International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(4):531-541

Review Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i04.01133

Bioenergy and Valuable Products from Floral Waste - Sustainable Approach

Iadalin Ryntathiang[1], Shajni Krishna GM[2], Sivasankari Sekar[3], Archana Behera[1], Silambarasan Tamil Selvan[1], Mukesh Kumar Dharmalingam Jothinathan[1]*

[1]Centre for Global Health Research, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, India, [2]Department of Obstetrics and Gynecology, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, India, [3]Department of Green Energy Technology, Microbial and Bioprospecting Bioenergy Laboratory, Madanjeet School of Green Energy Technologies, Pondicherry University, Kalapet, Puducherry, India. *Corresponding Author's Email: itsmemukesh@gmail.com

Abstract

Flower waste has emerged as a noteworthy issue, especially in the context of India's growing floriculture sector. According to the Indian floriculture market report, specifically, the floriculture market is growing at a very high Compound Annual Growth Rate (CAGR) of 11%. 4% expected between 2024 and 2032. However, flower waste is still considered as one of the growing issues in the environment but is rarely addressed. Floral remains are among the most common organic wastes that are often dumped in landfills or any water bodies hence polluting the environment and emitting greenhouse gases including methane and carbon dioxide. This review aims at reviewing new strategies of converting floral waste into bioenergy and other products, presenting a sustainable solution to this issue. Some of the approaches like anaerobic digestion and solid-state fermentation are presented as efficient ways of utilizing floral waste in production of energy like biogas and bioethanol and other valuable products like organic fertilizers and natural dyes. This way, it is possible to decrease the negative effects of the floriculture industry and support the sustainable development goals by using the floral waste as valuable materials. Furthermore, these approaches not only help in reducing pollution but also in offering other sources of energy hence serving two major goals of environmental conservation and energy security. The sustainable management of floral waste can therefore go a long way in addressing some of the current environmental issues and at the same time promote the circular economy.

Keywords: Anaerobic Digestion, Biogas Generation, Fermentation, Floral Waste.

Introduction

India is experiencing a rapid increase in the output of solid waste due to population growth, rapid industrialization, and urbanization. India produced 133,760 tons of trash every day viz., vegetables, fruits, flowers, tree leaves, and kitchen garbage. The majority of the 70% organic waste found in municipal solid waste (MSW) trash plastic and biological trash is combined to create mixed MSW (1). The floral waste was generated from religious locations, hotels, wedding gardens, and other civilizing and sacred activities. A significant quantity of floral debris is gathered from residential neighborhoods, community centre, and religious locations such as mosques, gurudwaras, and temples. In India, West Bengal is ranked fourth for flower promotion, behind Andhra Pradesh (AP), Karnataka, and Tamil nadu (2). Daily production of separated flower garbage is estimated to be 300 tons; in India, this amount is 1.5 tons, which is taken away individually at a floral debris collection centre (1). It has been stated that in certain regions of India, floral used for spiritual and ceremonial reasons are disposed of in lakes and rivers or mixed with MSW in a few hours, severely damaging the environment. Research on food waste and related waste

(Received 18th May 2024; Accepted 17th October 2024; Published 30th October 2024)

categories has been conducted in several studies; however, there has been very little composting research on flower waste too far. It was deemed important to carry out the composting research due to the rise in the amount of floral waste and its potential for pollution. The floral waste decomposes naturally and may be thrown wherever for breakdown resulting in temporary garbage disposal sites, which serve as a haven for disease-breeding organisms (3). Flower waste has been recycled into various value-added products, such as its high sugar content, perfume, and food coloring agents. Floral waste can be converted into fertilizer, which is suitable for agricultural applications due to its rich content of micronutrients such as manganese, iron, zinc, and copper, as well as macronutrients including phosphorus, calcium, potassium, and iron. MSW has been found to include 21–64% cellulose, 5–22% hemicelluloses, and 3–28% lignin (4). These days, the ideas of environmental preservation and sustainable development, and biogas as a fossil fuel substitute, are more popular in this context. Specifically, the technique of biogas production could help lower greenhouse gas emissions as well as trash production. This is why biogas production has been continuously rising globally in recent years. Biogas generation is also expected to be a major choice in the energy sector of many nations, leading to an increase in the global market size from USD 55.84 billion in 2022 to USD 78.8 billion by 2030 (5). Waste can be generated and managed in a variety of ways. One of them is to utilize it as a source of energy to produce useful products like biogas, which promotes the circular economy. When used as substrates or feedstock in bio digestion, a range of substances, such as wastewater, effluent, and organic solid waste can be converted into biogas. The anaerobic bacteria's activity in a condition of humidity and the lack of oxygen allows for the production of biogas (6). Anaerobic bacteria may convert any substrate into biogas or methane, which is known as feedstock. Solid wastes, easily degradable wastewater, and sludge are among them. There must be a significant amount of organic content in this garbage for it to be turned into biogas. Anaerobic digestion is a commonly used method for treating sewage sludge from aerobic treatment (7). The focus on achieving sustainable energy solutions and environmentally friendly resource management has resulted in the creative exploitation of floral waste for the production of bioenergy and the extraction of valuable products. This strategy not only encompasses the ideals of sustainability but also provides a practical solution to the increasing environmental difficulties caused by garbage. Through the conversion of the waste materials generated by the floriculture sector into bioenergy, we may effectively decrease our carbon emissions and alleviate the consequences of greenhouse gas emissions. Moreover, the extraction of valuable substances from floral waste is in line with the worldwide transition towards a bio-based economy, which advocates for the utilization of renewable resources instead of limited fossil fuels. This sustainable approach not only preserves natural resources but also creates new economic prospects, promoting a more environmentally friendly and affluent future.

