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PERSPECTIVE

The Future of Flash Graphene for the Sustainable Management of Solid Waste

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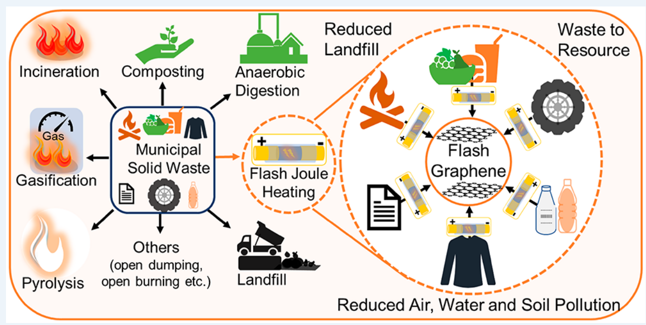
ABSTRACT: **Graphene research has steadily increased, and its commercialization in many applications is becoming a reality because of its superior physicochemical properties and advances in synthesis techniques. However, bulk-scale production of graphene still requires large amounts of solvents, electrochemical treatment, or sonication. Recently, a method was discovered to convert bulk quantities of carbonaceous materials to graphene using flash Joule heating (FJH) and, so named, flash graphene (FG). This method can be used to turn various solid wastes containing the prerequisite element carbon into FG. Globally, more than 2 billion tons of municipal solid waste (MSW) are generated every year and, in many municipalities, are becoming unmanageable. The most commonly used waste management methods include recycling, composting, anaerobic digestion, incineration, gasification, pyrolysis, and landfill disposal. However, around 70% of global waste ends up in landfills or open dumps, while the rest is recycled, composted, or incinerated. Even the various waste valorization techniques, such as pyrolysis and gasification, produce some waste residues that have their ultimate destination in landfills. Thus, technologies that can minimize waste volume or convert waste into valuable products are required. The thermal treatment process of FJH for FG production provides both waste volume reduction and valorization in the form of FG. In this Perspective, we provide an overview of FJH and its possible applications in various types of waste conversion/valorization. We describe the typical current MSW management system as well as the potential for creating FG at various stages and propose a schematic plan for the incorporation of FG in MSW management. We also analyze the strengths, weaknesses, opportunities, and threats of MSW as an FG precursor in terms of technical, economic, environmental, and social sustainability. This valuable waste valorization and management strategy can help achieve near-zero waste and an economy-boosting MSW management system.**



Graphene, a carbon-based nanomaterial, has a two-dimensional (2D) layer of sp^2-hybridized carbon atoms arranged in a hexagonal crystalline structure.[1] Graphene has been the focus of intense research because of its excellent physicochemical properties, including large surface area, high electron and thermal mobility, and high mechanical strength.[2−4] Graphene at bulk scales is mainly produced *via* chemical exfoliation of graphite, a top-down approach that requires chemical reagents, large volumes of solvents with high-energy mixing, shearing, electrochemical treatment, and/or sonication.[5−7] This harsh chemical treatment results in the formation of graphene with structural defects and can require a subsequent reduction step.[7] In comparison, laser-induced graphene (LIG) is a one-step chemical-free approach to generate graphene directly on most carbonaceous substrates using an infrared CO_2 laser.[8−10] However, LIG is better suited for the fabrication of patterned or conformal graphene embedded on surfaces compared to the generation of bulk graphene. Alternatively, a bottom-up approach such as chemical vapor deposition produces high-quality graphene but is often restricted to small quantities.[11,12] Recently, we discovered a method to turn bulk quantities of inexpensive carbon sources, such as coal, petroleum coke, tires, biochar, discarded food, carbon black, and mixed plastic waste, into valuable graphene flakes in less than 1 s, using a short electrical pulse accompanied by a bright flash of blackbody radiation. We termed the resulting product "flash graphene" (FG).[13,14] This technique can convert

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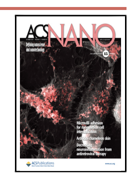

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coal, food waste, or plastic into graphene quickly (10 ms) by flash Joule heating (FJH) carbon-containing materials; FG synthesis does not use any furnace, solvents, or reactive gases, and it does not require any purification steps.[13,14] The yield of FG depends on the carbon content of the source.[14] Nevertheless, bulk production of FG is feasible because its synthesis can be achieved by requiring a minimal amount of electric energy depending on the carbon source used and as little as $30 of electricity per ton of carbon converted to graphene.[14] This FJH method has thus provided a framework to optimize solid waste management with the generation of FG, a value-added product from municipal solid waste (MSW).

More than 2 billion tons of MSW is generated worldwide per year, and this amount is expected to increase to 3.4 billion tons by 2050.[15] The increase in MSW generation is mainly due to population growth, industrialization, urbanization, population migration from rural to urban areas, and the rise in living standards in developing countries.[16−19] Municipal solid waste collected from households consists of various components, including paper, plastics, metals, organic waste, textiles, leather, metals, rubber, ceramics, glass, and other miscellaneous materials. The World Bank reported that the global waste composition consists of 44% biowaste, 2% rubber and leather, 2% wood, 5% glass, 4% metal, 17% paper and cardboard, 12% plastics, and 14% other.[15] Hence, MSW is mainly carbon and, therefore, is well suited for conversion to FG. The MSW composition varies from country to country and depends on the economic prosperity of the country. Effective management of MSW is an extremely large and complex task for municipalities that collect significant quantities of compostable and organic wastes generated daily.[16,20] Various methods, including recycling, composting, incineration, pyrolysis, gasification, and landfill disposal, have been used for better MSW management. Worldwide, open dumping/landfilling is the most common waste disposal method. Urban or nonbiodegradable wastes having relatively low moisture content are incinerated.[21,22] Incineration has many advantages over landfill disposal, including a high percentage of volume reduction.[21,23,24] However, relatively higher costs, pollutant emission, and low-moisture waste restrictions limit its application in developing nations, especially in countries with high annual rainfalls. Economically developed countries consider MSW a valuable asset for manufacturing fuel, energy, and heat.[21,25−27]

> Flash Joule heating waste valorization, which generates high-value turbostratic flash graphene, might be the best option for carbon-rich municipal solid waste management.

