Chapter

Toxicity of 2D Materials and Their Future Prospect

Subash Adhikari

Abstract

Miniaturization of the devices in terms of size and the necessity of high speed device performance have created opportunities as well as challenges in the material research community. Nanomaterials like 0D and 2D materials are one of such material choices that can help realize the nanosize and ultrafast devices. However, the growth process of these materials, especially emerging 2D materials, needs to be reviewed in terms of human, animal and environmental toxicity along with the economic cost for synthesizing material. Moreover, the green and sustainable alternatives for minimizing or eliminating the toxicity should also be considered for the commercial scale nanomaterials synthesis and device fabrication. This topic will thus highlight the currently developed 2D materials, their growth process, application prospective, toxicity effect and their possible sustainable alternatives.

Keywords: nanostructures, 2D materials, growth toxicity, nanomaterial toxicity, green synthesis

1. Introduction

The need of efficient and convenient human lifestyle has induced new and innovative research in fields of food, agriculture, technology, construction, transportation, environment and health [1]. These modern global needs are possible with the use of new and more efficient materials and technology. In such, wide range of nanomaterials from zero dimensional (0D) quantum dots to one dimensional (1D) nanorods/nanowire and two dimensional (2D) sheet having large surface to volume ratio; ability to bind with various other materials; ballistic transport of charges; tunable optical, electrical and magnetic properties; low volume of material consumption; and superior overall performance than its bulk counterpart have shown various new possibilities in the field of health, technology developments, energy devices, transport, communication, computation and agricultural productivity [2]. Moreover, the rise of these nano-dimensional materials and nano-based technology have replaced many of the traditional industries ranging from electronic, optics, energy storage/production, pharmaceuticals, transport, cosmetics, agriculture, food production to material processing [3, 4]. At present the global nanotechnology market is worth 75.8 billion USD which mainly comprises industries related to electronic, sporting goods, automotive, energy storage, aerospace, defense, food and pharmaceutical [5, 6]. However, having superior physical and chemical properties than pre-existing bulk materials, the nanotechnology based products should have been a global need with high economic prospective. The major factors restraining the development of global nanotechnology market from its rise in early 2000 are toxicity of nanomaterial on human health and environment and stringent requirements of the government bodies on adopting the nanomaterials and nanotechnology in commercial products [3, 7, 8]. Nanomaterials have adverse toxicological effect on both animal and plant cells [9]. Nanomaterials upon interaction with body cell of an organism can have inflammatory response, dysfunction of organs, tissue damage, tumors and upon interaction with nervous system can accumulate in the brain leading to neurological diseases. Similarly nanomaterials upon interaction with plants can prevent plants protein, chlorophyll, carotenoids and biomass content as well as extend the plant harvest period [10]. However these effects are mostly observed in plants if high concentration of nanomaterials are used and more importantly, the use of synthetic nanomaterials which are non-biodegradable are primarily harmful for plants and humans.

Various global acts and forums like Pollution Prevention Act of 1990, regulations of European Union Observatory for Nanomaterials, Food and Drug Administration in United States (US), US Environmental Protection Agency, Intergovernmental Forum on Chemical Safety including many others have initiated governmental and global alliance to minimize the rising issue of chemical toxicity and hazard from nanostructure materials and its synthesis techniques on human, animal and environmental health [11]. The additional initiative of these acts and agencies are to prevent chemical waste, synthesize safer and less hazardeous chemicals and chemical products, use of natural resources against high toxicity materials and procedures, design of energy efficient procedures for material production, reduce derivative products and promote biodegradable and sustainable materials [12]. Currently, based on these policies and acts, the industrial application of various nanomaterials, nanocompounds and nanocomposites either as a final product or as an additive supplement have been approved after extensive research on toxicity, stability and the wide scale applicability [13].