Flower Waste Composition

Differing from location to location, there are different types of flowers used to make flower trash. For example, in Dargahs, the majority of the waste is made up of jasmine flowers; in Gurudwaras, the majority of the waste is made up of marigold flowers; and in temples, the waste is made up of rose, lotus, marigold, etc (8). High amounts of crude fibers, cellulose, lignocelluloses, essential oils, crude proteins, nitrogen-containing substances, etc., are found in floral wastes. This floral debris is useful as a bio-energy resource store. Flavonoids, volatiles, myricetin, and quercitrin are naturally occurring substances found in chrysanthemum blooms (9). In addition to flavonoids, phenolic, saponins, and steroids, jasmine blossoms incorporate essential oils (10). Rose petals include high levels of mineral salts, riboflavin, tannins, tartaric acid salt, pectin, and sugar (11). *Hibiscus rosa-sinensis* is known to include alkaloids, cardiac, quinines, phenols, flavonoids, tannins, steroids, carbohydrates, protein, sugars, and essential oils. In most target species, reports of carotenoids, phenolic chemicals, and terpenoids have been found. The lotus flower contains a number of alkaloids and flavonoids (12).

Problems in Managing Floral Waste

Dealing with flower waste is more challenging than managing household and other community garbage due to the spiritual significance of the flowers used in worship, which then become part of temple trash (13). Some religious sites hesitate to separate floral waste from temple trash for conversion into beneficial goods like composting, mostly due to religious beliefs (14). Consequently, the majority of flower waste is discarded in reservoirs, leading to their deterioration. The decay of floral trash in water depletes dissolved oxygen, causing harm to aquatic life such as fish (15). Additionally, dumping flower waste contributes to landfill problems, leading to the contamination of surface and groundwater. Despite being biodegradable, there's a misconception among individuals that flower debris dissolves swiftly upon disposal. Flower waste decomposes more slowly than household garbage (14).