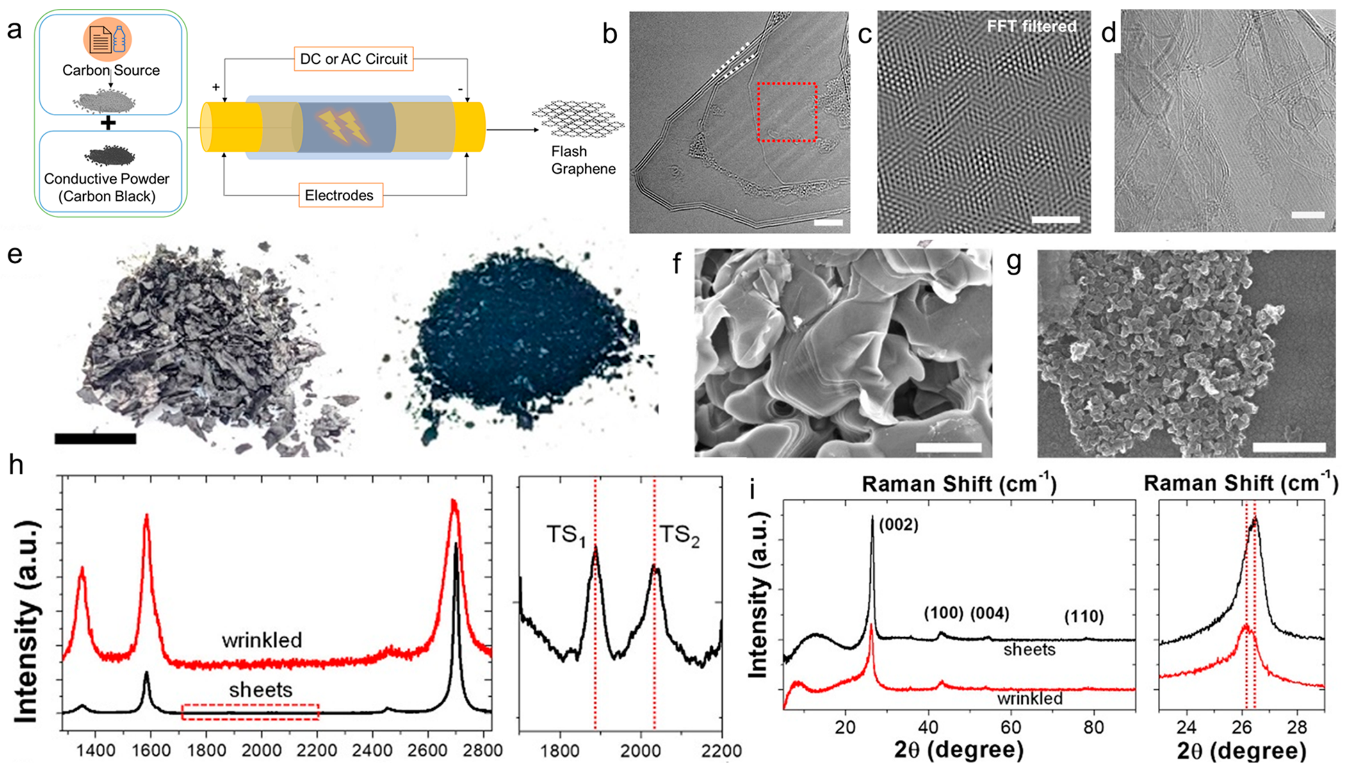

Figure 1. (a) Schematics of the flash Joule heating process. (b) Transmission electron microscopy (TEM) image of turbostratic flash graphene (tFG) sheets with striations in the image denoting rotational mismatch. A portion of the red boxed region is further studied in panel c. Scale bar is 5 nm. (c) Fast Fourier transform (FFT) filtered image of the inset region revealing a moiré pattern. Scale bar is 2 nm. (d) TEM image of tFG showing more striations indicating a rotational mismatch. Scale bar is 5 nm. (e) Photographs of FG that was passed through a 250 μm sieve. Gray crystals are separated from a fine black powder. The scale bar is 3 mm. (f) Scanning electron microscopy (SEM) image of the gray crystals showing delaminating sheets. Scale bar is 500 nm. (g) SEM image of the black powder that is composed of nanoparticles. Scale bar is 300 nm. (h) Representative Raman spectra for sheets and wrinkled structures. Expansion of the red boxed region from the sheets (right) exhibit TS_1 and TS_2 peaks that are characteristic of turbostratic layers and show a missing M band. (i) X-ray diffraction of sheets and wrinkled structures. A shift in the peak position of (002) peak is exhibited for the wrinkled structures. Adapted from ref 28. Copyright 2020 American Chemical Society.

