles were analyzed between the frictional surfaces under external applied pressure. Bucholz et. al. [77] performed theoretical evaluations of wear properties of carbon nano-onions amid the friction surfaces. In this regard, Figs. 7 A a-b demonstrate molecular dynamic simulation diagrams for carbon nano-onions rolling movement between friction surfaces, both in nonbonded and interfacially bonded states. Herein, interfacial bonding of nanoparticles to the frictional surfaces obviously hindered the rolling movements of carbon nano-onions [78]. Fig. 7 B presents friction force and normal force scans for rolling/sliding movements of carbon nano-onions between the friction surfaces. Accordingly, sliding movements (0.151) prominently contributed to the frictional properties of the carbon nanomaterials at interfaces, relative to rolling motion (0.024).

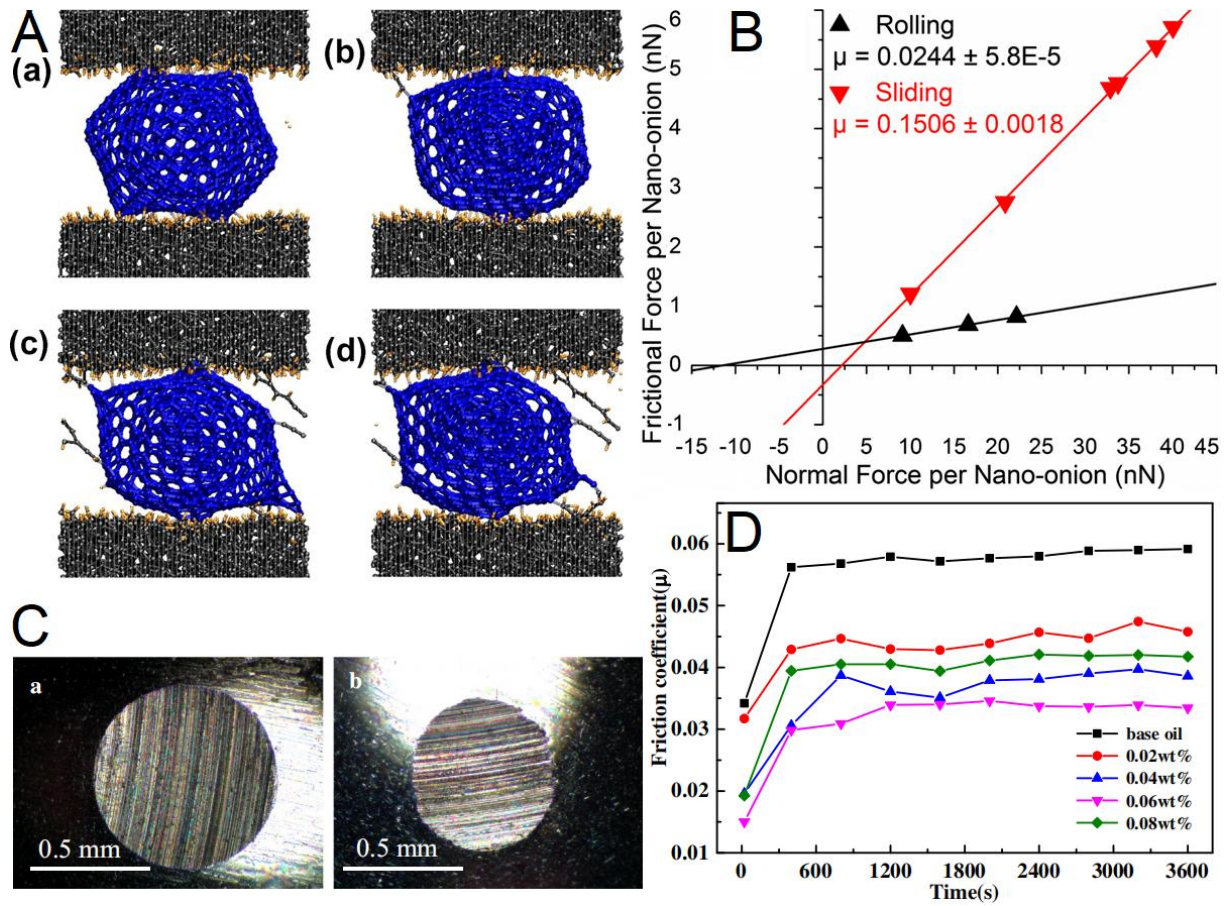


Fig. 7. Molecular dynamics simulations of: (A) carbon nano-onions sliding at 5 GPa compression between resistance surfaces as: (a) non bonded and (b-d) interfacially bonded nanoparticles; (B) friction force vs. normal force scans for rolling and sliding of carbon nano-onions between surfaces [77]. Reproduced with permission from Elsevier; (C) wear scar microstructures using a steel ball for: (a) base oil; and (b) carbon nano-onion sample (0.06 wt.%); (D) friction coefficients vs. time scans via four ball test using varying carbon nano-onions contents and unfilled base oil [79]. Reproduced with permission from Elsevier

Among initial experimental studies, Matsumoto et. al. [80] scrutinized tribological properties of carbon nano-onions, fullerene, and carbon nanotubes. During a wear test using 0.51-1.10 GPa applied pressure, carbon nano-onions depicted lower friction properties than the allied carbon nanostructures. It can be suggested that multilayered carbon shells in carbon nano-onions significantly promoted better microbearing effects (enhanced load capacity and reduced friction torque through microscale lubrication), as compared to carbon nanotube and fullerene. Microbearing mechanism depends upon quasi spherical layered structure of carbon nano-onions causing rolling effects in lubricating systems. Recently, Shang et. al. [81] performed comparative analysis for frictional properties of carbon nano-onions and nitrogen doped carbon nano-onions. For this purpose, carbon nano-onions and nitrogen doped carbon nano-onions (sizes ~ 50 -200 nm) were manufactured using a microwave method. According to coefficient of friction analysis, nitrogen doped carbon nano-onions had lower value (0.31), relative to pristine carbon nano-onions (0.36). Moreover, nitrogen doped carbon nano-onions were more competent to decrease the coefficient of friction and wear rate by 52 % and 67 %, respectively, than the pristine nanocarbon. It seems that nitrogen doping effectively altered the carbon nano-onions surfaces by enhancing the lubrication characteristics. Here, doping with nitrogen can enhance anti-wear and friction reduction features by optimizing interlayer spacing and strengthening the protective materials.

Further, Luo et. al. [79] preferred four ball test to investigate the tribological characteristic of carbon nano-onions containing lubricant base oil. Figs. 7 C a & b show wear scar microstructural analysis for base oil lubricant and carbon nano-onions reinforced lubricant. As per results, including nanoparticles reduced the appearance of scratches in the microstructure, due to superior bearing and lubrication effects. Fig. 7 D illustrates friction coefficients and time plots for unfilled and carbon nano-onions filled lubricants. According to the outcomes, adding nanoentities resulted in reduced minimum friction coefficient, owing to inherent bearing and lubrication features. The fundamental mechanism for ultra low friction is nanobearing effect, where multi-shell graphitic structures roll and slide between surfaces.

Regarding inorganic hybrids, Fei et. al. [82] fabricated molybdenum disulfide and carbon nano-onions based nanomaterials by using high temperature graphitization technique. For this purpose, they formed carbon nano-onions through carbonization of rice husk. Relative to as neat carbon nano-onions, molybdenum disulfide/carbon nano-onions hybrid had ~ 58 % lower wear rate. This performance was attributed to the amalgamation of carbon and inorganic nanomaterials. Both materials can form a persistent protective film on rubbing surfaces, so reducing direct metal-to-metal contact.