Biogas Generation

In 2019, there were roughly 19.5 GW of biogas plants operating globally. The increase in biogas production was fueled by rising fossil fuel costs, the concerns regarding emissions and global warming convenient and the affordable availability of biomass feedstock. Typical raw materials used for biogas production includes household waste (such as food, vegetables, and fruits), public moist wastes from food establishments and marketplaces, organic waste from manufacturing sectors with high water content and decay, and animal byproducts (such as dung and chicken waste materials). The production of biogas can be generated by the process of anaerobic digestion, plays a significant role in protecting the environment and preserving natural resources (16). Biogas generation from flower waste is a sustainable and environmentally friendly process that transforms organic matter found in floral residues into biogas through a method known as anaerobic digestion. Anaerobic decomposition is an ecological method that produces nitrogen-rich fertilizer and biogas by decomposing the organic components of trash without the presence of oxygen. Various forms of organic waste, such as high-moisture trash, can be decomposed through anaerobic digestion. Biogas is composed of several gases, consisting of 25–40% carbon dioxide, 2% nitrogen, 50–75% methane, 2–7% water, and less than 1% hydrogen and hydrogen sulphide (17). The most affordable and environmentally friendly energy source in these nations can be biogas, which is created from the organic portion of MSW. One possible option for biogas generation is flower waste, which makes up a significant amount of the organic waste in the MSW from numerous religious locations and flower marketplaces. Flower waste is acidic, alkalizing the waste is necessary for producing biogas in an appropriate manner (4). Atal et al. conducted an experiment in which floral waste, namely *Chrysothemis pulchella*, *Hibiscus sabdariffa*, *Markhamia lutea*, *Peltophorum africanum*, *Albizia julibrissin*, and Jasminum, were combined with cow dung as an inoculum to produce biogas. In comparison, the biogas generated from vegetable waste decomposed in 9.1 g/kg less time than the biogas produced from floral waste, which took 16.7 g/kg longer. Moreover, the majority of flowers in India may be extracted for biogas, which will develop a sustainable idea of wealth from waste. Various types of flowers can be utilized to generate biogas, a fuel source for power production (2). Figure 1 depicts the visualization of the production of biogas from flower waste. Fermentation commonly incorporates germs or microbes to turn sugar into ethyl alcohol. Ethanol is the most carefully considered and practical energy alternative when compared to other fossil fuels. It has been recorded from historical and traditional sources that some tribal people in Andhra Pradesh, Maharashtra, and Chhattisgarh, India, cultivate and gather mahula flowers for alcoholic beverages using traditional ways.

There are significant financial benefits to using mahula flowers as a substrate for submerged fermentation, which produces ethanol (18). According to Adhikary, an additional report about the anaerobic digestion of roses in a batch reactor to produce biogas was discovered (19).

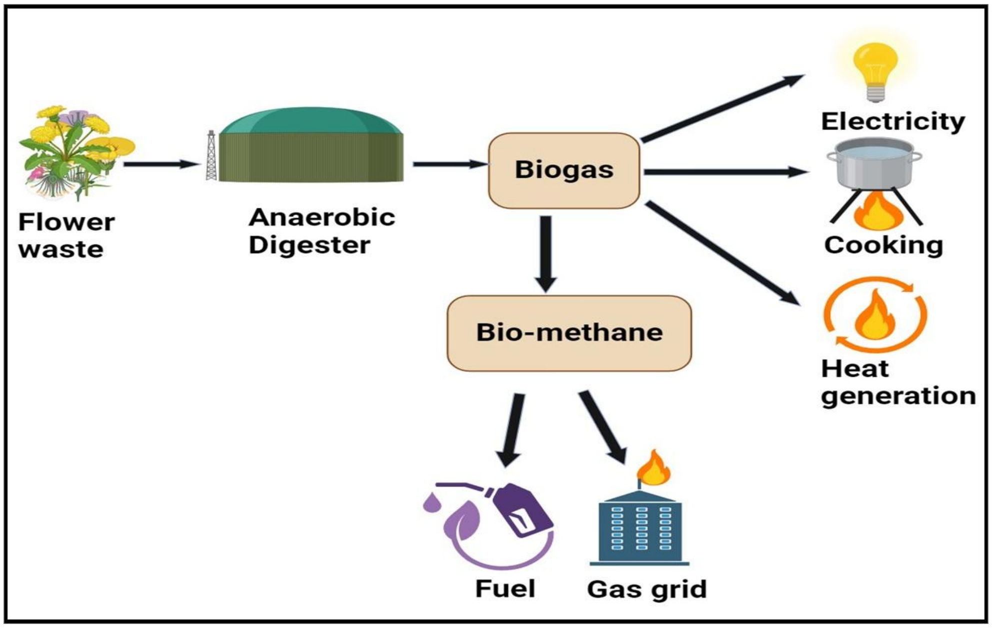

Figure 1: Diagrammatic Representation of the Production of Biogas from Flower Waste

Flower waste can be converted into biogas, serving as a fuel source and utilized for energy production. Ranjitha et al. reported varying amounts of biogas produced from Kenyan flower waste per kilogram of substrate. A 2.5-liter batch reactor containing rose debris was employed for a 30-day digestion process at room temperature. Various characteristics were analyzed every 5 days, including Total Kjeldahl Nitrogen (TKN), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Volatile Solids (VS), Chlorides, and Total Solids (TS). The approach potentially eliminates 73% of TS, 45% of VS, 82% of chloride, 42% of BOD, and 58% of TKN, while also generating biogas. Figure 2 illustrates the scheme of using flowers as a fermentable substrate in the fermentation process for generating biogas (20).