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Thus, FJH waste valorization, which generates high-value turbostratic FG, might be the best option for carbon-rich MSW management. In this Perspective, we demonstrate the potential application of FJH in solid waste management along with waste valorization in the form of FG. We show that the FJH process is a better alternative to the existing management techniques and might complement some current best practices. In the following sections, we provide an overview of FJH and its potential applications for FG production in various carbon-containing MSW components. We propose MSW systems that incorporate FJH for FG production and provide analyses of the strengths, weaknesses, opportunities, and threats for MSW as FG precursors. Such FJH-incorporated MSW systems will help minimize waste disposal needs. Moreover, the conversion of MSW into FG can act as a terminal natural sink for carbon; microbial decomposition takes hundreds of years and, due to the geological stability of graphite, it almost never returns to the carbon cycle. Thus, the valorization of waste as FG can build sustainable solid waste management practices leading to positive environmental impacts.

FLASH GRAPHENE IN SOLID WASTE MANAGEMENT AND VALORIZATION

Flash Graphene. In the FJH process, the carbon source is first compressed between two conductive electrodes inside a quartz or ceramic tube (the tube can vary, as needed for scaling) and 5−10 wt % of conductive additive (*e.g.*, carbon black or FG from a former run) is added as needed. A high-voltage discharge is applied to raise the temperature of the carbon sources above 3000 K within 1 s (Figure 1a). This flash heating causes the instantaneous conversion of carbon sources, resulting in turbostratic FG (tFG), which has a higher interlayer distance (3.45 A) than does AB-stacked graphene (3.35 A). Figure 1b shows the high-resolution transmission electron microscopy (HR-TEM) of tFG sheets. The rotational mismatch of the sheets results in striations where the overlapping of mismatched sheets is present. The rotational mismatch-induced moiré pattern is visible in Figure 1c, and striations that developed because of rotational mismatch between neighboring tFG sheets are shown in Figure 1d. The FG obtained *via* FJH is composed of gray crystals and fine black powder, which can easily be separated by screen-sieving (Figure 1e). Scanning electron microscopy images reveal that the fine black powder is the smaller graphitic carbon particles (wrinkled graphene), whereas the gray crystals are the readily exfoliated and delaminated networks of tFG sheets (Figure 1f,g). Figure 1h shows the representative Raman spectra of FG morphologies with the TS_1 and TS_2 peaks for the tFG sheets, confirming the turbostratic nature of the FG. The asymmetric (002) peak with a weak (100) peak observed in X-ray diffraction (Figure 1i) is typically seen in turbostratic graphene.

> The valorization of waste as flash graphene can build sustainable solid waste management practices leading to positive environmental impacts.

The yield of FG *via* the FJH process mainly depends on the quantity of the carbon in the source; for example, carbon black, calcined coke, or anthracite coal can give a yield in the range of 80−90% with >99% carbon purity. A conductive additive can further enhance FG yield. Such yields require only ∼7.2 kJ/g of electrical energy, and no further purification of FG is required.[14] The FG synthesis requires no solvents, reactive gases, or furnaces. Potential carbon sources for FG production are abundantly available, renewable, and even include waste, such as biochar, human hair, food wastes, mixed plastics, and rubber tires. A high-carbon-content product can be obtained with synthetic polymers because noncarbon atoms sublime out of the system as small molecules during the FJH process. However, depolymerization of rubber and polymers can supply oligomers that get sublimed before conversion to FG. Thus, it is more economical to use the byproducts of pyrolysis because these volatile compounds can be used for fuel sources. The residual carbon can then be converted into FG;[29] therefore, the FJH process provides a facile method of turning waste into valuable graphene. In addition, FG is also dispersible in water/surfactant, which can be attributed to the turbostratic arrangement with a lower interlayer attraction force permitting efficient exfoliation. When the tFG obtained from plastic waste pyrolysis ash was checked for colloidal stability, the *in situ* tFG concentrations reached ∼3 mg/mL in a 1% aqueous surfactant solution (Figure 2a). Figure 2b shows the optical images of the 300× diluted tFG dispersions at various concentrations. The tFG showed high degrees of dispersibility in organic solvents, and stable tFG dispersions in dimethylformamide (DMF) of ∼0.8 mg/mL were obtained when 7 mg/mL was loaded (Figure 2c). In comparison, commercial graphene was reported to be 60 times less dispersible (Figure 2c).[29] Commercial graphene, exfoliated graphite, and tFG were also found to show good dispersibility in 1% Pluronic F-127 in water, which is an additive dispersing agent used in cementitious materials. The tFG dispersions remained well-dispersed and stable even after 1 week; however, exfoliated graphite and commercial graphene precipitated within 24 h (Figure 2d,e). The tFG exfoliation was easier because of the increased interlayer spacing and dispersed easily into single sheets compared to AB-stacked graphene (Figure 2d,e). The high dispersibility and stability of tFG suspensions can be used for making construction materials, graphene-based membranes, and other composites. Recently, we exploited the FJH method to synthesize any ratio ^{12}C:^{13}C tFG with different ^{13}C initial loading. This method has potential future applications in materials science, geochemistry, 2D physical studies, and biological applications.[30] Interestingly, an unusual enhanced Raman spectra D′ band was reported with the long-sought C═C stretch in the infrared spectrum. Such bulk production of tFG can be used for research on the biological and environmental fate and transport of graphene.[30]