Besides, in recent years, important designs of polymer/carbon nano-onion hybrids have been explored for high performance lubricants [83]. Zhang et. al. [84] manufactured carbon nano-onions using a facile combustion route. Later, carbon nano-onions were modified with polyethylenimine through candle burning based heat treatment method. The polyethylenimine chains formed self assembled nanostructures on carbon nano-onion surfaces. Owing to nano-level synergies and interfacial connections between polyethylenimine and carbon nano-onions, significant reduction in friction and wear properties were observed. Accordingly, polyethylenimine/carbon nano-onion hybrids revealed lowering in wear volume and coefficient of friction (~ 61 % and 400 %, respectively), compared with that of the water. The anomalous advancement in the lubrication performance of polyethylenimine/carbon nano-onion hybrids was attributed to the nanobearing effects caused by interfacial behavior. An analogous attempt by Zhang et. al. [85] mentioned the fabrication of polyethylenimine/carbon nano-onion and polyethylenimine/garlic acid/carbon nano-onion hybrids using carbonization and aza-Michael techniques ([86]). The polyethylenimine/garlic acid/carbon nano-onions depicted desirably lower coefficient of friction (~ 0.11). Moreover, the wear volume of the nanomaterials was notably decreased by ~ 77 %. Carbon nano-onions can decrease wear volume and friction by acting as nanoscale bearings which easily roll and slide between rubbing surfaces. These carbon nanoparticles can offer superior antiwear performance under boundary lubrication conditions with scientific studies reporting up to a 77 % reduction in wear volume [87]. Furthermore, Guo et. al. [88] developed a lubricant based on polytetrafluoroethylene and carbon nano-onions for triboelectric nanogenerators (Fig. 8). Including carbon nano-onions improved the tribological and triboelectrical characters of polytetrafluoroethylene/carbon nano-onions hybrids. Notably, interfacial contact between the polymer and carbon nano-onions enhanced the lubrication effects of the nanocomposite layer applied to the desired surface. Consequently, applying polytetrafluoroethylene/carbon nano-onions to the triboelectric nanogenerator parts reduced the coefficient of friction, by > 75 %. It was suggested that carbon nano-onions based lubrication layer acted as micro-bearing between the two friction layers of triboelectric nanogenerator parts; thereby increasing the overall lubrication performance.

Similarly, few more reports can be seen carbon nano-onions and related hybrids for enhancing the tribological performance of industrial grade lubricant oils and materials [89]. Among tribological systems, polymer/carbon nano-onions nanocomposites exhibited remarkable potential to lower the coefficient of friction and wear volume [85, 88], relative to

allied inorganic hybrids [82]. These nanomaterials provide lubrication through effective nanoparticle dispersion, synergistic interfacial effects between spherical rolling carbon nano-onions and matrices, and tribofilm formation; thereby leading to better tribological performance. Nevertheless, for industrial grade utilization of carbon nano-onions based lubricants, concentrated future efforts seemed to be desirable.

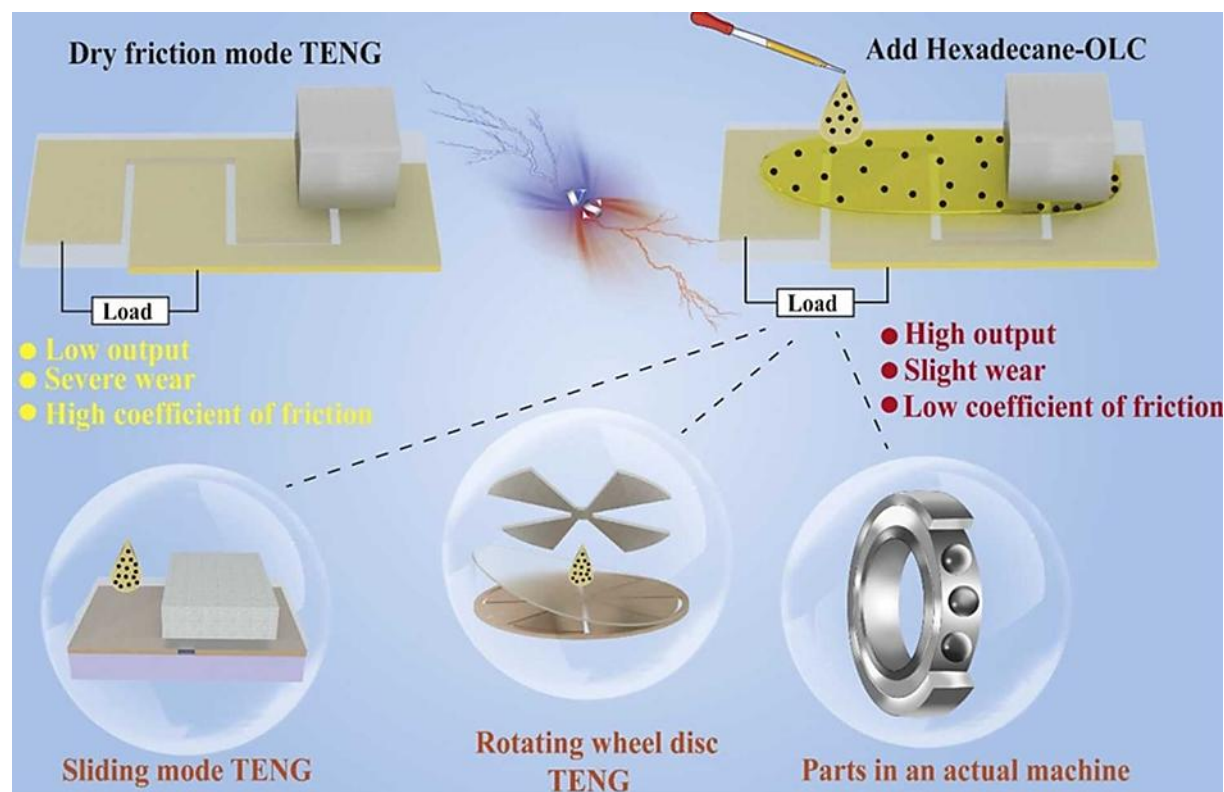


Fig. 8. Lubricant based on polytetrafluoroethylene and carbon nano-onion [88]. TENG = triboelectric nanogenerators; OLC = onion like carbon. Reproduced with permission from Elsevier

CORROSION PROTECTION POTENTIAL OF MULTIFUNCTIONAL CARBON NANO-ONION HYBRIDS

To resolve the rusting problems of metals, metallic alloys, and ceramic based structures, numerous efficient inorganic, polymeric, and carbon derived materials/nanomaterials have been considered by the scientific community [90]. In particular, recent anticorrosion research tendencies have been observed for carbonaceous nanomaterials (graphene, nanodiamond, carbon nanotubes, etc.) [91-93]. Carbon nanoparticles can valuably form percolation networks for superior electrical conductivity and ensuing corrosion potential. Moreover, the consistent interconnecting pathways can act as valuable barriers for percolating corrosive species through the materials [94].

Analogous to other nanocarbons, anticorrosion potential of carbon nano-onions and derived multifunctional carbon nano-onion hybrids has been inspected in the literature [95, 96]. These multilayered spherical nanoentities offer promising surface area, surface properties, structural veracity, and defense barrier against corrosive molecules and ecological effects [97]. Additionally, anticorrosion of carbon nano-onions based coatings seemed to be enhanced with the increment in material thickness [98, 99]. In addition to the as obtained

carbon nano-onions, their inorganic hybrids have been reported for notable erosion resisting characteristics [100, 101]. In this regard, Yeon et. al. [102] selected laser pyrolysis technique to form platinum/carbon nano-onions and platinum/carbon hybrids. The corrosion resistance performance of these hybrids was accessed using accelerated stress test. The transmission electron microscopy micrographs for platinum/carbon nano-onion hybrids are given in Figs. 9 A & B, respectively. Hither, carbon nano-onions can be observed as discrete nanoparticles on the platinum surfaces. The thermogravimetric analysis plots (Fig. 9 C) depicted superior initial degradation temperature ($\sim 450\text{ }^{\circ}\text{C}$) for platinum/carbon nano-onions, compared to that of the platinum/carbon hybrid ($\sim 400\text{ }^{\circ}\text{C}$). The higher thermal stability of platinum/carbon nano-onion was noticeably due to intrinsic structural integrity of carbon nano-onions and well integration nanocomposite formation with platinum. The electrochemical impedance spectroscopy scans for platinum/carbon nano-onions and platinum/carbon hybrids are given in Fig. 9 D. Here, appearance of smaller semicircle at low impedance indicated fine electrochemical reaction kinetics and corrosion resistance of platinum/carbon nano-onions, than platinum/carbon hybrid. Besides, polarization and power density vs. current density plots are scanned in Fig. 9 E. As per outcomes, platinum/carbon nano-onions exhibited greater power density of $\sim 240\text{ mW/cm}^2$, relative to carbon/platinum (187 mW/cm^2) system. Here again, these results indicated valuable corrosion resistance due to nanostructural and interfacial compatibility. Basically, platinum/carbon nano-onion hybrid consists of concentric graphitic shells with limited edge-plane sites (primary sites for corrosion). In addition, carbon nano-onion curvature permits strong electronic interactions with Platinum particles and reduce platinum-catalyzed oxidation of carbon or corrosion phenomenon.