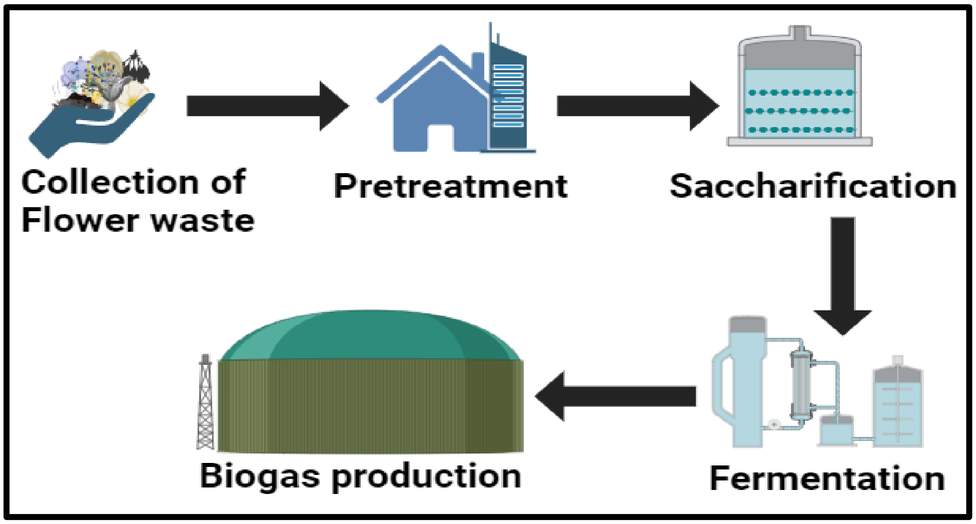

Figure 2: Diagram Illustrating the Use of Floral Debris as a Fermentable Substrate in the Fermentation Process to Produce Biogas

According to several studies, compared to vegetable waste, floral waste produces more biogas per unit substrate and at a higher rate of biogas production (21). To evaluate the efficiency of the biogas reactor, biogas was generated in a continuous reactor with a size of 2 m^3 utilizing crushed flowers, cow manure, and water over both summer and winter seasons (22). The study produced more biogas in the summer than in the winter because it used a non-heating digester with over 50% of the methane concentration in the biogas. Microbial activity was shown to be lower at lower temperatures, which was the reason for the wintertime decline in biogas production. Biogas is produced in a 230-liter pilot-scale digester from food waste after undergoing an initial pre-treatment process involving drying, mechanical shredding, and alkaline pre-treatment (23).

The authors used sodium hydroxide, sodium bicarbonate, or sodium chloride to create an alkaline solution in which floral waste was immersed for 24 hours to perform an alkaline pretreatment. The authors observed that raw flower waste did not produce biogas. Nevertheless, the application of sodium carbonate and sodium bicarbonate resulted in a substantial increase in biogas production, ranging from 103 to 106%. The pretreatment cost exhibited a reduction ranging from 90 to 96% when compared to the cost of using sodium hydroxide. It was observed that the biogas had a methane content of 57.52%, while the CO_2 and H_2S contents were 26.28% and 800 ppm, respectively. Solar heating enhanced the output of biogas by 122%, demonstrating the effectiveness of this technique for raising the yield of biogas from flower waste. Additionally, the study found that co-digesting 30% food waste and 70% flower waste enhanced biogas generation by 32.60%. By eliminating CO_2, H_2S, and moisture from the biogas, the authors enhanced its methane concentration by the application of chemical absorption technology. In order to eliminate carbon dioxide from the raw biogas, the columns were filled with a solution of 1.5 M sodium hydroxide and a 10% aqueous solution of monoethanolamine. Moisture was eliminated using steel wool and silica gel, while H_2S was eliminated using iron oxide. After filtration, the gas included 96.91% methane, 0.04% CO2, and 100 parts per million H_2S. CO_2 was removed with an efficiency of 99.85% and H_2S with an efficiency of 87.5%. This approach is cost-effective for purifying biogas from food waste since sodium hydroxide is easily accessible from local markets, and silica gel and monoethanolamine may be replenished (24).

