A Review on Environmental and Economic Impact of 2D Nanomaterials-Based Heat Transfer Fluids

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2D nanomaterials-based heat transfer fluids show excellent thermal properties due to their large specific surface area; hence, they find large-scale applications in automobile industries and cooling processes. Therefore, it is very essential to study the environmental and economic aspects of these 2D nanomaterial-based nanofluids. In this review, we have discussed the environmental impact of 2D nanomaterial-based heat transfer nanofluids under various conditions. The environmental impact analysis of these materials has shown excellent capability in reducing the energy consumption for heat transfer operations. Moreover, the possibility of nanomaterials and base fluid recovery makes it a sustainable alternative. In addition, health risk assessment on humans, cytotoxicity, and life cycle analysis have also been explored. The price-performance index has been successfully used to study the economic impact of 2D nanomaterial-based heat transfer fluids. The overall economic impact of 2D nanomaterial-based heat transfer nanofluids provides an optimistic perspective over conventional heat transfer fluids. Moreover, graphene production, market trend, and commercialization obstacles were also discussed.

1. Introduction

1.1. 2D Nanomaterials as a Heat Transfer Fluid. From the overview of the second law of thermodynamics, heat transfer is the transmission of heat due to the temperature gradient. Heat transfer technologies apply virtually to any area which requires the addition or removal of heat, such as refrigeration, energy production, and air conditioning systems. Heat transfer fluids such as ethylene glycol, oil, and water, which are commonly used, have very poor thermal conductivity, leading to low heat transfer efficiency [1].

In the late 20th century, the advent of nanoscience and nanotechnology and its accelerated growth led to the development of ways to enhance the thermal convection coefficients of operating fluids in heat transfer applications using nanoparticles, known as nanofluids. Nanofluid is a modern kind of heat transfer medium that comprises nanoparticles (1-100 nm) that are dispersed in a base fluid uniformly and stably. These scattered nanoparticles, typically a metal or metal oxide, dramatically boost the nanofluid thermal conductivity and increase the conduction and convection coefficients, facilitating further heat transfer.
2D nanomaterials such as graphene nanosheets, molybdenum disulfide (MoS$_2$) nanosheets, tungsten disulfide (WS$_2$) nanosheets, hexagonal boron nitride (h-BN), and MXenes (M$_{n+1}$AX$_n$ (n = 1, 2, 3)) are some of the common nanostructures for the preparation of nano fluids as an alternative coolant for replacing conventional heat transfer fluids because of their unique structure and superior properties [2–6], where M is a d-block transition metal (such as Ti, Sc, and Cr). In MXenes, A is a main group element and X is either C or N atom. However, the thermal properties of such fluids are affected by various factors such as the concentration of nanosheets, temperature, stabilizer concentration, and material properties such as size, shape, and thermal conductivity [7]. Other commonly used nanostructures can be classified into ceramic particles, pure metallic particles, and carbon nanotubes (CNTs) [8]. These nanoparticles and their derivatives as nano fluids for heat transfer are being extensively studied due to their exceptionally high thermal conductivity. Since the particle size and concentration of nanoparticles in the operating nano fluid had a major impact on its thermophysical properties, further investigation and optimization of these parameters are required. In addition to nano fluid, 2D materials also find other applications such as in transistors, photonics, optoelectronics, storage device, sensors, and catalysis [9–12]. They also find application in biomedical, health, and environmental monitoring [13–16].

Figure 1 represents the number of research articles from a search engine for different 2D nanomaterials in the titles, abstracts, or keywords from 2010 to 2021 in Elsevier.

Figure 1: Research articles from a search for different 2D nanomaterials in the titles, abstracts, or keywords from 2010 to 2021 in Elsevier.