Regarding polymer nanocomposites of carbon nano-onions, Kausar et. al. [103] designed a blend of polyaniline, polybenzimidazole, and polyimide by in situ and solution processes. The resulting polyaniline/polybenzimidazole/polyimide blend matrix was reinforced with carbon nano-onions. Consequently, adding nanofillers resulted in valued electrical conductivity ($\sim 3.3\text{ S cm}^{-1}$) of the multifunctional polyaniline/polybenzimidazole/polyimide/carbon nano-onion hybrid, relative to that of the original carbon nano-onions ($\sim 2.0\text{ S cm}^{-1}$). Moreover, corrosion protection of the as designed nanocomposite was also upsurge by $\sim 70\%$, than neat nanocarbons. In an allied attempt, Kausar et. al. [104] proposed an efficient corrosion protection system of polyurethane/poly(2-chloro-5-methoxyaniline)/carbon nano-onion hybrids. Herein, valued electrical conductivity of $\sim 1.3\text{ S cm}^{-1}$ was observed due to nano-level collaborations of conjugated polymers and carbon nano-onions. It seems that conducting polymer and carbon nano-onions based nanocomposites can form multifunctional coatings to prevent metal corrosion by combining electronic properties of polymers with spherical structure and conductivity of nanoparticles. These nanocomposites prevent corrosion through the combination of superior electrical passivation, barrier effects, and mechanical durability.

As per careful analysis, limited articles to date were noted for corrosion defensive aspects of inorganic and polymer based carbon nano-onion hybrids. Out of these nanomaterials, the reinforced polyaniline derivatives and blends exhibited superior electrical conductivity ($> 1\text{--}3\text{ S cm}^{-1}$) and subsequent corrosion protection characteristics [103, 104]. It seems that conjugated polymer/carbon nano-onions nanocomposite coatings act as anode, enabling the formation passive oxide layer on metal surfaces. These hybrids can form dense and less porous structures to restrict the percolation of corrosive agents. In addition, redox ability of conducting polymers can maintain stable passive state of metals. For industrial and commercial level developments, precise nanocomposite systems need to be established using conjugated matrices and functional carbon nanoentities.

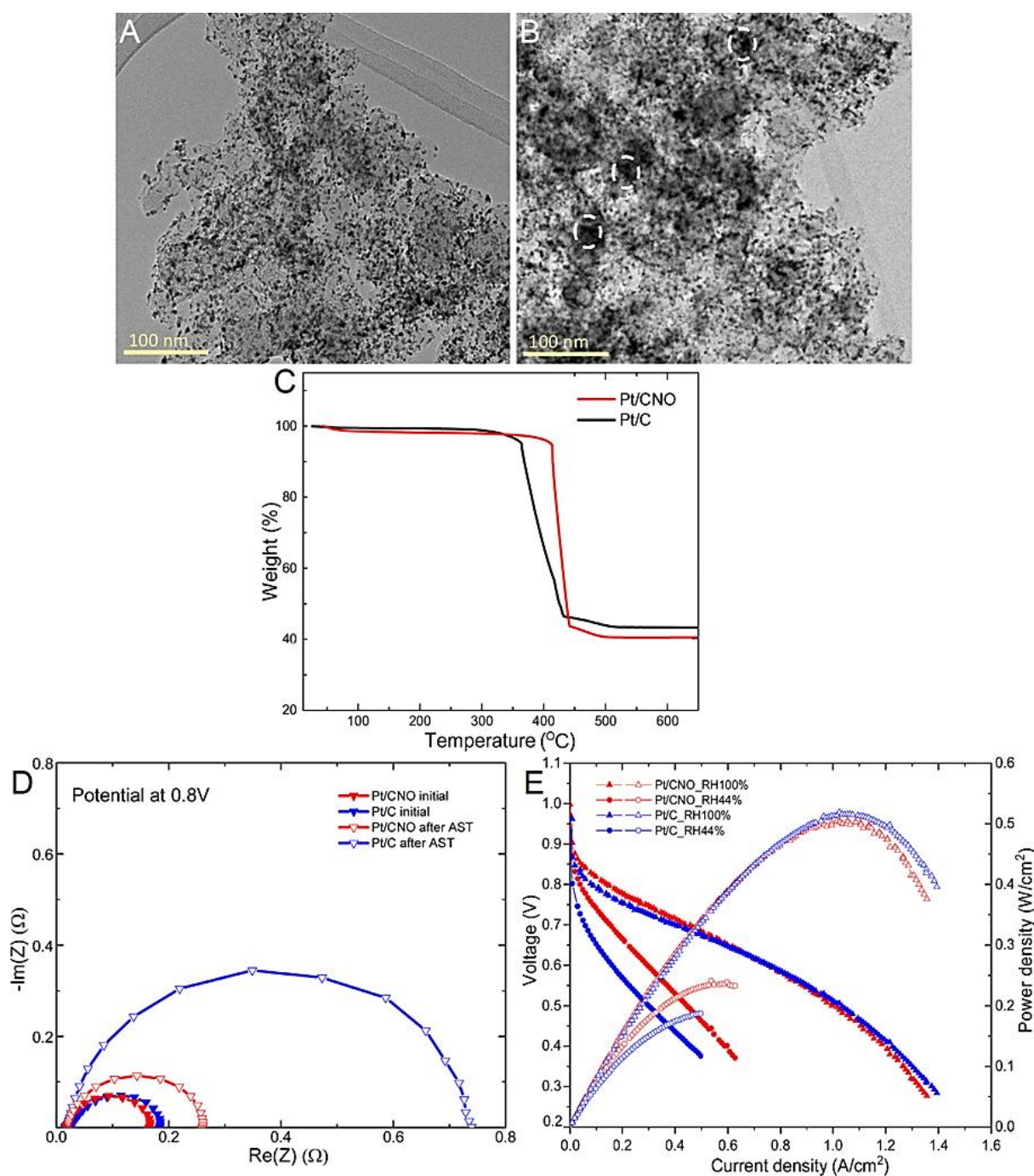


Fig. 9. (A & B) Transmission electron microscopy images for platinum/carbon nano-onion hybrids, before and after accelerated stress test, respectively; (C) thermogravimetric analysis plots for platinum/carbon nano-onions and platinum/carbon; (D) electrochemical impedance spectroscopy (0.8 V) for platinum/carbon nano-onions and platinum/carbon, before and after accelerated stress test; (E) polarization (J-V) and power density plots (vs. current density) for platinum/carbon nano-onions and platinum/carbon (relative humidity 44 & 100 %) [102]. Platinum/carbon nano-onions = Pt/CNO; platinum/carbon = Pt/C; AST = accelerated stress test; RH = relative humidity. Reproduced with permission from Elsevier

FIELD ENCOUNTERS AND CONCLUDING REMARKS

Carbon nano-onions own countless structural, physical, and performance characteristics to contribute as a most distinct member of the carbonaceous nanomaterial family [105]. Owing to budding scientific interests in these nanoentities, technically valuable radiation shields, antiwear, and anticorrosion coatings have been discovered (Fig. 10) [106]. All these engineering features and technological deployments of carbon nano-onions in turn can be useful for future space, automotive, civil, and electronic systems.