This enhanced bio-methane serves two purposes: it can fuel vehicles and provide energy. In a separate study, biogas was produced at 30°C for 60 days using the leaves and stems of the decorative plant *Bougainvillaea spectabilis*. The study discovered that, compared to the plant's leaves and stems, flowers yielded the largest cumulative methane output. The explanation for this finding can be attributed to the fact that flowers possess a less complicated lignocellulosic structure. Over a period of 60 days, the methane production grew significantly from 0.6 to 1369 ml. The greatest rate of methane generation from food waste was observed to be 65.95 mL/(g.VS) (25). The findings suggest that the production of biogas can serve as a viable alternative for managing food waste. These types of chemicals used to alkalize the slurry has a substantial influence on the quantity of production of biogas from floral waste. Therefore, research efforts should focus on co-digesting floral waste with naturally alkaline wastes to overcome this limitation and minimize the amount of chemicals added.

In comparison to earlier studies, one study found that biogas derived from floral waste contained over 57% methane (26). On the other hand, methane usually makes up between 50 and 60% of cow dung biogas (27). Because it is the primary energy source, methane is the most valuable part of biogas. As a result, biogas produced from floral waste is more efficient and easier to break down because it contains more organic material and less lignin, thus having a higher calorific value than biogas made from cow dung (26). Cow dung can improve process stability and nutrient balance due to its higher nitrogen content and lower carbon-to-nitrogen ratio compared to floral waste (28).

Anaerobic Digestion Process

Anaerobic metabolism is a method that generates biogas from a variety of organic substances. Anaerobic digestion is a complex process in which organic matter undergoes chemical and biological interactions to produce biogas and effectively manage trash. The anaerobic action of several bacteria systematically degrades large organic polymers into smaller molecules throughout the biogas production process. Anaerobic digestion is organic process that utilizes hydrolysis, acidogenesis, acetogenesis, and methanogenesis to convert biomass into biogas (16). Figure 3 displays the schematic of anaerobic digestion production.