2D nanomaterials, use of MXenes is gaining more attraction since 2020. Moreover, since the invention of the mechanical exfoliation process a decade ago, more than 10,000 patents have been awarded to graphene-related technologies [17]. By 2022, the worldwide graphene market is expected to surpass 200 million USD [18]. As a result, it is critical to examine such materials and emerging technologies with such distinct characteristics and widespread use and demand. Owing to the huge demand in the future, environmental and economic impact assessments of 2D nanomaterial-based heat transfer fluids will be considered a major area of research for academics and the industrial sector. Recently, many companies have started launching graphene-based heat transfer fluids for commercial products such as lubricating oils and engine oils. Italy has launched a new lubricating oil synthesized using graphene which shows less wear and tear in engine parts, thereby enhancing the engine performance [19]. A Malaysian group from Sunway University has launched and commercialized graphene-based lubricants with brand name “Infinoil” for application in automotive and industrial sector [20]. Thus, there is a huge potential for 2D-based heat transfer fluids in the commercial market.

1.2. 2D Nanomaterials in Heat Transfer Applications. 2D nanomaterials have drawn significant interest for many applications because of their high specific surface area, surface-to-volume ratio, and distinct physicochemical properties. A majority of these applications enhance heat transfer using coatings in heat exchangers, nano fluids, thermal interfacial materials in batteries, semiconductors, and electronics such as wearable devices, while some use composites and nanomaterials in photothermal therapies. A list of 2D nanomaterials with their specific surface area is given in Table 1.
Thermal interface materials (TIMs) are used to improve heat dissipation by sandwiching the layer between the heat source and the heat sink. TIMs include phase change materials (PCM), thermal pastes, thermal tapes, thermal adhesives, thermal gap fillers, and thermal conductive pads. The most promising possibilities for thermal dissipation of electronic devices are carbon-based TIMs (Figure 2) [34]. For instance, a nearly 338% increase in thermal conductivity was reported by Ye et al. [35] after applying graphene-Cu to crosslinking polyurethane as a foam interface material. Daneshazarian et al. [36] assessed the nanoenhanced PCM for thermal storage and reported a 12.6% increase in the heat storage rate. A study on paraffin-based PCM using nanocarbons was performed by Sun et al. [37], which concluded that nanographite was more effective than nanococonut shell charcoal in melting the PCM. Moreover, Wen et al. [38] studied the effect on the thermal resistance of thixotropic ZnO nanoparticle paste for TIM in a light-emitting diode and found that the lowest thermal resistance was obtained at 50% filler concentration. Wang et al. [39] have reported the use of MXenes in Ag/epoxy composite, thereby increasing the thermal conductivity by 24.7%. A similar report by Ji et al. [40] shows that the MXene/Ag-epoxy nanocomposite is used as a thermal management material.

Coatings, like TIMs, are used to improve heat transfer by reducing heat loss. In an experimental study, Afra et al. [41]
used ceramic- and silica-based nanocoatings to minimize heat loss in steam injection tubes. The heat transfer coefficient increased 2.5 times, and heat losses were decreased by ~45 percent. In addition, the use of 2D nanomaterials increases the heat transfer properties and the corrosion resistance. Bordbar et al. [42] analyzed the performance of silver nanoparticles in polyurea coating on the internal tubes of a gas heater and obtained optimal thermal efficiency as well as a significant improvement in corrosion behavior.

Another notable application of nanostructures is photothermal therapy for cancer treatment. It employs nanoparticles to transform near-infrared light into heat for cell ablation. Chang et al. [43] found IR-780 modified hydroxyapatite nanorods as photothermal agents and reported an efficiency of 69.3% followed by photostability after four irradiation cycles. Furthermore, Li et al. [44] assessed polymer nanoenzymes for enhanced cancer therapy and observed a 3.5-fold enhancement in photothermal therapy. Rosenkranz et al. [45] have demonstrated Ti$_3$C$_2$T$_x$ nanosheets (MXenes—few and multilayer) having higher compatibility and conversion of light to heat towards better efficacy in inhibiting growth of S. aureus and E. coli bacteria. Jakubczak et al. [46] discussed the potential application of novel 2D transition metal borides (MBenes) in various biotechnological fields.