These nanomaterial are synthesized mainly from physical, chemical and biological synthesis procedures. Among these, physical vapor deposition, chemical vapor deposition, sol-gel and colloidal methods are currently commercialized for large scale synthesis [14]. Moreover, the high cost required in the material synthesis, toxicity of the synthetic material and the synthesis procedure along with the environmental issues arising due to toxicity have led to the development of biological synthesis method which utilizes green chemistry approach for synthesizing nanomaterials [15]. Hence as an alternative, bio-nanomaterials produced from biological sources using green synthesis techniques are being extensively explored. Also green synthesis employs clean, cost effective, safe and environment friendly process of constructing nanomaterials using natural substrates like bacteria, yeast, fungi, algae and plants or agricultural resources [16]. Especially, carbon materials derived from plant and agricultural byproducts along with the organic chemicals derived from natural products can be used for synthesizing nanomaterial and nanocompounds. Similarly, thermal and hydrothermal synthesis techniques like biosorption, pyrolysis and hydrolysis can also be used for biologically synthesizing 2D nanostructures. Hence both these synthesis techniques produces bio-degradable nanomaterials without the use of synthetic chemicals. Moreover, biomass derived nanomaterials are non-toxic bio-nanomaterials that can be used safely in medicines, fertilizers, devices and cosmetic products.

In this review, we will mainly focus on the toxicity arising from the material synthesis procedure as well as the toxicity of the materials itself on human, animal and environment health mainly focusing on the 2D material family. We will also highlight the current research trend in utilizing green and sustainable procedure for synthesizing 2D materials.

2. Growth mechanism of 2D materials and their toxic effects

Among the class of nanomaterials, 2D materials are recently developed materials that exists in various materials forms. Present in layered form and bonded by the van der Waals (vdW) interaction, these materials in various form from metallic like graphene to semiconducting like Transition metal Di-chalcogenides (TMDs), insulating like hBN, superconducting like NbSe2, thermoelectric like PbTe and topological insulator like HgTe quantum wells [17, 18]. Also depending on the layer number and doping the optical, electrical and magnetic properties of these materials can be tuned. Because of these wide range of physical, chemical and structural properties that does not exist in bulk form and the additional advantage of flexibility, high strength and tunable bandgap, these materials are being considered for electronics, optics, optoelectronics, computing, transport, energy storage/production, health, drug design and agriculture industries [19–21].

The development of 2D materials started with the exfoliation process wherein bulk form of crystals arranged in layered structure through van der Waals (vdWs) interaction are exfoliated using a simple scotch tape. These exfoliated crystals were used for successful demonstration of various interesting low dimensional electrica, optical, optoelectronic phenomenon in room temperature like integer quantum hall effect, extremely high intrinsic mobility, ballistic transport, tunable bandgap, excitonic features, high optical transmittance and high quantum yield [22–27]. However, the limitation of material size within few micrometers in the exfoliated crystal and the manual operation process to obtain the 2D flakes are one of the major bottleneck for large scale device integration. Hence various other alternative synthesis techniques were developed using top-down or bottom-up synthesis approach. Moreover with the competitive research on developing large area and high quality 2D materials, various new and emerging synthesis techniques are developed. These techniques however, comes with various bottlenecks including quality of the 2D materials, size of 2D materials produced and more importantly the cost of the system and the human, animal and environmental toxicity that is associated with the synthesis techniques. The chapters below summarize the two main 2D material synthesis techniques based on their toxicity and cost.

2.1 Toxicity from top-down synthesis

Top-down synthesis based on solution is one of the cost effective, fast and scalable methods to obtain commercial scale 2D crystals [28, 29]. Here 2D crystals like graphene, various TMD materials like MoS2, WS2, Black Phosphorous and MXenes are obtained either using chemical based intercalation or liquid based exfoliation (LPE) [30–34]. Intercalation method mainly usages ion or molecule that can penetrate into the layers of bulk 2D crystal by weakening the van der Waals interaction either through driving force of reaction, attractive force of van der Waals and repulsive force of polarization between ions of same charge to disintegrate the 2D layers into individual 2D layers [35, 36]. The intercalation method can be carried out through electrochemical process, solution based and vapor based. In the electrochemical process ions like Li^+, Na^+, Co^{2+}, cetyl-trimethylammonium (CTA^+), tetra-heptyl