Waste Management and Waste Valorization in the Form of Flash Graphene. *Common Practices in Municipal Solid Waste Management.* The contents of MSW have varying carbon content and can be used as raw materials for the synthesis of FG (Figure 3a). Carbon content in plastic wastes is reported to be around 60−90% by weight for the major commercial plastics.[32] Biomass waste contains ∼40% carbon by weight.[33] Likewise, food residues, wood waste, paper, textile, and rubber contain ∼30−50, ∼40−50, ∼45, ∼45−60, and ∼90% carbon by weight, respectively.[34] Currently, the total amount of carbon in the waste and wastewater sectors is ∼1500 Mt (∼1.5×10^{12} kg) and is expected to reach ∼2100 Mt by 2050.[35] Among the total carbon content in the waste and wastewater sectors, ∼90% is accounted for by industrial waste and MSW, with 65% carbon content in waste coming from MSW.[35]

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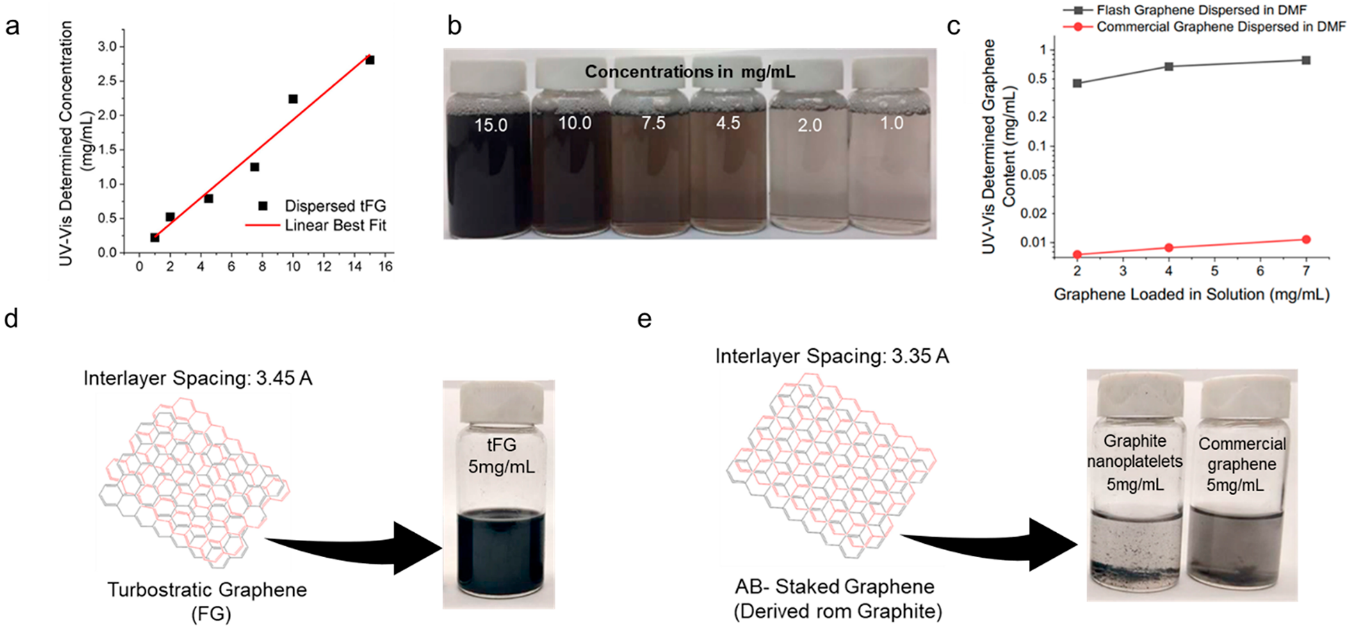

Figure 2. (a) UV−vis absorption data at 660 nm used to determine the concentration of turbostratic flash graphene (tFG) present in solution as a function of the amount loaded in the sample. (b) Photo of dispersions showing a 300× dilution of the tFG dispersions. (c) Graph comparing the dispersibility of tFG and commercially available graphene in dimethylformamide (DMF) solution, shown with a log-based scale on the *Y*-axis. Adapted with permission from ref 29. Copyright 2021 Elsevier. (d) 5 mg/mL dispersions of tFG in a solution of 1% Pluronic F-127 in water, (e) 5 mg/mL AB-stacked graphite nanoplatelets, and commercial graphene in a solution of 1% Pluronic F-127 in water. Adapted with permission from ref 31. Copyright 2021 Elsevier.