A variety of research studies focus on improving the thermal effectiveness of solar collectors using graphene-based heat transfer fluids. Al-sulttani et al. [47] have recorded an increase in thermal effectiveness of ~12.5% for 0.1 wt% graphene loaded ethylene glycol and water-based nanofluids in flat plate solar collectors. A comprehensive review of thermal performance of the solar collector by the addition of graphene in heat transfer fluid recorded by Mahamude et al. [48] shows superior thermal performance. Various other studies on the thermal efficiency of the solar collector using graphene nanoplatelet-based heat transfer fluid shows an enhancement of ~24% at 0.1 wt% loading (Kumar et al. [49]). A similar work done by Ahmadi et al. [50] shows an increase in thermal efficiency of ~19% at 0.02 wt% graphene nanoplatelet loading in water as base fluid. Akram et al. [51] have also shown an increase of thermal performance by ~18% using graphene nanoplatelet (0.1 wt% in water). Sarsam et al. [52] have evaluated the effect of the specific surface area of graphene nanoplatelet and found that the efficiency of the solar collector is directly proportional to the specific surface area of the nanomaterials. Vakili et al. [53] have evaluated the performance of domestic hot water systems where graphene nanoplatelet-based heat transfer fluid is used. An efficiency improvement of 33% was recorded by merely adding 0.005 wt% graphene nanoplatelet in water. Many reports have also recorded the improved thermal efficiency of photovoltaic thermal systems using graphene and MXene-based nanofluids (Wahab et al. [54] & Abdelrazik et al. [55, 56]). A schematic of such PV/T systems is shown in Figure 3. Other 2D nanomaterials have also been used in the solar collector application for enhancing its thermal efficiency. Al-sarraf et al. [57] have reported the use of MoS$_2$-based nanofluid. 2D MoSe$_2$-based nanofluid shows an increase in thermal conductivity by

![Figure 3: Schematic of PV/T system with nanofluid as (a) coolant, (b) spectral filter, (c) coolant and spectral filter with the double-pass channel, and (d) coolant and spectral filter with separate channels [63].](image-url)
~11% for its application in concentrating solar power [58]. Martinez-Merino et al. [59] have reported 26% increase in the heat transfer coefficient of the concentrated solar plant by incorporating 2D WSe₂-based nanofluids. Hazra et al. [60] have investigated the thermal characteristics of hexagonal boron nitride-based nanofluids for solar collector application. Asfattahi et al. [61] have reported the mean thermal efficiency of MXene-based nanofluid in a solar dish collector. Approximately 15% exergy efficiency was recorded by Said et al. [62] in a parabolic trough solar collector using MXene-based silicone oil nanofluid.

1.3. Environmental Impact of 2D Nanomaterial-Based Heat Transfer Fluids. While 2D nanomaterial-based heat transfer fluids have proven to be a better alternative than conventional heat transfer fluids, it is also important to compute their impact on the environment. Numerous processes require heat transfer fluids such as energy transfer (nuclear and renewable energy), air-conditioning, and heating. Although the present studies lack in evaluating the environmental impact of the 2D nanomaterial-based heat transfer fluids, a few authors illustrate that these nanofluids offer a sustainable solution.

Various criteria, such as the heat transfer coefficient, emission analysis, thermal conductivity, pressure drop due to viscosity change, and energy efficiency, need to be weighed when determining the environmental effect of heat transfer fluids. In general, energy efficiency is the ratio of the energy output to the overall energy input. In addition to energy efficiency, Sundar et al. [64] measured the thermal performance factor for the growth in the Nusselt number and the friction factor. It was used to measure the relative improvement in system performance.

The thermal performance factor (η) is calculated using

$$\eta = \frac{\text{Nu}_{nf}/\text{Nu}_{bf}}{(f_{nf}/f_{bf})^{1/6}},$$

where Nu is the Nusselt number and f is the friction factor (nf represents nanofluid and bf represents the base fluid).

A comparative study showed that energy efficiency improved to 83.51% by using Al₂O₃-water nanofluids in a solar collector (Said et al. [65]). Similarly, a 40% improvement in the heat transfer coefficient was found while using Cu nanoparticles instead of water [66]. Another investigation showed a large improvement in the nanofluid (aluminum oxide and copper oxide) convective heat transfer coefficient relative to ethylene glycol, varying from 2% to 50% [67], whereas while using multiwalled carbon nanotube solution, high thermal efficiency of 33.81% was obtained [68].