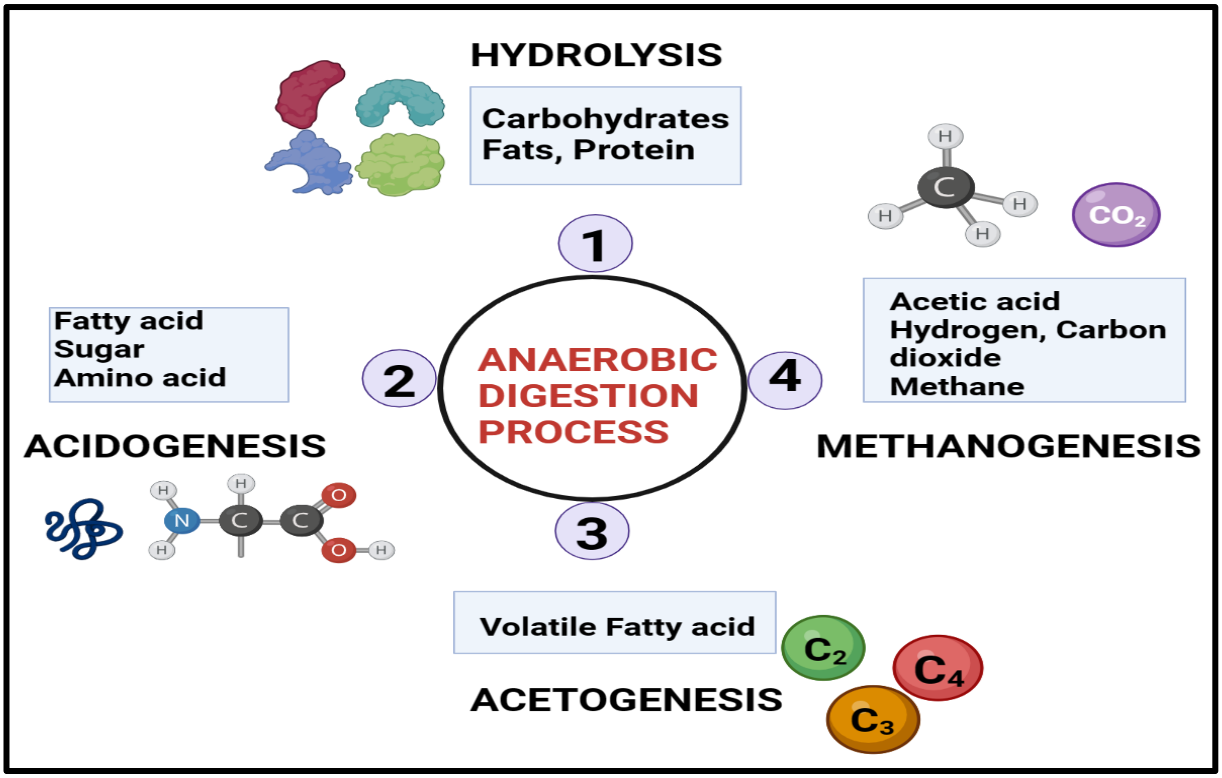

Figure 3: Schematic Representing of Anaerobic Digestion Production

Hydrolysis

Hydrolysis is the chemical method of breaking down water into OH^- anions and H^+ cations. Large biomass polymers in the substrate break down through hydrolysis in the presence of an acidic catalyst. Huge organic polymers found in lipids, proteins, and carbohydrates in biomass undergo breakdown into smaller molecules called simple sugars, amino acids, and fatty acids (29). Hydrolysis is a process in which fermenting bacteria, such as Clostridium, bactericides, and bifidobacterial, decompose biopolymers such polysaccharides, lipids, and proteins into fatty acids, amino acids and soluble sugars. Methanogens use acetate and hydrogen, which are the main byproducts of hydrolysis, in later stages of anaerobic digestion. The majority of hydrolysis products consist of complex compounds that need to be further decomposed in order for the acidogenesis process to produce methane (30).

Acidogenesis

In this process, the anaerobic activity of acidogens primarily produces hydrogen gas, hydrogen sulfide, organic acids, and alcohols. Acidogenic microorganisms decompose hydrolysis products in an acidic environment produced by fermentative bacteria to yield carbon dioxide, hydrogen sulfide, ammonia, carbonic acid, volatile fatty acids, alcohol, and other minor byproducts (31). However, since acidogenesis still yields significant byproducts, it is not the most efficient process for methane production. Therefore, it undergoes the acetogenesis process (32).

Acetogenesis

Acetogenesis is the process that converts acetic acid into acetate (33). During the anaerobic metabolism of acidogenesis' products acetic acid, carbon dioxide, and hydrogen is produced. Methanogens can react with the products of acetogenesis and some byproducts of other processes to produce methane once acetogens have completed their digestion (32).

Methanogenesis

Through the activity of carbon dioxide (CO_2) and acetoclastic methanogens (AM), which reduce methanogens, methane and carbon dioxide are produced in the final stage of methanogenesis. Anaerobic bacteria called methanogens perform the process of anaerobic digestion, which involves converting the byproducts of acetogenesis and other intermediate products from hydrolysis and acidogenesis into methane. These include *Methanococcus mazei*, *Methanosaeta concilii*, and *Methanosarcina barkeri* (33, 34).

Benefits of Biogas from Floral Waste

Recently, there has been an increasing acknowledgment of the necessity for sustainable and environmentally friendly energy alternatives. Floral waste presents a significant opportunity for generating renewable energy through biogas production. This article examines the diverse environmental and social advantages linked to utilizing flower waste for biogas production.

Renewable Energy Source

As floral waste is a renewable resource, utilizing floral debris as a substrate for production of biogas is an effective means of generating sustainable energy. Biogas is a multifunctional fuel that can be used for generating energy, heating, and cooking. Floral debris often overlooked after events, celebrations, and religious practices, can be transformed into a valuable energy resource. By redirecting floral waste away from landfills and utilizing it for the creation of biogas, we not only alleviate the strain on waste management systems but also generate environmentally friendly and sustainable energy

Mitigating Greenhouse Gas Emissions

By utilizing anaerobic digestion, biogas may be generated from floral waste, resulting in a significant reduction in methane emissions. Methane is a potent greenhouse gas that is released during the natural breakdown of organic materials. This decrease in greenhouse gas emissions contributes to endeavors to mitigate climate change.

Localized Energy Solutions Urban and peri-urban areas often generate floral waste as a result of events and festivities. Establishing biogas facilities in these regions enables local energy production, thereby reducing the need to transport energy resources over long distances and promoting energy resilience within communities.

Fertilizer Production for Sustainable Agriculture

Digestate, produced as a byproduct of biogas production, is an organic fertilizer rich in nutrients. This fertilizer can be utilized to enhance soil fertility, facilitating sustainable agricultural operations and completing the natural cycle.

Cleaner Air Quality

Biogas combustion is typically more environmentally friendly than conventional fuels, leading to decreased emissions of pollutants such nitrogen oxides, sulfur dioxide, and particulate matter. Consequently, this leads to enhanced air quality in the nearby regions.

Floral Waste Management and Its Diverse Value-Added Products

Various approaches for managing the disposal of flower debris can be repurposed to make rose water essence, incense sticks, natural dyes, vermicomposting, handmade paper, natural holi colours, and other products. In Figure 4 the utilization of flower waste and its related products are outlined below.