(THA^+), K^+, tetrabutylammonium (TBA^+) obtained from source electrolytes like LiC/LiO_2/$LiPF_6$/LiOxNy/LiOx, NaxOy, $CoSO_4$, cetyl-trimethylammonium bromide (CTAB), tetra-heptyl-ammonium bromide/N-methyl-2-pyrrolidone (THAB)/(NMP), KPF_6, tetra-butyl-ammonium bromide/dimethylglyoxime (TBAB)/(DMG) are used [37–40]. Among these Li ions the major ionic source that is commonly used for chemical exfoliation of 2D crystals. Similarly, in the solution based process metallic ions or molecules like Cu, Ag, Au, Sn, Pt, Mo, Fe, N2H4, $Co(Cp)_2$, etc. are used from the metal salts precursors. Moreover, in the chemical based intercalation process disintegration of ions occurs in presence of solvents like water, hexane, DMF, DEC, acetonitrile, toluene, acetone, isopropanol, etc. and the 2D layers obtained after exfoliation have to undergo treatment process like multiple washing in DI water, ultrasonication, AND centrifugation in organic solvents to obtain clean and isolated 2D crystals. Hence even though chemical based intercalation is much convenient process than mechanical exfoliation for large scale 2D materials synthesis, the use of toxic chemicals limits its wide scale application prospective. It is mainly because, commonly used intercalating metals like Li and Co has an increasing demand in battery manufacturing, aerospace industry, missile systems, radar and sensor industries [41]. Along with this, metallic Lithium is also considered health, physiochemical and/or ecotoxicological hazard according to the National Occupational Health and Safety Commission (NOHSC) [42]. Beside the metals that are used for intercalations, the organic solvents that are used for disintegration of metal ions as well as for cleaning the exfoliated 2D materials are also considered hazardous for human health and environment. Commonly used organic solvents like hexane, benzene, acetonitrile, DMF, toluene, acetone, isopropanol (IPA), chloroform and ethyl alcohol have shown acute oral toxicity in rats [43] as well as some of these commonly used organic solvents like benzene and chloroform are considered carcinogen by United States and European Union with sever toxicity to humans and environment [44]. Similarly alcohols like ethanol, methanol, IPA are considered toxic alcohols as it can damage human organs like retina, liver, kidney and brain with excess consumption and it can also increase risk of certain types of cancers [44–46].

Liquid phase exfoliation can be a substitute to chemical intercalation method for 2D material exfoliation as it is simple physical method that usages external forces like high intensity ultrasound mediums like high power sonic probes, sonic baths and tip ultrasonicators [47–49]. This has been used in exfoliation of graphene and other 2D materials like black phosphorous, boron nitride including various TMDs and topological insulators [50–53]. However, due to the high external vibrations, the exfoliated 2D layers are usually non-uniform in size and thickness and there is a high possibility for the phase transition of 2D materials during exfoliation process [54]. Hence the process requires stabilization and sorting after exfoliation [55]. These process are carried out using various organic solvents including polymers, co-polymers and alcohols like DMF, odichlorobenzene, N-methyl-2-pyrrolidone, octylbenzene, poly(styrene co-butadiene), polystyrene, poly(vinyl acetate), polycarbonate, ethanol and IPA for exfoliation of various 2D materials including graphene, TMDs and topological insulators [44, 56–61]. Moreover, all these organic polymers, co-polymers and alcohols have high toxicity [43, 44, 62] and many of these organic solvents even have high boiling points thus producing aggregated and unstable 2D layers [55]. Beside these, other top-down method that can be used for exfoliating 2D materials are laser based exfoliation and ball milling assisted exfoliation. However, ball milling produces non-uniform flake size of 2D crystals [63, 64] and laser based exfoliation is known to create various defects during the exfoliation process mainly from the heat generated in the exfoliation process [65, 66]. Hence even though there is no toxicological effect in these 2D materials synthesis process, the quality and size of flake is the major issue that has inhibited in using these techniques.