Renewable energy is a promising and much-needed field as per the present environmental conditions, and hence, harnessing energy from such sources must be efficient. 2D nanomaterial-based heat transfer fluids are more efficient due to their high surface area and high thermal conductivity. This also leads to size reduction of the apparatus, as shown by Sundar et al. [64]. This results in less CO₂ emission and more eco-friendly processes. Although the emissions are low during nanoparticle synthesis, they should be taken into account while computing the environmental impact.

1.4. Environmental Impact Analysis on a Synthesis of 2D Nanomaterial. Despite the widespread use and advantages of 2D nanomaterials, their production has a detrimental environmental impact that must be assessed. The improper disposal of effluents from the 2D nanomaterial production process and poisonous emissions has had a negative impact on ecosystems and human health [69]. Nanomaterials are typically manufactured using techniques such as chemical vapor deposition (CVD), chemical reduction, the sol-gel process, pulsed-laser ablation, and physical processes [70–75].

The CVD process achieves high yield processing of carbon nanotubes (CNTs) and other multifunctional 2D nanomaterials at an industrial scale at comparatively low cost and is thus regarded as a common technique for 2D nanomaterial manufacturing [76]. An environmental impact study for preparing CNT using CVD using life-cycle assessment was performed by Trompeta et al. [77]. Emission analysis, effluent discharge, and power generation were all considered, and their environmental effects were assessed for two different pathways of CNT production by CVD. Furthermore, Singh et al. [69] used SimaPro 7.0 software to perform an environmental impact study of CNT production and observed smog formation as well as the formation of unconventional effluents such as Fe₂O₃, Co₃O₄, MoO₃, and NaOH. While the effects of these effluents could not be measured due to software constraints, it was recommended that these effluents be treated to reduce their environmental impact.

In addition, the chemical reduction methods used to prepare 2D nanomaterials in the past resulted in surface degradation and cytotoxicity [78, 79]. Kabashin & Meunier [80] addressed the toxicity issue by improving the laser ablation process to produce biocompatible gold nanoparticles in the absence of toxic by-products. High-purity 2D nanomaterials can be fabricated using the laser ablation technique without producing any harmful emissions or by-products [70].

Despite the fact that there is substantial literature on the synthesis of 2D nanomaterials using various approaches, their environmental effects have received little attention. Proper by-product analysis and disposal methods are needed to analyze the process’ environmental footprint effectively. Efficient recovery of the base fluid and nanostructures from the nanofluids will have a major environmental impact by restricting the pollution of water bodies. Thus, designing and developing a suitable recovery process such as centrifugation followed by evaporation of supernatant play a crucial role in the recovery. Thus, we propose a possible scheme for the former discussed method as shown in Figure 4.

1.5. Health Risk Assessment of 2D Nanomaterial. In general, novel materials and chemicals have posed health and environmental risks, such as polychlorinated biphenyls, dichlorodiphenyltrichloroethane, tributyltin, benzene, and halocarbon emissions; thus, they must be properly assessed to eliminate any health hazards [81]. According to several studies, nanoparticles could aggregate in the lungs, alimentary tract, liver, heart, spleen, kidneys, and cardiac muscle.
The potential health risk of these nanomaterials such as graphene and MoS2 [87]. The potential health risk of 2D nanomaterials such as graphene materials [86]. For instance, researchers investigated the potential of TiO2 nanostars to be more hazardous to human embryonic osteoblasts, osteosarcomas, and pancreatic duct cells [89]. Sato et al. [88] reported that Cu nanoparticles were hazardous to human cells at 20 mg/L and that the effects were caused by physical disruption to cell membranes. Moreover, Wang et al. [108] investigated the impact of graphene oxide on human fibroblast cells and mice. Doses more...
than 0.4 mg/L and 50 mg/L were shown to be harmful in mice and humans, respectively. Inflammation in the lung, liver, spleen, and kidney was indicated as a harmful consequence in mice. It was believed that due to its size and structure, graphene is difficult for the body to dispose of, resulting in poor elimination.

