Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-022-02353-z

ORIGINAL ARTICLE

Characterization of floral waste as potential candidates for compost and biofuel production

Smita Dutta[1,2] · M. Suresh Kumar[1,2]

Received: 10 November 2021 / Revised: 13 January 2022 / Accepted: 17 January 2022

Abstract
Floral waste (FW) forms the most overlooked part of municipal solid waste (MSW) in India and is one of the major sources of water pollution due to the traditional method of disposing of the FW. The current study focuses on the characterization of FW samples based on proximate, ultimate, elemental, morphological, and biochemical analyses. The samples had moisture content (MC) ranging from 6.1 to 12.86%, whereas volatile matter (VM) and ash content (AC) were in the range of 79.99–88.68% and 4.35–9.79%, respectively. NPK values and elemental analysis suggest that the FW samples are also promising feedstock for compost production without any adverse effect on the environment. However, FW samples were found to be acidic in nature (3.88–5.47) with a variable C/N ratio, ranging from 11.82 to 38.26. Morphological studies show that the FW samples have heterogeneous surfaces. FW samples were also found to be high in cellulose (22.31–37.22%) and hemicellulose (19.19–38.89%) content and low in lignin content (1.76–4.54%). Stoichiometric methane potential (SMP) and stoichiometric ethanol potential (SEP) of FW were calculated based on the ultimate and biochemical analyses, respectively of FW. SMP was found to be in the range of 0.170–0.434 L CH_4 g^{-1} VS, whereas SEP was found in the range of 0.433–0.582 Lg^{-1}. The results exhibit that FW can be used as a potential candidate for bioenergy and compost production.

Keywords Floral waste · Biogas · Bioethanol · Compost

Abbreviations

FW	Floral waste
MSW	Municipal solid waste
MC	Moisture content
VM	Volatile matter
AC	Ash content
SMP	Stoichiometric methane potential
SEP	Stoichiometric ethanol potential
LCB	Lignocellulosic biomass
FC	Fixed carbon
HR	Hibiscus
OM	Orange marigold
YM	Yellow marigold
PA	Frangipani
WK	White kaner
PR	Pink rose
RR	Red rose
YC	Yellow chrysanthemum
OC	Orange chrysanthemum
CJ	Crepe jasmine
SL	Spider lily
HHV	Higher heating value
SEM	Scanning electron microscope
NDF	Neutral detergent fiber
ADF	Acid detergent fiber
ADL	Acid detergent lignin
VS	Volatile solids
ICP-OES	Inductively coupled plasma–optical emission spectrophotometer
ND	Not detected

✉ Smita Dutta
duttasmita2@gmail.com; s.dutta@neeri.res.in

1 Environmental Impact and Sustainability Division, CSIR-National Environmental Engineering Research Institute, Nehru Marg, Nagpur 440020, India

2 Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

1 Introduction

The increasing global population, urbanization, and industrialization have tremendously increased the global energy requirements and solid waste generation in the last couple of decades, which have led to the depletion of finite fuel reserves and various environmental issues [1]. As a result, the world today looks towards the concept of bioeconomy for sustainable growth and development. Bioeconomy is based on the usage of renewable biological materials to produce energy and materials [2]. In 2017, approximately 2.01 billion tons of municipal solid waste (MSW) was generated globally, which is estimated to rise to 3.40 billion tons annually by 2050 [3]. Sarsaiya et al. [4] estimated that by 2047, India alone would generate approximately 300 million tons of MSW, requiring 169.6 km^2 to dispose of this waste. Organic waste, which forms more than 50% of the MSW generated in India, increases the land area required for dumping. It also increases methane emissions and leachate production from landfills.

Floral waste (FW) is one of the most significant yet overlooked parts of the organic portion of the MSW produced from religious places, floricultural activities, various social events, flower markets, roadside plantations, and different recreational places. Flowers are used in bulk in religious places where they are offered to God with other items of worship like vermillion, incense sticks, coconut shells, various plant parts, and various plastic, cloth, and synthetic items. It is estimated that around 2 million temples are spread around India [5]. The most common flowers found in religious places are rose, marigold, chrysanthemum, hibiscus, and jasmine. After worship, they are left unused and become colossal waste. Flowers used for religious purposes are considered sacred entities with sentimental values and are thus not thrown into the garbage. Currently, there are no proper rules for the collection, segregation, management, and disposal of FW [6]. The FW generated from temples is thrown in nearby water bodies as per tradition or discarded in open spaces. Such practices cause various ecological risks and aesthetic pollution and create a breeding ground for insects [7]. Although most of the blame for river pollution is accredited to industrial runoff and sewage discharge, the dumping of FW into rivers is an overlooked source of water pollution in Indian rivers. Table 1 shows the quantity of floral waste generated from some of the famous religious places in India. According to Sharma et al. [8], India produces 4738 tons of FW daily, out of which Varanasi and Surat, considered two of India's holiest cities, produce around 10 tons of FW [9]. In a study conducted in Koyambedu Wholesale Market Complex, Chennai, India, FW made up approximately 2300 tons monthly of the total horticultural waste produced, with chrysanthemum and marigold forming the major part of the generated waste [10]. FW generated from markets, recreational places, and roadside plantations are often discarded alongside other MSW, ultimately finding their way to landfills.