2.2 Toxicity from bottom-up synthesis

Various limiting factors like grain size, defects, uniformity and mainly the toxicological effect of top-down synthesis techniques has inhibited its commercialization prospective. However, with the development of chemical vapor based 2D materials synthesis technique, wafer scale and layer controlled grown of various kind of 2D materials like graphene, MoS_2, $MoTe_2$, WS_2, WSe_2 and hBN have been possible [67, 68]. Additionally, high purity and commercial scale 2D materials with controlled morphology, crystallinity and defect engineering is possible with the CVD. Here 2D materials are synthesized at high temperature through the chemical reaction of gaseous substances which react in the gas phase to produce 2D materials on various metallic and insulating substrates. For example CVD graphene having 3–4 layers was first grown in nickel surface [69] and later high quality, centimeter scale monolayer graphene using methane gas as a carbon precursor were grown on copper foil [70]. Moreover, with the use of high quality copper film with large grain boundaries and using polished copper surface to enhance the graphene grain size are currently practiced to produce few tens of centimeter scale polycrystalline graphene flakes [71]. However, these large scale graphene are grown in high temperature and high pressure systems which are expensive, requires complex preparation process and more importantly usages gaseous materials like methane which are toxic in nature [72, 73]. Listed as a greenhouse gas, methane is highly flammable and can ignite even a relatively low pressure and low concentration levels and possesses various health hazards including coma and death due to deprived oxygen level when inhaled [74–76]. Hence either high level of safety has to be ensured in CVD based graphene growth system which required additional expenses in producing graphene or alternate synthesis routes has to be considered.

Besides graphene, CVD is also one of the primary tools for the synthesis of TMD materials. Millimeter scale poly-crystalline monolayer MoS_2 on SiO_2/Si were first reported by Lee et al. [77] using MoO_3 and S powders as a precursor material synthesized at 650°C in a nitrogen environment. After the successful demonstration of large area monolayer MoS_2, the same method were replicated for the synthesis of other TMD materials like $MoSe_2$, WS_2, WSe_2 and $MoTe_2$ simply by tuning the metal precursor and chalcogenides precursors. However, melting temperature of pure chalcogenides are lower than 500°C while transition metals have melting temperature >2000°C [78]. Hence high quality and uniform crystals in large area are difficult to achieve using a single zone furnace in TMDs synthesis. For this, instead of using a single heating zone for both transition metal and chalcogenide, two or three temperature zone CVD furnace for heating the transition metal, chalcogenide precursor and/or the substrate separately are used for growing wafer scale high quality TMDs [79]. Thus controlling various parameters like temperature, pressure, gas flow rate and precursor concentrations are key to obtaining high quality and large scale monolayer TMDs. Moreover, the complexity of the CVD system and the gas precursors required for growth like Ar, N and Hydrogen as activating agent, surface cleaning, impurities/defects reduction, transport agent and surface states/precursor molecule reduction makes TMD synthesis an expensive process [80, 81].

In addition to this, the toxicity of some transition metals and chalcogens are another important issue that needs to be considered. Especially molybdenum, selenium and tellurium are the major elements that are known to be toxic. A toxicology study conducted by Franke and Moxon [82] on Albino rats fed with salts of molybdenum, tellurium and selenium at levels of 25 and 50 parts per million of the elements in their diets showed that selenium salts had the highest toxicity causing distinct disturbance of the hematopoietic systems while tellurium and then molybdenum showed lower toxicity effects. Additionally, another study conducted by Larner [83] in rats showed that tellurium can damage mitochondria and produce defects in mitochondrial energy metabolism that can eventually produce cognitive impairment and cerebral lipofuscinosis. The high concentration of Selenium is known to cause blindness and premature deaths [84] while acute Tellurium can cause glad malfunctioning and paralysis of nervous systems [85].