The Quantitative Structure-Activity Relationship (QSAR) method is a straightforward way of effectively forecasting bioactivity prior to synthesis. To estimate the cellular absorption of 109 functionalized magnetofluorescent metallic nanoparticles, Qi et al. [109] developed two nano-QSAR models. Their molecular structure characteristics were defined using the Simplified Molecular Input-Line Entry System. The most significant considerations for cellular absorption were discovered to be atom count, molecular weight, and mass percentage of carbon atoms. However, calculating the toxicity of all viable nanoparticles is problematic due to the vast number of newly functionalized nanoparticles currently available in biological fields and the high cost and long time needed to assess their absorption level in different cell lines.

1.7. Life Cycle Assessment Analysis of 2D Nanomaterial Production. The Life Cycle Assessment (LCA) technique is designed to calculate the effects of goods on the environment and the resource. This approach may be used to evaluate effects across a product life cycle, from the extraction of raw materials to manufacture and usage to its lifespan [110]. Figure 6 provides a schematic representation of several key factors in assessing life cycles. Solid arrows indicate materials and energy flows, whereas dashed arrows show the process of evaluating the life cycle.

Several LCA studies have been conducted on nanomaterials; those that have been conducted typically find manufacturing to be significantly more energy-intensive than traditional materials, despite the fact that production decisions, for example, precursor selection and process temperature, can severely influence life cycle energy consumption and related environment issues [111]. Although the production of nanoparticles requires a significant amount of energy, this might be offset during use if the nanomaterial outperforms traditional materials [112]. For instance, using self-cleaning nanoparticle coating to remove maintenance

### Table 2: Health risk of different 2D nanomaterials.

| Sl no. | Name of 2D nanomaterial | Associated health risk | References |
|-------|-------------------------|------------------------|------------|
| 1     | Graphene                | Hyperpermeabilization of the intestine, impairing the defecation ability | [87] |
| 2     | Molybdenum disulfide    | Decrease in the alanine aminotransferase (ALT) level and platelet counts | [87] |
| 3     | Tungsten disulfide      | Inflammation and fibrosis in lungs | [91] |
| 4     | Hexagonal boron nitride | Mild toxicity at high dose (0.4 mg/mL) | [92] |

Figure 5: Exposure pathway, circulation, distribution, and final excretion of nanomaterials inside the human body [86].
during usage balances the rise in environmental effects during the manufacturing process [113]. It was also shown that using a graphene-reinforced lightweight composite material can result in a net decrease in life cycle energy consumption [114]. Arvidsson et al. [115] performed a LCA of graphene synthesis by ultrasonication (USR) and chemical reduction (CRR). Based on their sensitivity analysis, researchers determined that diethyl ether recovery may considerably reduce the environmental effects of the USR and Hummers’++ method, to the point where it surpasses all other toxicity impacts (Figure 7).

Furthermore, Cossutta et al. [116] undertook a LCA of three graphene manufacturing methods (electrochemical exfoliation of graphite rods, chemical oxidation/thermal reduction, and chemical vapor deposition) for providing a comparison of lab-scale and commercial-scale production. Although the use of hypothetical production scenarios may have introduced ambiguities, it was discovered that chemical reduction procedures had the least influence on large-scale graphene synthesis. Additionally, Miseljic and Olsen [112] conducted a LCA of engineered nanomaterials (ENM). It was discovered that ENM derived from Ag had a greater eco-toxic impact than those derived from TiO₂. As a result, LCA studies on 2D nanomaterials analyze alternative production routes and their consequences, assisting in developing a synthesis process with minimum environmental impact.

2. Economic Impact of 2D Nanomaterial-Based Heat Transfer Fluids

2.1. Cost-Effectiveness and Volume Effectiveness of Fluids. The use of nanofluids has a major influence on costs as well. The 2D nanomaterial-based heat transfer fluids provide excellent thermal properties, which decreases the operation costs. They offer an opportunity to reduce the volume of fluid needed to accomplish the same heat transfer as conventional fluids. This also allows resizing the equipment to a smaller version and cutting down the overall investments. However, incorporating 2D nanomaterial in a base fluid increases the viscosity of the solution, due to which extra pumping power is required [117]. In order to make...
nanofluid systems commercially effective, the improvement in the heat flow of applied nanofluids must be more substantial than the additional pumping power supply [118].