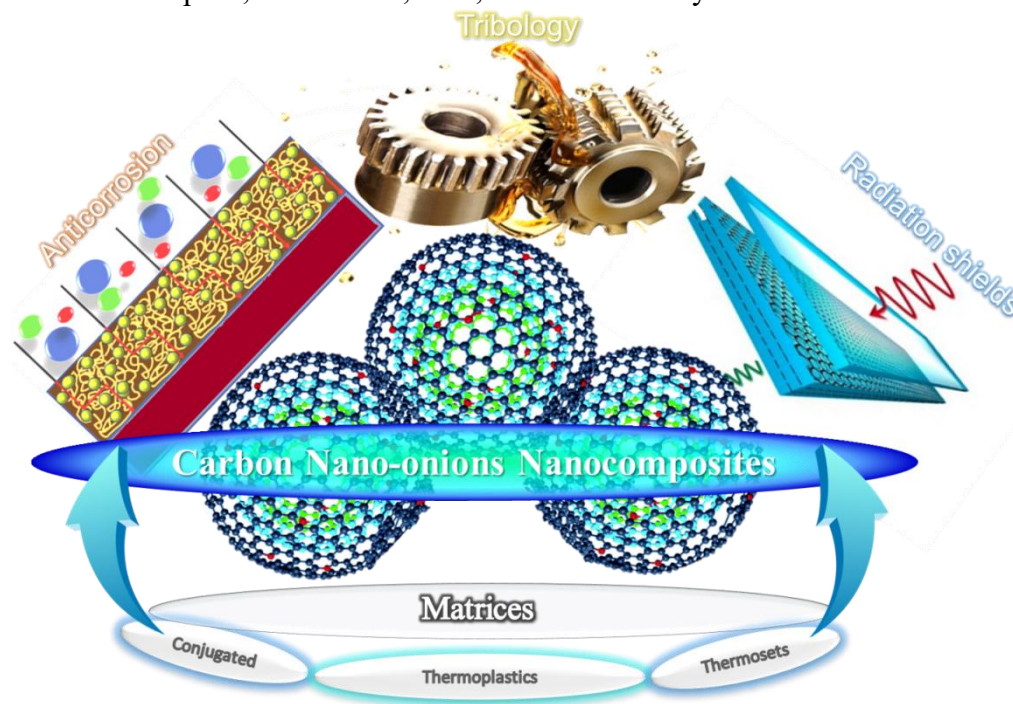


Fig. 10. Focused application areas of carbon nano-onion nanocomposites

As debated in previous sections of this manuscript, carbon nano-onions and derived multifunctional hybrid nanostructures have established their potential for absorption or dissipation of undesirable microwave radiations (Table 1) [107]. In this regard, electrical conductivity, dielectric, magnetic, and permittivity properties of carbon nano-onions and related hybrids played key role for cutting-edge electromagnetic interference shielding performance [108]. However, future of industrial scale radiation defensive shields of carbon nano-onions and multifunctional carbon nano-onion hybrids relies on focused and preplanned research efforts by the field scientists [109]. Identification and control of structure-performance relationships of carbon nano-onions and derived hybrids in terms of microstructures, electron transfer, and dielectric features need to be concentrated by the field experts. Hence, there is utmost need to design efficient polymer/carbon nano-onion hybrids having considerable reproducibility and scalability for deployments in defense and device related industries.

Notably, appropriate designing of functional carbon nano-onions and carbon nano-onions nanohybrids own remarkable competence to upsurge the tribological profiles (Table 2) [110]. Particularly, adding carbon nano-onions and derived nanomaterials between friction surfaces have been reported for notable lubrication effects by minimizing the wear rate and coefficient of friction values. Herein, carbon nano-onions, being zero dimensional nanoentities, can efficiently roll between the surfaces via microbearing effect to reduce the friction properties [111]. Even so, limited theoretical studies noted to date to unveil the actual phenomenon

behind tribological effects of carbon nan-onion containing nanomaterials. It seems that upcoming comprehensive field efforts may lead to promising antiwear/antifriction lubricants for engines of turbojets, aircrafts, supersonics, and other aerospace vehicles and engineering structures [112].

Table 1. Implication of carbon nano-onions and multifunctional carbon nano-onion hybrids for radiation shielding

Matrix/2 nd phase	Nanofiller	Fabrication	Functional faces/applications	Ref
-	Carbon nano-onions	Solution process	Electrical percolation; nanocarbon dispersion; electromagnetic attenuation ~ 26-38 GHz	[55]
	Hollow core carbon nano-onions	Chemical vapor deposition method; iron/nickel metal catalyst	Electromagnetic interference shielding; minimum reflection coefficient (~ 2.4 GHz); shield thickness ~ 2.5 mm	[56]
Nickle nanoparticles	Carbon nano-onions	Atomic layer deposition technique	Electromagnetic interference shielding; minimum reflection loss around - 47 dB; shield thickness ~ 2.5 mm	[57]
Nickle nanoparticles	Carbon nano-onions	Layer by layer assembly process	Electrical conductivity 125 S m ⁻¹ ; electromagnetic interference shielding effectiveness ~ 67 dB; minimum reflection loss of around - 51 dB	[58]
Titania nanoparticles; silica nanoparticles	Carbon nano-onions	Flame pyrolysis method	Electromagnetic interference shielding; minimum reflection loss of -54.4 dB; maximum effective absorption of 5.5 GHz; microwave absorption mechanism	[59]
Poly(methyl methacrylate)	Carbon nano-onions	Nanodiamond detonation technique; annealing (1400-1800 K); coagulation method	Electromagnetic interference shielding; microstructural analysis; multilayered nanoparticles of sizes ~ 100-200 nm; radiation absorption mechanism	[61]
Polyaniline	Magnetic carbon nano-onions	In situ polymerization practice	Electromagnetic interference shielding; core shell microstructures; polyaniline radial spikes of ~ 100 nm on nano-onion surfaces; shield thickness ~ 1.5 mm; minimum reflection loss and electromagnetic wave absorption wavelength around - 47.8 dB and 4.40 GHz, respectively	[62]

Into the bargain, carbon nano-onions nanoadditives in polymer and inorganic hybrids were applied to enhance the corrosion protection of the metallic or associated surfaces [113]. For this application, dispersion and network formation of carbon nano-onions have been valuably studied for enhancing their electrical conductivity, electrochemical, and corrosion resistance performance [114, 115]. Consequently, carbon nano-onions based nanomaterials have been studied for barrier effects and corrosion inhibition capabilities against corrosive species and environmental factors [116, 117]. Nevertheless, few challenging aspects have been noticed hindering the advances for the development of anticorrosion carbon nano-onion hybrids. Most importantly, limited studies seen so far unfolding the mechanisms of facilitated electron flow, electrical percolation, and barrier effects (towards invading corrosion species) of carbon nano-onions based coatings [118]. Hither, future research efforts for the development of well optimized functional carbon nano-onions and hybrids, by overcoming the identified limitations in this field, may lead to high anticorrosion coatings for space, automotive, energy, electronics, and medical devices and structures.

For all the above debated literature, it is important to understand the mechanisms behind radiation shielding, tribology, and anticorrosion of polymer/carbon nano-onion nanocomposites.

Electromagnetic shielding protects sensitive electronics and environment by attenuating electromagnetic waves by two major mechanisms, i.e., reflection and absorption [119]. Reflection phenomenon is usually observed in highly conductive materials, where free electrons interact with waves [120]. On the other hand, absorption mechanism is usually noticed in materials with superior magnetic permeability/dielectric loss, where energy is converted into heat. For high performance electromagnetic interference shielding, combination of both reflection and absorption mechanisms are considered useful. Consequently, high surface conductivity is needed to reflect incident waves, whereas thick magnetic layer can eliminate the undesirable radiation by high absorptivity features. Furthermore, tribological rolling/sliding effects involve complex interactions of wear, friction, and lubrication in materials used as bearings and gears. Herein, crucial sliding mechanisms involve slide-to-roll ratio, degree of slip, fatigue, energy loss, wear pattern, etc. [121]. Besides, anticorrosion barrier mechanisms usually act as physical shields between metal substrate and corrosive media. These mechanisms are important to block water, oxygen, and ions involved in electrochemical reactions [87]. Thus, anticorrosion coatings act as barriers to reduce permeability of corrosive agents through the materials and to enhance electrical resistance of anodic/cathodic sites on metals [122].