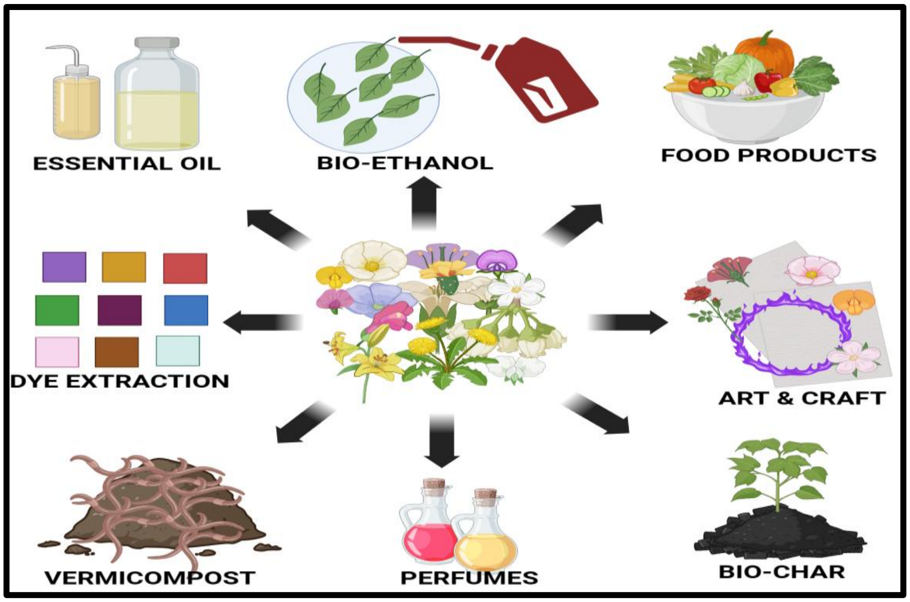

Figure 4: Managing of Flower Waste for Generating other Valuable Added Products

Floral waste generated by temples can be repurposed as a reliable and continuous supply of raw materials for the production of handcrafted paper. This strategy minimizes the amount of waste generated by municipal worship centers by reusing and repurposing it into environmentally friendly paper. One benefit of using floral waste to make handmade paper is that it is completely free of wood and chemicals, and it doesn't produce any harmful byproducts during the manufacturing process (19).

We now know that flowers' metabolites, found within their bodies, also provide therapeutic benefits. Several studies have found that calendula oil, produced by infusing dried calendula flowers in olive oil, is high-quality massage oil derived from processed flower waste. Lily is used for treating jaundice, respiratory, and gastrointestinal diseases, while rhododendron blossom juice is employed to manage high blood pressure. Passionflower relieves anxiety, stress, and sleeplessness. Essential oil of chamomile is used to ease muscle cramps and treat skin conditions including dermatitis (35).

Utilizing particular species of earthworms with high organic matter content instead of chemical fertilizer can convert flower waste into organic fertilizer. This vermicompost could be beneficial for improving the nutrient content of the soil (36). The decomposed flower debris can serve as fertilizer NPK for its high levels of nitrogen, phosphorus, and potassium. To overcome the issues associated with flower waste generation, a microbial consortium can be created from it (14).

The food industry can use edible floral waste, such as marigolds and roses, to make syrups, cakes, ice creams, biscuits, jams, jellies, candies, drinks, and more, since they are high in nutrients (35). Around 300,000 metric tonnes of flowers per year India utilizes for variety reasons such as bouquets, pesticides, pigment extraction, decorations, and aroma compounds. Flowers offered to the gods can be repurposed for extracting essential oils, with roses alone constituting half of the floral waste in temples (37). Colorful flowers are harvested for their pigments, which are then used in: (a) The textile sector for fabric dyeing, (b) Crafting colorful candles, (c) Coloring eggs, vegetables, etc., in the food industry, (d) Producing powdered colors from dried flowers using a solar dryer, providing a safe and organic option for making Holi and Rangoli colors (38).

Flower perfume is versatile and can be incorporated into shampoos, cosmetics, aromatherapy, and lotion items (39). Discarded flowers are repurposed to create incense sticks and handmade paper. Dried flowers have multiple uses in arts and crafts projects and can also be given to animals as food (8).