Also elemental tellurium has been known to cause significant neurotoxicological effects in animals even though they are poorly absorbed by gastrointestinal tract [86]. It was also observed from the study that fumes of tellurium dioxide and volatile tellurium esters can be easily absorbed through the lungs and skin. Beside elemental toxicity, hydrogen selenide is also known to be toxic for human health which when absorbed through lungs can cause pallor, nervousness, depression, languor, dermatitis and gastrointestinal disturbances [87]. Moreover, CVD based growth of TMDs relies mostly on compound like tellurium and selenium which undergoes vapor based reaction under nitrogen, argon and hydrogen environment. Hence the possibility of fume production as well as production of toxic ternary compounds of calcogenide including hydrogen selenide and hydrogen telluride are possible [88]. Moreover, there are other bottom-up synthesis techniques which can produce high quality 2D materials like Molecular Beam Epitaxy, Magnetron Sputtering and Pulsed Laser deposition. But these techniques can produce 2D materials within few tens of micrometer and the operation of these systems requires high vacuum well as the system are complex and expensive to operate [89–91].

3. Toxicity of 2D materials on human, animal and environment

The interesting optical, electrical and magnetic phenomenon in 2D materials at an atomic dimension have developed new research avenues in industrial sectors of electronic, opto-electronic, energy harvesting/production and health. More importantly, in the field of biology for drug discovery/design, drug delivery, nano biomedical equipment development and cellular level research, nanomaterials is considered an important tool. It is mainly because, nanomaterials due to their atomic dimension; high surface area; tunable electrical, optical and magnetic properties; ballistic transport of carriers and high optical gain can enhance the optical/electrical response in disease detection, increase the drug loading efficiency, ensure targeted drug delivery within specific region of cell and organs for disease cure, promote the development of nano-chips and nano-kits for disease diagnostic and more importantly minimize the cost of disease detection and prevent organ damages in animals [21, 92–94]. However, 2D materials are in its early stage of development. Even though various new materials are being developed in material research communities around the globe, many of these materials have not been tested for its toxic effect in human and animals [95]. Besides the toxicity effect of 2D materials on animal, environmental toxicity is another important aspect that needs to be considered with the rapid development of new and emerging 2D materials. Since 2D materials have high strength, high melting temperature and are confined in atomic dimensions, they can neither be filtered, incinerated or collected for disposal with normal equipment and techniques. Hence, once these 2D materials are released or dumped in environment as a waste, they will pollute the soil, air and aquatic environment. Moreover, the toxicity induced by 2D materials can further enhance the soil, air and aquatic health in addition to the material based toxicity. In such, specific and in-depth toxicological studies are being carried out in order to find the material toxicity on both human and environment. These finding are summarized below.

Primary research on the toxicity effect of graphene started in 2010, soon after the discovery of graphene in 2004. A study by Zhang et al., in 2010 studied the in vitro toxicity of graphene using neuronal PC12 cells [96]. Reactive oxygen species (ROS) which are usually generated in human cell during mitochondrial oxidative metabolism as well as during cellular response to xenobiotics, cytokines and bacterial invasion [97], were generated even at a low concentration of 0.1 μg/ml concentration. ROS were also generated with graphene studied on human primary umbilical vein endothelial cells [98]. The study also concluded that besides ROS, few layer graphene can exert cellular toxicity employing oxidative stress, in HUVEC cells altering critical cell parameters like cytoskeletal dysfunction, reduction in metabolic activity, compromised plasma, membrane integrity, lipid peroxidation, ionized calcium and deposition of mitochondrial membrane potential. Moreover, ROS generation is known one of the major cyctotoxicity from graphene based 2D materials. Especially functionalized graphene or reduced graphene oxide (rGO) are one of the primary 2D materials that are known to generate ROS activities in human and animal. Graphene oxide based study on human using HEK 293T cells showed activated ROS generation with increase DNA damage [99], in vitro and in vivo studies on human corneal epithelium cells and human conjunctiva epithelium cells showed increased intracellular ROS [100], graphene oxide incubated with human plasma having different diseases exhibited ROS production together with lipid production and increased nitrogen oxide levels [101], and in vitro study in GLC-82 pulmonary adenocarcinoma cells showed ROS production and apoptosis with dysregulation of cell cycles [102]. Similarly, studies of graphene oxide on animal using chorion of zebrafish embryos also showed high generation of ROS including DNA damage and apoptosis [103, 104]. W1118 flies studied with low concentration of graphene oxide showed excessive accumulation of ROS with rapid weight loss, developmental delay thus reducing lifespan [105] and industrial organism like Pichia Pastoris under graphene oxide showed accumulation of ROS with cell membrane damage [106]. Other forms of carbon like graphene nanosheets also showed increased ROS activities in studies carried out on embryonic stem cells derived cells [107].