There are several large scale synthesis limitations preventing industrial uses of carbon nano-onions based materials. For instance, conventional carbon nano-onions synthesis techniques (like chemical vapor deposition, laser ablation, arc discharge) are costly, energy sweeping, and produce low yield. Afterwards, post synthesis purification (to remove amorphous carbon, metallic impurities) difficulties involve the use of hazardous acid reflux techniques, which can introduce surface defects on carbon nano-onions surfaces. Agglomeration issues are usually observed due to strong aggregation tendency of carbon nano-onions because of van der Waals forces. Such carbon nano-onion aggregates are usually > 100 nm with reduced surface area and limited utilization in catalysis or energy applications. Interfacial compatibility problems have also been observed for pristine carbon nano-onions due to their hydrophobic and inert nature. Thus, carbon nano-onions have poor interfacial adhesion and dispersion patterns in polymer matrices. The resulting polymer/carbon nano-onions hybrids usually reveal poor structural, electrical, or thermal properties in composites. Although, carbon nano-onions are chemically inert and resistant to biodegradation, few environmental and toxicity concerns have been observed. For instance, even functional carbon

nano-onions may reveal reaggregation, bioaccumulation, and toxicological effects during long term uses. Hence, limited long term durability and sustained functioning have been observed for polymer/carbon nano-onion materials. Subsequently, economic feasibility of these hybrids is usually compromised due to their high production costs, complex post synthesis purification/functionalization, low yield, etc.

Another aspect of polymer/carbon nano-onions nanocomposites is synthesis-structure-property relationships, which are tightly coupled. Since, synthesis technique defines surface area, surface defects, and surface properties of carbon nano-onions and ultimately their effectiveness as nanocomposites. These correlations rely on choice of synthesis technique and matrix-nanofiller interfacial interactions, which define final performance of carbon nano-onion based nanocomposites. The preferred methods for large scale synthesis of carbon nano-onions include Kuznetsov method (high temperature annealing of nanodiamonds), chemical vapor deposition, and arc discharge method. Owing to high surface area, graphitization, and surface defects of carefully designed carbon nano-onions can develop strong matrix-nanofiller links leading to substantial physical property enhancements. Key upgraded characteristics of polymer/carbon nano-onions hybrids include superior electrical conductivity, thermal resistance, and mechanical stability (strength, Young's modulus, toughness).

Convincingly, despite the technical advancements up till now, systematic investigations and industrial level researches need to be conducted for developing future industrially viable radiation protective, antiwear, and anticorrosion designs of carbon nano-onions and multifunctional carbon nano-onion hybrids. For all these engineering fields identified so far for carbon nano-onion hybrids, we note an utmost need of focusing low price, low density, environmental friendliness, degradability, reproducibility, and structure-property mechanisms, to expand their applicability, from space vehicles to device related industries.

Table 2. Tribological and anticorrosion significance of carbon nano-onions and multifunctional carbon nano-onion hybrids

Matrix/2 nd phase	Nanofiller	Synthesis	Properties/applications	Ref
-	Carbon nano-onions	Theoretical evaluations; molecular dynamic simulations	Tribological performance; Interfacial bonding of nano-onions to frictional surfaces; bearing effects; sliding movement coefficient of friction ~ 0.151; rolling motion coefficient of friction ~ 0.024	[77]
-	Carbon nano-onions; fullerene; carbon nanotubes	=	Tribological properties; wear test in the range 0.51-1.10 GPa; microbearing effects superior lubrication features of carbon nano-onions	[80]
-	Carbon nano-onions; nitrogen doped carbon nano-onions	Microwave method	Tribological competence; nanoparticle sizes ~ 50-200 nm; nitrogen doped carbon nano-onions had lower coefficient of friction (0.31), relative to pristine carbon nano-onions (0.36); nitrogen doped carbon nano-onions caused decline in coefficient of friction and wear rate by 52 % and 67 %, respectively; lubrication characteristics	[81]

-	Carbon nano-onions	Reinforcement	Tribological features; lubricant; four ball test; adding nanoentities reduced minimum friction coefficient; microbearing	[79]
Molybdenum disulfide	Carbon nano-onions	High temperature graphitization technique	Tribological performance; hybrid had ~ 58 % lower wear rate, than pristine nano-onions; bearing characteristics	[82]
Polyethylenimine	Carbon nano-onions	Candle burning combustion route; heat treatment method	Tribological application; hybrids caused lowering in wear volume and coefficient of friction (~ 61 % and 400 %, respectively), than water; nanobearing	[84]
Polyethylenimine; polyethylenimine/garlic acid	Carbon nano-onions	Carbonization method; aza-Michael technique	Tribology; lower coefficient of friction ~ 0.11; wear volume decreased by ~ 77 %.	[85]
Polytetrafluoroethylene	Carbon nano-onions	Solution method	Tribological and triboelectrical features; reduced coefficient of friction, by > 75 %; lubrication layer; micro-bearing between friction surfaces	[88]
Platinum	Carbon nano-onions	Selected laser pyrolysis technique	Anticorrosion potential; microstructure; carbon nano-onions as discrete nanoparticles on platinum surfaces; superior initial degradation temperature ~ 450 °C; electrochemical reaction kinetics; polarization curves; power density ~ 240 mW/cm ²	[102]
Polyaniline; polybenzimidazole; Polyimide	Carbon nano-onions	In situ technique; solution process	Corrosion resistance; higher electrical conductivity ~ 3.3 S cm ⁻¹ , than original carbon nano-onions (~ 2.0 S cm ⁻¹); corrosion protection upsurge by ~ 70 %, than neat nanocarbons	[103]
Polyurethane; poly(2-chloro-5-methoxyaniline)	Carbon nano-onions	Solution process	Corrosion protection; electrical conductivity ~ 1.3 S cm ⁻¹ ; nano-level matrix-nanofiller collaborations	[104]

REFERENCES

1. Thamizhchelvan, A.M. and N. Lien, *Unique Nanostructures of Carbon Nano Onions*, in *Handbook of Functionalized Carbon Nanostructures: From Synthesis Methods to Applications*. 2024, Springer. p. 181-228.
2. Kausar, A., *Radiation Shielding Performance of High Entropy Alloys and Derived Nanomaterials Towards Nuclear Irradiation/Electromagnetic Interference Environments-Fundamentals and Technicalities*. *Advances in Materials Science*, 2025. **25**(2): p. 73-103.

3. Kausar, A., *Structural Integrity of Three Dimensional Printed Carbon Fiber Composites/Nanocomposites for Aeronautical Components—Current Scenarios and Opportunities*. Advances in Materials Science, 2024. **24**(4): p. 67-96.
4. Kabir, M.H., et al., *Effects of Waste-Plastic-Derived Carbon Nano-Onions as Additive on Rheological and Tribological Performance of Oil Lubricant*. Journal of Tribology, 2026. **148**(3): p. 032102.
5. Zhang, X., et al., *Heterointerface between Carbon Nano-Onions and Fluorinated Boron Nitride Nanostructures for Improved Microwave Absorption Properties*. ACS Applied Materials & Interfaces, 2025.
6. Zhou, H., et al., *Template-free water splitting preparation of carbon nanotube foam for high-efficiency charge storage and electromagnetic interference shielding*. Journal of Power Sources, 2025. **644**: p. 237096.
7. Berman, D. and A. Erdemir, *The Role of Tribocatalysis in Friction and Wear: A Review*. Lubricants, 2025. **13**(10): p. 442.
8. Ayan, M., et al. *Examining the Corrosion Behaviour of Carbon Steel Pipelines with Bio-Corrosion Inhibitors in Sub-Sea Environments*. in *Abu Dhabi International Petroleum Exhibition and Conference*. 2024. SPE.
9. Kadyan, P., et al., *Decoration of Zeolitic Imidazole Framework With Carbon Nano-Onions for Enhancing Electrochemical Performance of ZIF-(67 and 8) for Supercapacitor*. Energy Storage, 2025. **7**(3): p. e70163.
10. Hasan, N., et al., *Assessing the Sustainability of Energy-Related Nanomaterial Synthesis: Emphasizing the Need for Energy-Efficient Nanomaterial Preparation Techniques*. Energies, 2025. **18**(3): p. 523.
11. Pallavolu, M.R., et al., *Superior energy-power performance of N-doped carbon nano-onions-based asymmetric and symmetric supercapacitor devices*. International Journal of Energy Research, 2022. **46**(2): p. 1234-1249.
12. Cao, J. and B. Liao, *Carbon Dots for Anti-corrosion: A Review Describing in Detail the Application and Mechanism of Corrosion Inhibitors*. Current Analytical Chemistry, 2025.
13. Nair, A.S., et al., *Application of Corn Oil Derived Carbon Nano-onions Using Flame Pyrolysis as Durable Catalyst Support for Polymer Electrolyte Membrane Fuel Cells*. Electrocatalysis, 2025. **16**(2): p. 292-302.
14. Ugarte, D., *Onion-like graphitic particles*, in *Carbon nanotubes*. 1996, Elsevier. p. 163-167.
15. Chholak, A., et al., *Carbon Nano Onions: Synthesis and Potential Applications*. Carbon, 2025: p. 120814.
16. Almeida Gonzalez, H.D., et al., *The Promise of Carbon Nano-Onions: Preparation, Characterization and Their Application in Electrochemical Sensing*. Analysis & Sensing, 2025. **5**(1): p. e202400035.
17. Kumari, P., et al., *Synthesis and Applications of Carbon Nano Onions and their Composites for the Remediation of Organic Pollutants from Wastewater*. RSC Sustainability, 2025.
18. Tohamy, H.-A., M. El-Sakhawy, and S. Kamel, *A greener future: carbon nanomaterials from lignocellulose*. Journal of Renewable Materials, 2025. **13**(1): p. 21.
19. Pakpum, C., et al., *Synthesis and characterization of carbon nano-onions-like structure produced by C₂H₂ microwave plasma and application in bio-imaging*. Materials Chemistry and Physics, 2025: p. 131033.