The concentration of 2D nanomaterial in a fluid can change the thermal properties as well as the costs involved, and therefore, it is necessary to optimize it. The price-performance factor (PPF) is an important parameter to evaluate the economic feasibility of nanofluids. It depends on the thermal performance of the nanofluid and the cost of the materials used. For convective studies, PPF is evaluated based on the flow conditions.

Under laminar flow, PPF is calculated using the following:

$$\text{PPF} = \frac{C_\lambda/C_\mu (\text{ratio} > 0.25)}{\sum_n \text{price}($/g)},$$

(2)

And under turbulent flow, PPF is calculated by using

$$\text{PPF} = \frac{T (\text{for} > 1)}{\sum_n \text{price}($/g)}.$$

(3)

In equations (2) and (3), $C_\lambda$/$C_\mu$ and $T$ are parameters which estimates the thermal performance of nanofluids. For meeting the economic needs, $C_\lambda/C_\mu < 4$ and $T > 1$ for laminar and turbulent flows, respectively, where $C_\lambda/C_\mu$ and $T$ are calculated by the following equations (4) and (5), respectively,

$$\frac{C_\mu}{C_\lambda} = \left(\frac{\mu_{nf} - \mu_{bf}}{\lambda_{nf} - \lambda_{bf}}/\lambda_{bf}\right),$$

(4)

$$T = \left(\frac{\lambda_{nf}}{\lambda_{bf}}\right)^{0.67} \times \left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{0.8} \times \left(\frac{c_{p,nf}}{c_{p,bf}}\right)^{0.33} \times \left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{-0.47},$$

(5)

where $\mu_{nf}$ and $\mu_{bf}$ are the viscosity of the nanofluid and base fluid, respectively. $\lambda_{nf}$ and $\lambda_{bf}$ are the thermal conductivity of the nanofluid and base fluid. $\rho_{nf}$ and $\rho_{bf}$ are the density of nanofluid and base fluid; $c_{p,nf}$ and $c_{p,bf}$ are the specific heat of nanofluid and base fluid, respectively.

A price-performing factor was calculated by [119] for the economic analysis of the thermal performance of $\text{Al}_2\text{O}_3$-$\text{CuO}$-$\text{TiO}_2$-$\text{Cu/W}$ ternary hybrid nanofluid. It was found that 0.7 vol% and 1 vol% of the hybrid nanofluid have greater cost-effectiveness for the laminar and turbulent regions. Similar assessments have shown that $\text{Al}_2\text{O}_3$-$\text{CuO}$-$\text{EG}$-$\text{W}$ hybrid nanofluid is effective in laminar flow, whereas $\text{Al}_2\text{O}_3$-$\text{EG}$-$\text{W}$ single nanofluid is the better alternative when considering turbulent flow [120]. However, the price-performing factor has not been reported for 2D nanomaterial-based heat transfer fluids in the literature.

2.2. Comparing Different Commercial Heat Transfer Fluids.

While an absence of comparative economic study between different heat transfer fluids was observed in the literature, differences in thermal properties are widely studied. An analogy can be made with exceptional heat transfer properties and operational costs; with higher efficiency, the return-on-investment increases. Prajapati and Patel [121] performed the thermoeconomic optimization of the nanofluid-based organic Rankine cycle and observed that the enhancement of the thermal transfer properties due to the introduction of nanofluids shortened the payback period.

Some of the widely used heat transfer fluids, such as water, air, hydrocarbon oils, and refrigerants, are abundant and cheap but require processing which is one of the major contributors to the operating costs of the process plant. And due to their weak heat transfer properties, there are significant thermal losses. With their high thermal conductivity and efficiency, 2D nanomaterial-based heat transfer fluids can reduce these losses and increase the overall efficiency of the process plants.

2.3. Economic Analysis of 2D Nanomaterial-Based Heat Transfer Fluids.

The overall economic impact of 2D nanomaterial-based heat transfer fluid provides an optimistic perspective over conventional heat transfer fluids. Although 2D nanomaterial-based heat transfer fluids are economically sound, the high cost of nanomaterials is still a matter of concern. A variety of researchers have suggested cost-effective methods for manufacturing nanomaterials, but most of the techniques yield very small quantities [122, 123]. Investigations performed by Maji et al. [124] and Chatterjee et al. [125] have suggested inexpensive and large-scale preparation methods for copper nanopowder. With the implementation of these techniques, the cost of nanofluids can be minimized, thereby reducing the total expenses.