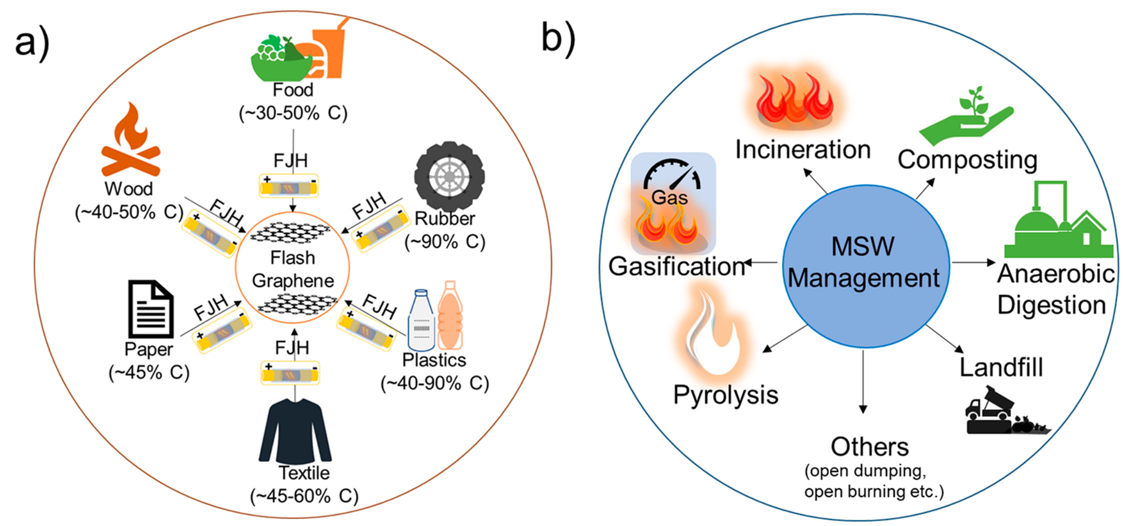

Figure 3. (a) Potential sources of flash graphene from various components of municipal solid waste (MSW) along with their typical carbon content. (b) Different possible final step in MSW management. FJH is flash Joule heating.

The final step in MSW management includes landfilling, composting, anaerobic digestion, incineration, pyrolysis, or gasification (Figure 3b). However, around 70% of global waste ends up in landfills or open dumps, whereas only ∼19% is composted and recycled and 11% is incinerated.[18,36] Landfilling and open dumping discharge various contaminants to the environment, including greenhouse gases, volatile organics, potentially toxic elements, and persistent organic pollutants.[21,37,38] Landfills emit methane, water vapors, CO_2, and other non-methane organic compounds, including hazardous gaseous pollutants and volatile organic compounds (VOCs).[16,39,40] Open dump and landfilling sites are one of the major contributors to methane gas emission—a major source of global warming.[21,41] The methane can also trigger open fires and explosions.[16,41] In addition, landfills also emit H_2S and other odorous compounds, including toluene, benzene, xylene, and ethylbenzene.[21,42] Long-term exposure to minute concentrations of these VOCs can adversely affect human health.[16,37,43,44]

The decomposition of solid waste results in liquids called landfill leachate, which is rich in organic and inorganic substances.[16,45] Landfill leachate originates with an underflow of groundwater or infiltration of rainwater through deposited waste. Moisture content in the MSW also significantly affects the volume of leachate generated.[16,45] Leachate discharge from landfill areas has been found to be toxic toward invertebrates, algae, higher plants, fishes, and humans.[21,46,47] Also, the

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presence of trace metals such as Cd, Cu, Hg, Mn, Ni, Pb, and Zn in elevated concentrations has been found as well, which can bind to dissolved organic carbon particles enhancing their transportation capacity.[21,45,48] Thus, landfill leachate is a highly complex type of wastewater.[21] Moreover, landfills consume land resources that might otherwise be used for other needs in a growing population.[49−51] Because most of the MSW management techniques produce some residue waste, landfilling will continue as the primary MSW management technique for which proper principles of sanitation should be followed.[50] However, most of the treatment technologies have higher environmental burdens. For example, valorization products often have lower market value and do not offset their higher processing cost. Thus, advanced MSW waste management and valorization technologies might solve the problems of existing waste management and provide sustainable revenue for MSW management.

Currently, waste valorization has three sustainable paths: production of fuel/energy, production of high-value chemicals, and production of useful materials.[52] The commonly used waste valorization methods are thermal treatment and biochemical treatment of wastes. In recent years, thermal treatments such as incineration and pyrolysis have generated much interest due to their ability to reduce the volume of waste that enters landfills. Incineration reduces wastes by 70−80% in mass or 80−90% in volume.[21,38,50,53] Such benefits are significant for areas with land scarcity. Also, incineration can provide the opportunity to extract energy in the form of heat and electricity,[54] where wastes are burned at high temperatures of 750−1100 °C.[38] In this practice, various pollutants, including sulfur oxides (SO_x), nitrogen oxides (NOx), carbon oxides (CO_x), polyaromatic hydrocarbons (PAH), and heavy metals are generated, which need additional emission control and treatment.[38,55] Thus, the incineration process requires two additional steps: energy recovery and air pollution control, while leaving sterile ash as residue.[50,56]

Another such thermal valorization method is pyrolysis for fuel synthesis, in which waste is heated at high temperatures in the absence of oxygen to produce decomposed products.[52,57,58] This method is mainly used to generate bio-oil, a low-viscosity, complex fluid of short-chain aldehydes, carboxylic acids, and ketones. Pyrolysis has lower emission of pollutants and requires lower processing temperatures compared to incineration.[59−61] The three outputs from pyrolysis—solid (char), liquid (oil), and gas—can vary in proportion to each other by changing operating parameters such as temperature and heating rate. Apart from transforming low-energy-density materials into high-energy-density biofuels, pyrolysis also recovers high-value chemicals.[59,62,63] The operating conditions of pyrolysis are generally optimized for maximizing the liquid and gas fractions; the solid fraction of biochar, a carbon-rich matrix, may retain some heavy metals and hazardous elements that need to be taken into consideration.[59,64] In comparison to the incineration of solid waste, pyrolysis produces fewer pollutants and emissions due to lower temperatures and the absence of oxygen. Lowered fuel gas production can also reduce cleanup device dimensions, resulting in less investment and operating capital being required.