20. Ghavanloo, E., R. Lashani, and G.I. Giannopoulos, *Prediction of frequency band gaps in one-dimensional endohedral fullerene and carbon nano-onion chains*. Journal of Molecular Modeling, 2023. **29**(11): p. 349.
21. Alduhaidahawi, A.M.J. and A.H.M. Al-antaki, *Carbon types derivatives of nanoscience via nanotechnology with applications*. Magazine of Al-Kufa University for Biology, 2025. **17**(2).
22. Shamsuri, A.A., *Functionalized Carbon Nano-onions for Polymer Composites*. 2025, Scientific Archives. p. 1-3.
23. Dai, D., Y. Li, and J. Fan, *Room-temperature synthesis of various allotropes of carbon nanostructures (graphene, graphene polyhedra, carbon nanotubes and nano-onions, n-diamond nanocrystals) with aid of ultrasonic shock using ethanol and potassium hydroxide*. Carbon, 2021. **179**: p. 133-141.
24. Kausar, A., *The promise of carbon nano-onions for thermoplastic and biodegradable thermoplastic nanocomposites—status quo and future vision*. Journal of Thermoplastic Composite Materials, 2025: p. 08927057251387083.
25. Yasri, S. and V. Wiwanitkit, *Carbon Nano-onions for Drug Delivery*, in *Carbon Based Nanomaterials for Drug Delivery*. 2025, Springer. p. 385-411.
26. Glad, X., et al., *Synthesis of core-shell copper-graphite submicronic particles and carbon nano-onions by spark discharges in liquid hydrocarbons*. Scientific reports, 2021. **11**(1): p. 7516.
27. Thennarasi, A., et al., *Synthesis and application of onion-like carbons*, in *Nanocarbon Allotropes Beyond Graphene: Synthesis, properties and applications*. 2023, IOP Publishing Bristol, UK. p. 8-1-8-28.
28. Liu, L., et al., *Polydopamine-mediated phosphoric acid functionalized carbon nano-onions/sulfonated poly (aryl ether sulfone) composite membrane with enhanced proton transport capacity and chemical durability for fuel cell at low humidity*. International Journal of Hydrogen Energy, 2025. **144**: p. 262-274.
29. Muduli, S., S.K. Pati, and S.K. Martha, *Bio-waste derived carbon nano-onions as an efficient electrode material for symmetric and lead-carbon hybrid ultracapacitors*. International Journal of Energy Research, 2022. **46**(10): p. 14074-14087.
30. Nabaa, A. and R.A. Al-Husseiny, " *Eco-Friendly Photocatalytic Degradation of Organic Pollutants Using Nano-Semiconductors Derived from Onion Peel Extract: A Comprehensive Review*". Journal of University of Babylon for Engineering Sciences, 2025. **33**(3): p. 1-17.
31. Li, Y.-X., et al., *Portable multimodal platform with carbon nano-onions as colorimetric and fluorescent signal output for trypsin detection*. Talanta, 2025. **281**: p. 126819.
32. Li, H., et al., *Preparation and Hydrogen Evolution Property Tuning of Carbon Nano Onion Supported Co-Pt Alloy Catalysts*. Catalysis Letters, 2025. **155**(7): p. 237.
33. Ravikiran, N., P.K. Jain, and V.V. Srikanth, *Carbon Spheres and Carbon Soot for Tribological Applications*, in *Advanced Nanomaterials*. 2022, Springer. p. 191-216.
34. Soylukan, C., T.K. Yesıldal, and L. Akyüz, *Carbon Nano-Onions in Biological Applications: Recent Progress and Future Directions*. Aksaray University Journal of Science and Engineering, 2025. **9**(1): p. 1-9.
35. Sheldon, R.A., *The E factor at 30: a passion for pollution prevention*. Green Chemistry, 2023. **25**(5): p. 1704-1728.
36. Zhu, C., et al., *Advanced fiber materials for wearable electronics*. Advanced Fiber Materials, 2023. **5**(1): p. 12-35.

37. Çoşkun, Ö. and E.C.G. Demirel, *Effects of Electromagnetic Field Pollution on Human Health: Current Evidence*. Cumhuriyet Science Journal, 2025. **46**(3): p. 424-434.
38. Shi, Y., et al., *Advanced functional electromagnetic shielding materials: a review based on micro-nano structure interface control of biomass cell walls*. Nano-Micro Letters, 2025. **17**(1): p. 3.
39. Yasir, M. and S.R. Kim, *3D-structured polymer composites using advanced templating strategies for EMI shielding*. Polymer Composites, 2025.
40. Idumah, C.I., *Recently emerging trends in flame retardancy of phosphorene polymeric nanocomposites and applications*. Journal of Analytical and Applied Pyrolysis, 2023: p. 105855.
41. Li, H., et al., *Efficient adsorption of waste carbon nanotube by polyacrylamide gel to form wrinkled core-shell particles towards multifunctional composites for EMI shielding and sensing*. Separation and Purification Technology, 2025. **354**: p. 128903.
42. Lu, X., et al., *Stealth Materials Based on Laser-Induced Graphene: Developments and Challenges*. Nanomaterials, 2025. **15**(8): p. 623.
43. Song, X., et al., *Nanodiamond@ hollow carbon sphere architectures for synergistically enhanced electromagnetic absorption and thermal insulation*. Diamond and Related Materials, 2024. **141**: p. 110631.
44. Huang, W., et al., *Physical crosslinking optimized high-temperature capacitive energy storage of polyetherimide nanocomposites with ultralow C60 particles*. Composites Science and Technology, 2025: p. 111194.
45. Fallah, R., S. Hosseinabadi, and G. Pourtaghi, *Influence of Fe₃O₄ and carbon black on the enhanced electromagnetic interference (EMI) shielding effectiveness in the epoxy resin matrix*. Journal of Environmental Health Science and Engineering, 2022. **20**(1): p. 113-122.
46. Kausar, A., *Hybrid polymeric nanocomposites with EMI shielding applications*, in *Materials for Potential EMI Shielding Applications*. 2020, Elsevier. p. 227-236.
47. Tran, T.S., et al., *Solution-Processable Polymer Nanocomposites for Electromagnetic Interference Shielding*. Advanced Materials Interfaces, 2025: p. 2500225.
48. Gebrekrstos, A., et al., *Tailoring the Properties of 2D Nanomaterial-Polymer Composites for Electromagnetic Interference Shielding and Energy Storage by 3D Printing—A Review*. Advanced Engineering Materials, 2025. **27**(7): p. 2402179.
49. Marinković, D., et al., *New Electromagnetic Interference Shielding Materials: Biochars, Scaffolds, Rare Earth, and Ferrite-Based Materials*. Nanomaterials, 2025. **15**(7): p. 541.
50. Isari, A.A., et al., *Structural design for EMI shielding: from underlying mechanisms to common pitfalls*. Advanced Materials, 2024. **36**(24): p. 2310683.
51. Zeng, Y. and L. Tang, *Silicone Rubber Composites Reinforced by Onion-Like Carbon and Carbon Nanotube Hybrid Fillers for Flexible Dielectric Materials*. Polymer-Plastics Technology and Materials, 2025: p. 1-13.
52. Wang, Y.-Y., et al., *Carbon-based aerogels and foams for electromagnetic interference shielding: A review*. Carbon, 2023. **205**: p. 10-26.
53. Xu, H., et al., *Metal–phenolic coordination crystals derived magnetic hollow carbon spheres for ultrahigh electromagnetic wave absorption*. Nano Research, 2024. **17**(3): p. 1616-1624.
54. Ni, A., et al., *Rail-like heterostructured porous carbon composites derived from vanadium metal-organic framework/butterfly wings for enhanced microwave absorption*. Carbon, 2024. **221**: p. 118930.