Esfe et al. [126] analyzed the cost and thermal performance of double-walled carbon nanotubes/water nanofluids and lowered costs by 38% using the surface response technique. Furthermore, Mukherjee et al. [127] studied the cooling performance of $\text{Al}_2\text{O}_3$-water nanofluids and found that an increase in nanofluid concentration is not appropriate for cooling purposes, but an increase in temperature helps in economic efficiency. Although no work has been reported in literature on the economic analysis of 2D nanomaterial-based heat transfer fluids/nanofluid, the thermal effectiveness of 2D nanomaterial-based fluids can definitely be cost-effective as compared to other nanomaterials.

2.4. Graphene Production, Market Trend, and Commercialization Obstacles.

A key ongoing problem is the lack of cost-effective and scalable 2D nanomaterial production methods [128]. However, because of the unique features and extensive use of 2D nanomaterials, their industry has been expanding exponentially. In particular, China’s graphene material manufacturing sector has been quickly expanding, with a total yearly production capacity of 400 tonnes of tiny graphene sheets and 110,000 m² of graphene films [129]. Globally, the nanotechnology market is estimated to be 55 billion US dollars by 2022, and 70% of these growths will be in the electronics, energy, and biomedical sectors [130]. Figure 8 depicts the graphene markets and their application by 2025, together with their estimated revenues and compound annual growth rate (CAGR). The majority of projections indicate that energy storage applications, such as batteries and supercapacitors, have a very high
(>US$100 million) market potential. Graphene composites and conductive films/electrodes are predicted to have a high (>30%) CAGR and considerable revenues, whereas graphene-based (opto) electronics and sensors are expected to have a high (>20%) CAGR with no significant revenue. The insights on the prospective application areas depicted in Figure 8 must be converted into a real product and device innovation initiatives [131].

The global market value of graphene nanoplatelets alone is expected to exceed 100 million U.S. dollars in 2023. Reiss et al. [131] evaluated 20 market studies published between 2013 and 2019 and merged them into a metamarket analysis to discover common trends. It has been predicted from the minimum, maximum, and means revenue of the global graphene market that an average growth rate will be more than 40% up to 2025.

Furthermore, Wei and Kivioja [132] developed a three-stage value chain for graphene, from graphite ore supply to application in different products. They reported a variety of firms involved along with different phases of the graphene value chain and academic researchers investigating novel ways. Although developments in graphene fabrication provide the potential for scale-up and cost-cutting, current materials are equally vulnerable to technical and manufacturing advancements. Graphene’s competitive edge over conventional materials was assessed by researchers in a number of commodities and applications. They cite the sharp growth of graphene patents compared to other materials and graphene’s broad range of application fields as two signs of increased commercial activity in this area [133].

3. Conclusion

The world is shifting towards miniaturization, and nanotechnology is leading this transition with its exceptional properties. While achieving high heat transfer efficiencies is a primary objective of the industries, 2D nanomaterial-based heat transfer fluids have shown exceptional thermal properties. In comparison with conventional heat transfer fluids, nanofluids have a much higher thermal conductivity and improve the working fluids’ heat transfer coefficients. Owing to the high specific area of the nanoparticles, the volume of working fluids also decreases, allowing resizing of the equipment and, hence, cutting costs. The environmental impact analysis was discussed by analyzing health risk assessment, cytotoxicity, and life cycle analysis. The economic impact analysis was studied by using the price-performance index of 2D nanomaterial-based heat transfer fluids. Additionally, graphene production, market trend, and commercialization obstacles were considered for analyzing the overall economic impact of 2DM-based heat transfer fluids. Although more research is required to comprehensively evaluate the environmental and economic impacts of 2D nanomaterial-based heat transfer fluids, they are highly efficient and viable options for replacing traditional heat transfer fluids.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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