Biogas fuel can be used to treat biodegradable trash by eliminating existing bacteria. It is a versatile fuel that emits fewer greenhouse gases due to its manufacture through anaerobic digestion. Biogas can be used as a fuel in various conversion technologies and prime movers to generate power. Common tools and main drivers for producing electricity from biogas are combustion engines, specifically bi-fuel and dual-fuel engines, as well as dedicated petrol engines that may run on diesel or petrol. Additional turbines refer to gas and steam turbines of different sizes, including micro, small, or large, that are utilized in cogeneration, combined phase, or open-cycle operations. By utilizing biogas as their fuel source, sterling engines are engines that combustion capable of generating energy. The conversion can be performed directly through the use of clean fuel cells powered by biogas or renewable hydrogen generated by reforming biomethane or biogas. Biogas can also be used by utilizing the Fischer-Tropsch (FT) process, to produce renewable fuels for power generation and transportation. Therefore, biogas can be used as a pathway towards the sustainable energy transition by replacing fossil fuels such as power production, transportation, heating, and cooling applications (40-42).

Biochar is produced by heating biomass in a confined container with limited air in a process known as pyrolysis. In remote locations, biochar in the form of charcoal can be used as a power source. However, the traditional method of making this charcoal involves using wood, which is inefficient and causes deforestation, thus having adverse effects on the environment. As a substitute, the preparation of biochar from flower waste has been explored. There are accounts demonstrating successful conversion of floral debris to charcoal in Ethiopia. Such biochar can be utilized as a cooking fuel in rural regions instead of straight biomass, which can generate toxic emissions from incomplete combustion (43).

Composting is a popular method for disposing of floral waste, which is biodegradable and can be utilized as growing media or soil conditioner. Therefore, in addition to using earthworms, various methods can be employed to break down flower waste into compost. Compost made from flower waste can be used on its own or, for optimal results, combined with sawdust or manure. Sharma et al. and other researchers have optimized combinations of sawdust, cow dung, and flower debris using the reacting surface technique. An optimal composting mixture consisted of sixty-five kilograms of floral debris, twenty-five kilograms of cow dung, and ten kilograms of wood dust. Similarly, when a 1:1 mixture of dung and floral waste was used, the highest number of adults, cocoons, and young worms of *Eudrilus eugeniae* were utilized for the composting process (1, 41).

Conclusion

This review discusses the problem of flower waste produced in places of worship. The inappropriate treatment and disposal of flower debris have a detrimental impact on the quality of the soil, water, and air in the surrounding area. Flower debris is a great resource for producing biogas and other goods due to its high content of lignocellulose and organic materials. Substantial bioenergy can be generated from floral waste, offering dual advantages: addressing environmental issues, supplying cost-effective, and eco-friendly energy. Floral waste can be utilized to recover valuable chemical compounds in addition to generating bioenergy, which are in great demand by many industries.

Biogas usage contributes to global environmental sustainability as it effectively controls the release of greenhouse gases and helps to alleviate the potential dangers linked to climate change and global warming. Biogas utilization effectively reduces the adverse environmental and healthcare consequences resulting from the substantial amount of agricultural waste produced on a global scale. Biogas offers significant benefits in terms of financial stability, economic viability, environmental sustainability, and improved health for individuals whose livelihoods and basic necessities depend on agriculture. Developing biogas production facilities that utilize agricultural wastes will stimulate job creation and generate additional income. This will reduce unemployment, boost smallholder agriculture income and sustainability, and a greater involvement of farmers in the shift towards low-carbon and environmentally friendly energy sources. As a result, there will be a notable and beneficial social impact. Over two-thirds of the global population relies only on agriculture for survival, highlighting the crucial role of agricultural and animal husbandry in providing food for all.

Biogas production from floral waste emerges as a win-win solution, addressing both environmental challenges and the need for sustainable energy. Transforming a seemingly ephemeral byproduct into a valuable resource is not contribute to the fight against climate change but also empower communities and promote a more circular and sustainable economy.

Abbreviations

CAGR: Compound Annual Growth Rate, MSW: Municipal Solid Waste, TKN: Total Kjeldahl Nitrogen, COD: Chemical Oxygen Demand, BOD: Biochemical Oxygen Demand, VS: Volatile Solids, TS: Total Solids, AM: Acetoclastic Methanogens.

Acknowledgement

Nil.

Author Contributions

All authors contributed equally to bringing out this research article.

Conflict of Interest

The authors report no financial or any other conflicts of interest in this work.

Ethics Approval

Not applicable.

Funding

There is no funding to report.

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