55. Kuzhir, P., et al., *Nano-scaled onion-like carbon: Prospective material for microwave coatings*. *Metamaterials*, 2009. **3**(3-4): p. 148-156.
56. Su, X., et al., *Preparation and microwave absorption property of nano onion-like carbon in the frequency range of 8.2–12.4 GHz*. *Journal of Alloys and Compounds*, 2017. **695**: p. 1420-1425.
57. Xu, X., et al., *Magnetic Ni/graphene connected with conductive carbon nano-onions or nanotubes by atomic layer deposition for lightweight and low-frequency microwave absorption*. *Chemical Engineering Journal*, 2020. **382**: p. 122980.
58. Pan, F., et al., *Heterointerface engineering of β -chitin/carbon nano-onions/Ni-p composites with boosted Maxwell-Wagner-Sillars effect for highly efficient electromagnetic wave response and thermal management*. *Nano-Micro Letters*, 2022. **14**(1): p. 85.
59. Shoaib, M., et al., *The nearby dual-nanocarbon of CNO/TiO₂/SiO₂/CC nanohybrids with multi-interfaces for high-temperature microwave absorption*. *Journal of Alloys and Compounds*, 2025: p. 180904.
60. Ramesh, C., *Mechanical, wear, thermal conductivity and hydrophobicity behavior of Kevlar fiber-epoxy structural composites reinforced with onion peel carbon quantum dot and commercial carbon nanotubes: a comparative study*. *Biomass Conversion and Biorefinery*, 2025. **15**(6): p. 9059-9069.
61. Kuzhir, P.P., et al., *Carbon onion composites for EMC applications*. *IEEE transactions on electromagnetic compatibility*, 2011. **54**(1): p. 6-16.
62. Li, S., et al., *One-Step Synthesis of Chestnut-Like Magnetic CNOs@ PANI with Microwedge Enhanced Electromagnetic Wave Absorption*. *ACS Applied Electronic Materials*, 2024. **6**(6): p. 4608-4618.
63. Qin, C., et al., *Tribology in Nature: Inspirations for Advanced Lubrication Materials*. *Advanced Materials*, 2025: p. 2420626.
64. Liu, Y., et al., *Manipulating the structure of covalent organic frameworks through p - π resonance toward excellent tribological properties*. *Carbon*, 2025. **238**: p. 120307.
65. Jose, J., et al., *Tribological performance of electric transmission fluid enhanced with silicon dioxide and graphene nanoparticles: Impact of concentration on wear reduction and frictional behavior*. *Results in Surfaces and Interfaces*, 2025. **19**: p. 100517.
66. Qiu, J.-W., et al., *Effects of graphite fluoride nanoparticles on the tribological properties of lithium composite grease*. *Journal of Mechanical Science and Technology*, 2025: p. 1-7.
67. Li, Z., et al., *Preparation of Diisooctyl Phosphate-Modified Ultra-Small Zinc Oxide Nanoparticle and Investigation of Its Tribological Properties as Additive in Alkyl naphthalene*. *Lubrication Science*, 2025. **37**(3): p. 189-197.
68. Fu, X., et al., *Tribological behavior and lubrication mechanism of polyalphaolefin with added Cu-Ni bimetallic nanoparticles on a TiN coating*. *Applied Surface Science*, 2025. **679**: p. 161287.
69. Yang, K., et al., *Advanced Research on Graphene-Based Nano-Materials: Synthesis, Structure, Dispersibility and Tribological Applications*. *ChemNanoMat*, 2025. **11**(1): p. e202400428.
70. Singh, M., et al., *Enhancement of mechanical and tribological properties in glass fiber-reinforced polymer composites with multi-walled carbon nanotubes and ANN-based COF prediction*. *Composite Interfaces*, 2025. **32**(4): p. 439-459.

71. Diab, M.R., et al., *Wear-resistant and stable low-friction nanodiamond composite superhard coatings against Al₂O₃ counter-body in dry condition*. International journal of refractory metals and hard materials, 2025. **126**: p. 106955.
72. Drnovšek, A., et al., *Facile Synthesis Route for Bulk Production of Complex Fullerene-Like MoS₂ Nanostructures With Enhanced Tribological Properties*. ChemPlusChem, 2025. **90**(1): p. e202400480.
73. Opia, A.C., et al., *Effectiveness of Carbon Nanomaterials as Lubricant Additives: Recent Review*. Materials Today Nano, 2025: p. 100643.
74. Kolubaeu, A., et al., *Fundamental and Applied Aspects of Materials Science in Tribology*. Physical Mesomechanics, 2025. **28**(2): p. 145-169.
75. Ostroumova, G., N. Orekhov, and V. Stegailov, *Reactive molecular-dynamics study of onion-like carbon nanoparticle formation*. Diamond and Related Materials, 2019. **94**: p. 14-20.
76. Yang, X., Y. Wang, and J. Zhang, *Scaling up to macroscale superlubricity of sp²-dominated structural carbon films: Graphene and carbon onion*. Applied Surface Science, 2023. **636**: p. 157784.
77. Bucholz, E.W., S.R. Phillpot, and S.B. Sinnott, *Molecular dynamics investigation of the lubrication mechanism of carbon nano-onions*. Computational materials science, 2012. **54**: p. 91-96.
78. Xu, J., et al., *Influence of structural evolution on sliding interface for enhancing tribological performance of onion-like carbon films via thermal annealing*. Applied Surface Science, 2021. **541**: p. 148441.
79. Luo, N., et al., *One-step gas-liquid detonation synthesis of carbon nano-onions and their tribological performance as lubricant additives*. Diamond and Related Materials, 2019. **97**: p. 107448.
80. Matsumoto, N., et al., *Friction reducing properties of onion-like carbon based lubricant under high contact pressure*. Tribology-Materials, Surfaces & Interfaces, 2012. **6**(3): p. 116-120.
81. Shang, F., et al., *Rapid Synthesis of Onion-Like Nitrogen-Doped Carbon Nanospheres with Microwave and Study of its Tribological behavior*. Carbon, 2024: p. 119840.
82. Fei, X., et al., *Investigate on preparation and dry tribological behaviors of onion-like carbon/MoS₂ polyimide coatings*. Applied Surface Science, 2025. **684**: p. 161846.
83. Zhang, J., et al., *Reversal mechanism of triboelectrification in steel-polymer frictional interface for in-situ monitoring of transfer films*. Nano Energy, 2024. **120**: p. 109139.
84. Zhang, R., et al., *Fabrication of zwitterionic polymer-functionalized onion-like carbon nanoparticles as aqueous lubricant additives*. Langmuir, 2023. **39**(43): p. 15391-15400.
85. Zhang, R., et al., *Fabrication of Garlic Oil-Functionalized Onion-Like Carbon Nanoparticles as Effective Nanoadditives for Improved Lubricating Performance*. ACS Applied Nano Materials, 2024. **7**(12): p. 14443-14451.
86. Rulev, A.Y., *Weak Nucleophiles in the Aza-Michael Reaction*. Advanced Synthesis & Catalysis, 2023. **365**(12): p. 1908-1925.
87. Roshan, M.S., et al., *Nanomaterial-Enhanced Greases: A Review of Tribological and Rheological Advancement*. Journal of Tribology, 2026. **148**(2): p. 020802.
88. Guo, Y., et al., *Onion-like carbon as nano-additive for tribological nanogenerators with enhanced output performance and stability*. Nano Energy, 2022. **104**: p. 107900.
89. He, C., et al., *One-step rapid fabrication of high-purity onion-like carbons as efficient lubrication additives*. Journal of Materials Science, 2021. **56**: p. 1286-1297.