Gasification is a thermochemical process that converts carbonaceous substrates into a gas (syngas) using gasifying agents.[65] This process occurs at temperatures of 500−1400 °C, with the main products being syngas, tar, and char.[66,67] Syngas is the most desirable product of gasification because it can be used for heat and electricity generation. Liquid tar and solid char are unwanted products for gasification plants and can be 5−10% of the initial feedstock mass. Char from the gasification plants is considered to be waste that needs further disposal or management. Both char and MSW biowaste contain significant amounts of carbon; however, their high moisture content generally precludes them from incineration. Instead, anaerobic digestion (AD) and composting are often used for organic waste management and nutrient recycling.[68,69] In AD, the organic matter is converted to biogas and a nutrient-rich substance called digestate, whereas in composting, the organic waste is converted into compost, heat, and carbon dioxide. The anaerobic digestion and composting of biowaste require ample land and time for biological transformation or degradation.

Incorporating Flash Joule Heating in Municipal Solid Waste for Flash Graphene Production. The incorporation of FJH in MSW management has the potential to produce the value-added product FG in bulk, compared to conventional MSW thermal treatments that produce ash or char residue. Some residual ash is used in building and construction materials, but the unused ash finds its way to landfills.[70,71] However, when FJH is used, the final product is FG, which can be used in many applications, including building and construction materials.[13] The solid, carbon-rich residue from pyrolysis and gasification can also be utilized to produce FG,[29] replacing char disposal with valuable product formation and requiring minimal-to-no landfill dumping. Whereas biochemical conversion of MSW biowaste requires a larger footprint and longer treatment times, FJH of biowaste to FG can solve both issues. The potential use of FJH to dry waste, followed by conversion to FG in a single system, might also be possible in the near future.

Management of biomedical waste (BW)—deemed hazardous waste by the World Health Organization—has also attracted ample attention globally due to its health and environmental impacts.[72] The key sources of BW are hospitals, with minor contributions from medical institutions, blood banks, mortuaries, and laboratories. The treatment of this hazardous waste by conventional treatment methods, such as incineration, produces legitimate environmental concerns due to the release of carcinogenic polychlorinated dibenzo-*p*-dioxins and dibenzofurans, which also pollute the air and soil.[72,73] The chemical composition of BW consists of about 35% carbon.[74] Even though the carbon content is low, the BW can be managed using FJH for FG production and might reduce the complex handling of BW. Similarly, agricultural waste also contains organic and carbon-containing wastes, and global agricultural waste generation is more than four times that of MSW.[15] In Asia alone, ∼730 Tg of biomass is annually burned from various sources, including forest fires and crop residue burning, ∼18% of which is contributed by India.[75,76] In 2017, India generated 488 Mt of crop residues, of which ∼24% was burnt in agricultural fields. This burning was responsible for emitting 824, 58, and 239 Gg of particulate matter (PM2.5), elemental carbon, and organic carbon, respectively. Moreover, ∼200 Tg CO_2 equivalent greenhouse gases were added to the atmosphere.[76] The top three burners of crop residues in aggregate terms are China, India, and the United States.[77] Around ∼40, 55, and 45 million kg of biomass (dry matter) from maize, wheat, rice paddy, and sugar cane production are expected to be burned by India, China, and United States, respectively, by 2030.[77] Employing FJH for FG production instead will help reduce the environmental impacts of the burning of agricultural waste. Thus, BW and agricultural waste should both be explored as carbon sources for the FG production process *via* FJH.

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Plastic waste constitutes 12% of global solid waste and is a significant problem for municipalities because it is primarily nonbiodegradable.[15] Hence, bioremediation of such waste is a formidable challenge. However, the plastic waste contains as much as ~90% carbon by weight.[32] The carbon-rich nature of plastic waste makes it a suitable candidate for the production of FG. Thus, mitigating the problem of plastic waste/pollution is possible by converting it into revenue-boosting FG *via* FJH. Recently, we demonstrated the application of FJH for converting plastic waste into FG.[13] The conversion of plastic waste into FG does not require any solvents or subsequent purification of formed FG and is unaffected by the presence of plasticizers, dyes, adhesives, food waste, or organic or inorganic fillers. Moreover, the upcycling of plastic waste in the form of FG leaves no low-value ash as residue and does not require the plastic waste to be prewashed, thereby offering enormous water savings. Similar to plastic waste, other wastes having high carbon content can be the potential raw materials for FG.

The conversion of plastic waste into flash graphene (FG) does not require any solvents or subsequent purification of formed FG and is unaffected by the presence of plasticizers, dyes, adhesives, food waste, or organic or inorganic fillers.

The steps in a typical MSW management system are depicted in Figure 4a. The commingled wastes are first collected and then sorted to recover recyclable materials, including plastic, paper, cardboard, *etc.* Next, materials are separated into oversized and undersized materials. The oversized materials are then processed in a second stage sorting, during which further materials are recovered. The waste left after this second sorting is combined with the undersized materials and, in most cases, ends up in landfills. If volume reduction or any waste valorization steps are involved, then the waste undergoes a magnetic separation of ferrous wastes. The remaining waste generally undergoes either thermal treatment, such as incineration, pyrolysis, gasification, or biochemical transformation, such as composting and anaerobic digestion.