Apart from graphene based 2D materials, cytotoxicity studies using TMDs also have shown cellular toxicities in animal and environment. However, few of the 2D TMDs like MoS_2, hBN, WS_2 and WSe_2 have been studied for toxicity effects. MoS_2 dispersed in Pluronic F87 in liver cells have shown to induces dose-dependent cytotoxicity [108], human macrophages with MoS_2 can trigger cell stress and inflammatory response [109], and analysis of pulmonary hazard with aggregated MoS_2 induces strong proinflammatory and profibreogenic responses [110]. Similarly, studies with MoS_2 on Zebrafish embryos showed high toxicity affecting amino acid and protein biosynthesis and energy metabolism [111], eggs of Gallus gallus domesticus with MoS_2 showed growth defects and deaths [112], and mice exposed to MoS_2 via food showed Mo accumulation in mouse organs changing the intenstinal microbiota [113].

In study with chemically exfoliated WS_2 nanosheets in Algae showed oxidative stress, lipid peroxidation, membrane damage and photosynthesis inihibition [114], WSe_2 nanosheets on A549 cells showed reduced cell viability [115], hBN induced oxidative stress in rats by modulating thiol/disulfide homeostasis [116].

Similarly, the toxicological effects of 2D materials on plant and species have also shown various toxic effects on plant cells. For example, graphene can affect root and shot growth, biomass shape, cell death and influence ROS of cabbage, tomato, red spinach, and lettuce inhibiting plant growth [117], germination and growth of rice seeds can be affected by graphene by inhibiting stem length [118], grassland soil exposed to graphene can alter the bacterial communities [119], graphene oxide exposure to leaves of cabbage, spinach and tomato decreased size and number due to oxidative stress-mediated cell death [117], absorption of graphene oxide by roots of *Vicia faba* showed increased oxidative stress [120], wheat germination was inhibited with graphene oxide exposure by accumulating in the root and inducing oxidative stress [121], effect of MoS_2 on *Chlorella vulgaris* showed cell distortion and deformation [122], and unstable 2D materials like 1T MoS_2 in the environment can easily oxidize releasing the Mo ions which have high bioactivity in plants [123].

Besides these 2D materials there are several other 2D materials like topological insulators, perovskites, Metal-Organic Frameworks and 2D Oxides that are identified in research community. However, those materials are still in their early phase of research and still far from the commercialization prospective. Moreover, toxicity is one of the major issue that needs to be addressed before the materials are commercialized for practical applications. Hence simultaneous research on the application prospective as well as their toxicity study on human, animal and environment for specific materials that have high potential to be used by industries needs to be initiated.

4. Sustainable alternatives for synthesis of 2D materials

As mentioned in the previous section, toxicity is one of the key aspects of these emerging and highly potent 2D materials family which might inhibit its future practical applications. In such, either minimizing the hazard in synthesizing the materials, using less toxic chemical during material synthesis, completely replacing the material sources and synthesis process into sustainable alternatives or using other alternative materials having similar properties but with less hazard and toxicity are the only prospective for commercializing the materials and their functional devices. Various acts on environment protection have already directed the industrial communities to adhere to the principle of minimizing health and environmental hazard to human, animal and environment. Low material toxicity will also eventually help realize the biological application of 2D materials in drug synthesis and target drug delivery which is expected to provide better health treatment to living organisms [124, 125]. To achieve 2D materials with low toxicity, there are primarily two different resources: (i) using natural product resources like forest and agricultural waste as the source materials to derive 2D materials and (ii) using green synthesis techniques like plants based phytochemicals or microbes to synthesize 2D materials. Especially for synthesizing carbon materials, abundantly available biomass resources like forest and agricultural waste which contains around 55 wt% of carbon can be utilized [126]. Similarly, various phytochemicals derived from forest and agricultural resources and microbes like bacteria, fungi and yeast can be used in reducing various metal salts and compounds into nanostructure forms [127, 128]. Both these synthesis mediums utilizes green and sustainable resources hence producing toxic free and green nanomaterials.