90. Udorah, F.N. and A.O. Adeniran, *A meta-study on smart coatings with carbon nanoparticles*. Journal of environmental engineering and energy, 2025. **2**(1): p. 44-63.
91. Kulyk, B., et al., *A critical review on the production and application of graphene and graphene-based materials in anti-corrosion coatings*. Critical Reviews in Solid State and Materials Sciences, 2022. **47**(3): p. 309-355.
92. Maurya, S.S., et al., *Enhancement in the Hot Corrosion Resistance of Plasma-Sprayed NiAl Coating Through Nanodiamond Reinforcement*. Metallurgical and Materials Transactions A, 2025. **56**(5): p. 1773-1785.
93. Hao, X., et al., *Research Progress of Superhydrophobic Coatings Constructed by Arrayed and Non-Arrayed Carbon Nanotubes for Anti-Corrosion, Anti-Icing and Photothermal De-Icing*. Chemistry–An Asian Journal, 2025. **20**(3): p. e202401122.
94. Xu, H., et al., *Bioinspired mechanically tough, high Adhesion, and healable polyurethane coating for high-temperature anti-corrosion and anti-cavitation applications*. Applied Surface Science, 2025: p. 163584.
95. Vindhysarumi, A., et al., *A comprehensive review on recent progress in carbon nano-onion based polymer nanocomposites*. European Polymer Journal, 2023. **194**: p. 112143.
96. Bharadia, H.A., et al., *FUTURE OF ENVIRONMENT WITH CARBON ALLOTROPES*. Nirma University Journal of Pharmaceutical Sciences: Volume 11, Issue 1 (January-June 2024), 2024: p. 33.
97. ŞAHİN, F.İ., Y. OKUMUŞ, and N. ACARALI, *INNOVATIVE MATERIALS IN THE AEROSPACE AND DEFENCE INDUSTRY: COMPOSITES AND FUNCTIONAL COATINGS*. Research And Evaluations In The Field Of Engineering, 2025: p. 19.
98. Qiang, Y., et al., *Fabrication of environmentally friendly Losartan potassium film for corrosion inhibition of mild steel in HCl medium*. Chemical Engineering Journal, 2020. **406**: p. 126863.
99. Ansari, F.A., *Applications of Solid Waste-Derived Carbon Nanomaterials in Anti-corrosion, in Waste Derived Carbon Nanomaterials. Volume 2*. 2025, ACS Publications. p. 267-294.
100. Wang, F., et al., *Utilization of carbon dioxide as a carbon precursor: Review on mechanism and morphology*. Journal of Cleaner Production, 2024: p. 142600.
101. Uhlenbruck, N., et al., *A Carbon Capture and Utilization Process for the Production of Solid Carbon Materials from Atmospheric CO₂–Part 2: Carbon Characterization*. ChemSusChem, 2025. **18**(5): p. e202401780.
102. Yeon, J.H., et al., *Generation of carbon nano-onions by laser irradiation of gaseous hydrocarbons for high durability catalyst support in proton exchange membrane fuel cells*. Journal of Industrial and Engineering Chemistry, 2019. **80**: p. 65-73.
103. Kausar, A., *Polyimide, polybenzimidazole-in situ-polyaniline nanoparticle and carbon nano-onion-based nanocomposite designed for corrosion protection*. International Journal of Polymer Analysis and Characterization, 2017. **22**(6): p. 557-567.
104. Kausar, A., *Polyurethane/Poly (2-chloro-5-methoxyaniline) and carbon nano-onion-based nanocomposite: physical properties and anti-corrosion behavior*. Materials Research Innovations, 2019. **23**(6): p. 345-353.
105. Swain, S.K., et al., *Carbon-Based Nanomaterials: An Overview*. Carbon Based Nanomaterials for Drug Delivery, 2025: p. 1-37.
106. Lucherelli, M.A., et al., *Carbon nano-onions: Individualization and enhanced water dispersibility*. Carbon, 2024. **218**: p. 118760.

107. Panda, P.K., et al., *Development of carbon composite coatings for fire retardancy and electromagnetic interference shielding*. Progress in Organic Coatings, 2024. **194**: p. 108628.
108. Babu, M., et al., *Electromagnetic interference shielding behavior of flexible PVA composite of tunicated onion bulb biochar/Co/carbon fiber shielding composite: effects on X and Ku band frequencies*. Biomass Conversion and Biorefinery, 2023. **13**(1): p. 409-416.
109. Venugopal, V., et al., *Advances in microwave absorbing and shielding materials: the role of zero-dimensional carbon nanoparticles*. Materials Technology, 2025. **40**(1): p. 2496318.
110. Kharisov, B.I., et al., *Less-common carbon nanostructures*. Carbon Allotropes: Metal-Complex Chemistry, Properties and Applications, 2019: p. 111-302.
111. Saini, V., et al., *Carbon nanoparticles of varying shapes as additives in mineral oil assessment of comparative performance potential*. ACS Applied Materials & Interfaces, 2021. **13**(32): p. 38844-38856.
112. Kant, K., R. Singh, and S. Maji, *Opportunities to improve the lubrication, fuel efficiency, and emission reduction using nanotechnologies: a review*. Journal of Thermal Analysis and Calorimetry, 2025: p. 1-27.
113. Jojith, R., M. Sam, and N. Radhika, *Recent advances in tribological behavior of functionally graded composites: A review*. Engineering Science and Technology, an International Journal, 2022. **25**: p. 100999.
114. Fiorini Granieri, S., et al., *High-power density turbostratic carbon nano-onion functionalized carbon paper electrodes for vanadium flow batteries*. Journal of Energy Storage, 2025. **121**: p. 1-12.
115. Dhongde, N.R., et al., *Synthesis of carbon quantum dots from rice husk for anti-corrosive coating applications: Experimental and theoretical investigations*. Industrial Crops and Products, 2024. **212**: p. 118329.
116. Liu, X.-R., et al., *Research on correlation between corrosion resistance and photocatalytic activity of molybdenum zinc oxide modified by carbon quantum dots pigments*. Dyes and Pigments, 2020. **175**: p. 108148.
117. Zhang, X., et al., *Low secondary electron emission characteristics of carbon nano-onion coating via plasma enhanced chemical vapor deposition*. Carbon, 2024. **219**: p. 118852.
118. Qiu, Z.-H., et al., *Synergistic enhancement of mechanical properties and corrosion resistance of ultralight carbon nano-onion reinforced LA141 metal matrix composites fabricated by friction-stir processing*. Materials Characterization, 2025. **223**: p. 114940.
119. Zhang, B., et al., *Toward accurate modeling and assessment of cement-based electromagnetic wave absorbers: Enabling absorption-dominant shielding via multilayered carbon fiber architectures*. Construction and Building Materials, 2026. **506**: p. 144880.
120. Belous, A., et al., *Composite Microwave-Absorbing Materials with Magnetic Constituents: State-of-the-Art and Possible Ways for Improving their Parameters*. Advanced Engineering Materials, 2026. **28**(3): p. e202502088.
121. Dai, Y., et al., *Onion-like carbon nanoparticles as additives in lubricant oil deform inelastically during the wear testing for improved lubrication performances*. Materials Chemistry and Physics, 2024. **314**: p. 128836.
122. Wang, Z., et al., *Current progress and challenges of electromagnetic wave absorbing materials at high temperature*. Advanced Science, 2025. **12**(30): p. e04286.