The various stages of the MSW management system from where FG can be obtained are shown in Figure 4a. The recovered materials from the sorting stage can be exposed to FJH for substantial amounts of FG as these are mostly carbon-rich recovered materials like plastics, paper, cardboard, and rubber. The FJH can also be considered as an alternative to other thermal treatments and biochemical treatments. However, the energy, cost, and amount of wastes can play a deciding role here, which will need further research. Another alternative of FJH to save operational energy requirements can be by using carbon-rich residues from thermal conversion processes, such as pyrolysis and gasification, as the raw materials of FG. Recently, the carbon-rich char from pyrolysis has been reported to give a good yield of FG.[29] In the future, it might be possible to get near-zero waste disposal in landfills, as shown in Figure 4a. In this possible scenario, the MSW is first dried to reduce moisture content. Then hard to shred and risky materials like gravels and glass can be separated, followed by magnetic separation of metals. The remaining wastes can then be shredded into smaller pieces and pulverized, resulting in a powder form. This waste can be mixed with some types of carbon powder or FG itself, which

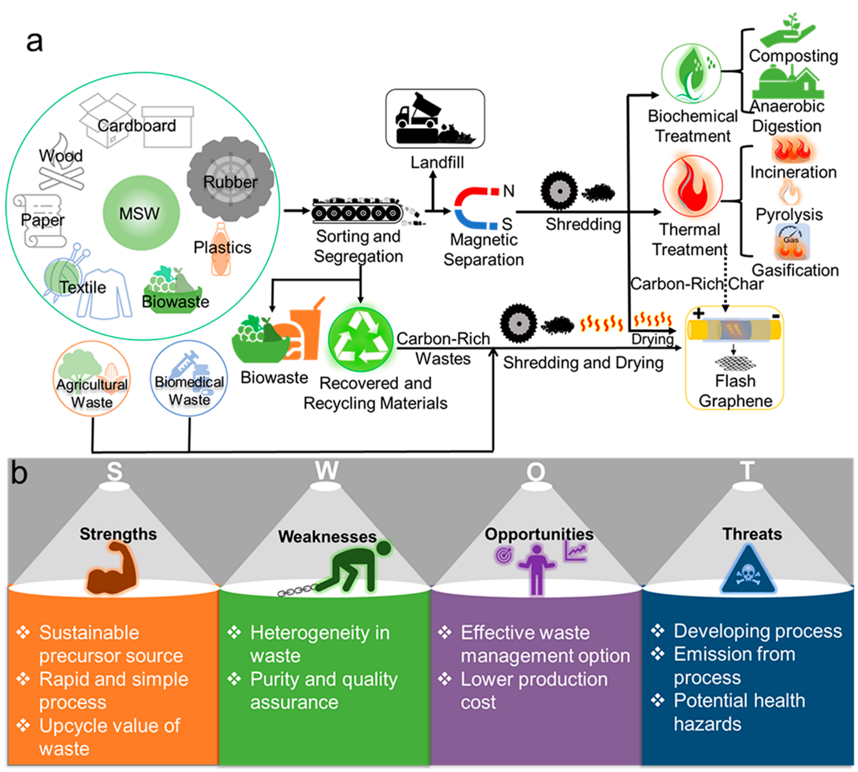

Figure 4. (a) Flowchart of various types of waste in the municipal solid waste (MSW) management system indicating where flash Joule heating can be implemented and flash graphene can be obtained. (b) Strengths, weaknesses, opportunities, and threats of using municipal solid waste as a graphene precursor.

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can be obtained from BW or agricultural wastes to increase the conductivity. The FJH can then convert all carbon content of the ground/powdered wastes into FG, while other materials are removed by sublimation.

Strengths, Weaknesses, Opportunities, and Threats Analysis for Municipal Solid Waste as a Flash Graphene Precursor. We analyzed the strengths, weaknesses, opportunities, and threats (SWOT) regarding the use of solid waste as an FG precursor in terms of technical, economic, and environmental sustainability (Figure 4b).

Strengths (S). Viable and sustainable raw materials are required for the production of graphene. Studies have investigated the utility of waste materials such as cups, hemp, rice husk grass, and plastic for producing graphene.[78] Because the FG process utilizes carbonaceous material, carbon-rich MSW is a pragmatic precursor. Flash graphene production provides a simple and effective management solution for carbon-rich MSW waste. In addition, FJH is superior to alternative graphene production methods because it is a cost-effective and rapid process. Solid waste as a feedstock can further bring down the cost of graphene production, making it more industry-friendly, creating more opportunities and avenues for graphene applications. Furthermore, the process does not require any solvents, produces fewer emissions, and provides a high yield.[13,14] Flash graphene production from MSW and other suitable wastes will upcycle the value of waste, provide economic advantages and environmental benefits, and help to promote sustainable development goals by taking a circular economy approach.

Weakness (W). The major weakness that MSW poses as a precursor for FG production is the heterogeneity of MSW. However, heterogeneity of the FG product might not be detrimental in some applications, such as improving the strength of composites and construction materials. Flash graphene quality can be increased by using homogeneous wastes, such as agricultural wastes (rice paddy), or well-sorted waste. Furthermore, different waste products may produce graphene of varying characteristics. Hence, quality assurance of the process needs to be studied in accordance with the waste precursors used. Because the FG production process was only recently developed, the safety of the process needs to be evaluated for scale-up. The stability and biodegradability of FG using waste as a precursor need to be evaluated for long-term applications, as well. Furthermore, at present, there are no direct regulations on graphene and graphene-based nanomaterials.[79]

Opportunities (O). Flash graphene production could be a sustainable and economically sound alternative for waste management. As a rapid process, a high quantity of waste can be handled per day. Furthermore, FG production from solid waste can be more cost-effective than conventional waste management options. The cost for producing FG is ∼$125 per ton of plastic waste with a yield of 180 kg graphene plus volatiles, and the price of graphene in the market ranges from $67,000 to $200,000 per ton depending on its purity.[13,80] Hence, one ton of FG from plastic waste can be produced at the cost of ∼$700, while the market price of graphene is currently at $67,000, creating a considerable window for the financial viability of mass production of FG. In contrast, recycling can generate ∼ $777−$1513 per ton, considerably less lucrative than FG. Further, graphene-based nanomaterials can potentially be used in construction, biomedical, and environmental fields. The use of waste to produce FG will provide a cost-effective way to make graphene commercially available and facilitate its use in commercial technologies.