Among the 2D materials family, carbon based 2D materials like graphene, graphene oxide and reduced graphene oxide have been successfully synthesized using the green synthesis technique. Using biomass as a source of carbon precursor, carbon gas can be generated which acts a natural carbon source to graphene synthesis. Mostly, low temperature carbonization of biomass to obtain pure carbon followed by high temperature graphitization yields layered graphene using the green synthesis technique [129, 130]. The successful demonstration of large area monolayers graphene synthesis on copper foil using forest resources like Camphor leaves was carried out by Kalita et al. using pyrolysis of camphor leaves in CVD at 1020°C [131]. Using similar approach, various biomass resources like rice husk, sugarcane bagasse, wheat straw, palm oil waste, fruit waste, soyabeans, newspaper, populous woods and various other lignin based biomass have been used to synthesize monolayer and few layer graphene. This has been reviewed in depth by Safian et al. and [132] and Saha and Dutta [133].

Apart from carbon based materials which are abundant natural resources, there are not much report on the green synthesis of TMDs and other 2D materials. This can be primarily because there are no natural resources for TMDs that are abundant and easily available in nature, as like carbon. Beside this, the reaction kinetics of transition metal with chalcogenide occurs with specific molecular structure which might be difficult to achieve with nature based resources. However, nanomaterial form of TMDs like CdS, CdSe, CdTe and its other ternary phases have been reported using green synthesis technique [134–136]. Here, greener synthesis are achieved primarily by using either non-toxic synthetic chemicals like hexylphosphonic acid (HPA) or tetradecylphosphonic acid (TDPA) or by aqueous or hydrothermal synthesis techniques using non-toxic chemical solvents like thiogycerol and mercaptopropionic acid (MPA) with metal salt precursors. This successful demonstration of nanomaterial form of TMDs further suggests that using less toxic synthetic chemicals and environmental conditions, synthesis of 2D materials are possible.

High temperature synthesis is another important factor that can induce reaction of precursor gases with oxidizing agents and environment to produce toxic gases and toxic chemicals. However, in the case of green synthesis the low temperature required for synthesis as well non-toxic precursor gases and solvents assures that there is no induced toxicity during material synthesis. This is thus an important prospective of selecting green synthesis techniques that is safe, non-toxic and economic to human and environment.

5. Conclusion

Tunable and quantum level electronic, optical and magnetic phenomenon in monolayer and few layer 2D materials makes it an unique and important material choice of twenty-first century. It is believed that the next generation of technology will be driven by low cost, low material volume, high speed, compact, flexible and tunable material properties and 2D materials are the only material choice that can incorporate all these interesting features. Moreover, growing concern of human and animal health is becoming a global issue. New and effective drug that can penetrate the specific region of human bodies; smart, effective and non-invasive biomedical and medical equipment; low cost and effective health care and management can only be achieved by using nanoscopic, high speed and highly efficient technologies using nanomaterials and nanodevices. Another important aspect of human development is quality of food and life. Global scale infertility of soil and chemically modified food using pesticides and insecticides have polluted soil, water and environment. Considering all these issues and choosing a right solution can be effective use of nanomaterials and nanotechnology. Moreover, this can only be possible if the material does not add any additional toxicity to the human, animal and environment health. Hence along with the development of nanomaterials and nanodevices using 0D, 1D or 2D materials, consideration should be taken in understanding the toxicity aspect of the material itself. The fast and growing research trend in 2D and 0D materials should be consistent with the toxicity study and long term toxicological effect of these materials on various global aspect. In doing so, high prospective materials that have instrumental effect on health of human, animal and environment can be industrially developed together with the pace of human needs and requirements.

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Author details

Subash Adhikari[1,2]

1 Madan Bhandari University of Science and Technology, Lalitpur, Nepal

2 Unnati Data Mapping and Mining, Hetauda, Nepal

*Address all correspondence to: subashadhikari@hotmail.com

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