Threats (T). Flash graphene production *via* FJH is a promising process; however, it is still in the development phase. The impact of parameters such as moisture content and waste heterogeneity on FG yield and quality need to be understood. Furthermore, toxicological studies of graphene and graphene-based nanomaterials for long-term impacts on human health and the environment are still in the research phase.[81,82] The toxicity of FG might be similar to that of graphene, but thorough toxicological studies for FG are required. Scientific awareness of FG exposure needs to be well understood to ascertain possible risks and uncertainties. The threats posed by FG can be overcome by extensive research studies in the field. Flash graphene is a promising nanomaterial, and researchers are actively working to eliminate potential barriers for its use and to understand the material and its production process. Initial FG studies have been based on a gram-scale level; the emission of gaseous pollutants has not yet been investigated but will be required for industrial-scale production. However, higher yields/conversions from different carbon sources to FG suggest lower carbon emission.

SUMMARY, CONCLUSIONS, AND OUTLOOK

Flash Joule heating can upscale the production of graphene in the form of FG from carbon substrates. The carbon source is exposed to the high-voltage discharge, which almost instantaneously converts the substrate into FG. The FG obtained comprises wrinkled graphene and tFG sheets. The FG yield depends on the carbon content of the source. Flash graphene production *via* FJH is a facile method that does not require any solvents, furnaces, or reactive gases. The noncarbon elements present in the source are believed to sublime out during FJH, leaving behind FG.

Municipal solid waste is a rich source of carbon substrates; thus, FG production *via* FJH offers a futuristic waste valorization system for MSW management. Flash Joule heating can be used separately or in combination with the existing final steps of MSW management, such as landfilling and thermal and biochemical treatments. The formation process of graphene is a time-saving method as it takes less than 1 s to generate FG from carbon precursors. This process can help reduce MSW storage time in landfills, which will prevent severe land and water pollution. Conventional thermal treatments of waste can reduce waste volume and provide energy, bio-oil, and fuel gas. However, there is residual waste, which in most cases end up in landfills. The solid residues in the form of char from the thermal treatments are rich in carbon content. Instead of sending the solid residues to landfills or using them in construction materials, they can be used as a precursor for highly sought-after FG. Flash graphene can then be used in many applications, including electronics, strengthening of composites, building and construction materials, and air and water treatments. Due to its moisture content, MSW biowaste normally undergoes anaerobic digestion or composting. However, advancements in FJH may make it possible to dry biowaste first by FJH and then to convert it into FG. In addition to MSW, other carbon-containing wastes, such as biomedical waste and agricultural waste, can also be explored for FG production.

Flash graphene has been shown to have 60 times higher dispersibility in organic solvents compared to commercial graphene, which can help in producing homogeneous, robust composites that contain graphene as a reinforcing element or

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additive. Flash graphene can be used in strengthening polymers, concrete, and cement composites. The addition of just 0.03−0.1 wt % of FG can increase the composite/concrete strength by almost ∼30%. As a result, less cement/concrete may be required in construction works eventually, thereby reducing the cost and energy involved.

Flash graphene also has demonstrated applicability in advanced energy applications, such as electrode materials,[14] and can be explored for use in graphene-based next-generation membranes. For example, FG can be used to fabricate electroconductive membranes (ECMs). Due to graphene's conductivity, graphene-based ECMs might perform better than those derived from conductive polymers and carbon nanotubes, reducing both the energy consumption and the cost of the ECMs and paving the way for large-scale industrial applications. In combination with enzymes, FG can also be tested for its performance in biomimetic dynamic membranes. Its turbostratic behavior may help its proper distribution along with the enzymes, enhancing both their respective and synergic effects.[83,84]

We propose a plan for incorporating the FJH process in conventional MSW management systems to obtain FG, with a goal of MSW management systems having zero waste disposal and creating circular economies. This plan may also attract the attention of industries and companies because they can use low- or no-cost waste to create highly sought-after graphene in the form of FG. In addition, FG production *via* FJH while handling MSW-like plastics has the potential to reduce greenhouse gas emissions; however, a thorough lifecycle analysis will be required to evaluate the full utility of FJH incorporation in MSW. Although FJH is a great way of upscaling graphene production, the uniformity of the FG produced will need to be improved. A proper analysis of the gases being sublimed out during FG production needs to be undertaken, and, if required, air pollution control strategies should be implemented. Overall, creating FG from MSW will open doors for economy-boosting MSW management.

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Notes

The authors declare the following competing financial interest(s): Rice University owns intellectual property on the FG process that has been licensed to Universal Matter Ltd. J.M.T. is a stockholder in Universal Matter Ltd., but not an officer or director. Conflicts of interest are managed by regular disclosure to the Rice University Office of Sponsored Programs and Research Compliance.

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