There is an urgent need to find ways, which are economically feasible and socially and environmentally acceptable, to valorize the FW generated. The management of the bulk of FW generated from religious places is still in its infancy, with most studies conducted on the valorization of this resource to produce dyes [19, 20] and incense sticks [21]. In the literature, lignocellulosic biomass (LCB) has widely been used to produce biofuels and other value-added products like biofertilizers, biochars, and activated carbon [22]. The use of LCB for biofertilizer production reduces the use of inorganic fertilizers, whereas its use as a feedstock for bioenergy production reduces the net CO_2 emissions associated with fossil fuels [23]. Several studies have reported the use of the organic portions of MSW for the production of biofuels [24–27]. However, variations in the physical and chemical composition of feedstock significantly affect biofuel and biofertilizer production and quality. Different methods are available to characterize the properties of organic feedstocks, including proximate analysis, chemical analysis, elemental analysis, compositional analysis, and surface morphological studies. There is no study in literature reporting the complete characterization of individual flowers present in FW. Considering the huge quantum of FW produced in India, the present research focuses on characterizing the commonly found flowers present in FW based on their physical and chemical compositions for their potential usage in biofuel and compost production. The present work aims to provide essential insights into different stakeholders for deciding the alternative usage of FW.

Table 1 Floral waste production from famous religious places in India

Temple	Quantity produced (kg/day)	Reference
Dakshineshwar Kali Temple, Kolkata	400	[11]
Sai Baba Temple, Gwalior	100	[12]
Kalighat Temple, Kolkata	2000	[13]
Jhandewalan Temple, Delhi	200–500	[14]
Moinuddin Chisti Dargah, Ajmer	2000	[15]
Ashtalakshmi Temple, Chennai	200	[16]
Marudeeshwar Temple, Chennai	125	[16]
Kabaleeshwar Temple, Chennai	800	[16]
Murugan Temple, Chennai	400	[16]
Sri Parthasarathy Temple, Chennai	400	[16]
Kashi Vishwanath, Varanasi	2000	[17]
Chatusrungi Temple, Pune	600	[18]

2 Materials and methods

2.1 Sample collection and preparation

FW was collected from Ganesh Tekdi, Nagpur, India, from October 2019 to February 2020. Ganesh Tekdi is

Table 2 Common flowers found in the mixed FW collected from religious places

Flower name	Scientific name
Hibiscus	*Hibiscus rosa sinensis*
Orange marigold	*Tagetes erecta*
Yellow marigold	*Tagetes erecta*
Frangipani	*Plumeria alba*
White kaner	*Cascabela thevetia*
Pink rose	*Rosa indica*
Red rose	*Rosa* sp.
Yellow chrysanthemum	*Chrysanthemum indicum*
Orange chrysanthemum	*Chrysanthemum indicum*
Crepe jasmine	*Tabernaemontana divaricata*
Spider lily	*Hymenocallis littoralis*

considered one of the most prominent temples in Nagpur producing around 500 kg of FW daily, which goes up to 1200–1500 kg on festive occasions and special days. The most commonly found flowers in the mixed FW were identified and are shown in Table 2.

FW from the temple were collected in the early morning hours, which formed the waste from the previous day. The flowers were either in loose form or in the form of garlands. Mixed FW was first separated from other kinds of wastes like threads, different plant parts, papers, and plastics, which were further segregated based on different species of flowers. Next, these flowers were washed with tap water and finally with distilled water to remove dust and other contaminants and sun-dried for 48 h to reduce the moisture content for further analysis. The sun-dried samples were ground in a mixer grinder to reduce the size to pass through a 2-mm screen. Prepared samples were stored in airtight containers and kept at 4 °C until further analysis.

2.2 Proximate analysis

Different proximate analyses were performed to analyze the major constituents of the FW samples, namely moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC). Moisture is not a structural component of biomass and can change with handling and storage. AC gives the approximate measure of mineral and other inorganic matter in biomass.

MC was measured according to the ASTM E1756-08 method, where 1 g of sample is taken in a pre-dried quartz crucible and oven-dried at 105 ± 3 °C for 3 h [28]. The samples were then allowed to cool in a desiccator and weighed. The process was repeated until the weight change of the sample was less than 0.3 mg. The MC was calculated using Eq. (1).

$$\mathrm{MC}(\%) = \frac{\text{Initial weight of sample} - \text{Final weight of sample}}{\text{Initial weight of sample}} \times 100 \quad (1)$$

The ASTM E1755-01 [29] method was used to determine AC. The oven-dried biomass samples were placed in a muffle furnace and ignited at 575 ± 25 °C for 3 h, cooled to room temperature in a desiccator, and weighed. The ignition process for an hour, cooling, and weighing were continued until a weight change within 0.3 mg was obtained. The difference in weight of the samples before and after ignition gives the AC. The ASTM E872-82 [30] method was used to estimate the VM. In this test, 1 g of oven-dried biomass was kept in a covered crucible and placed in a muffle furnace at 950 °C for 7 min. The crucibles were then withdrawn, cooled to room temperature in a desiccator, and weighed. The difference in weight due to devolatilization was used to calculate VM. The FC was calculated using Eq. (2) as given in the following [31]:

$$FC(\%) = 100 - (MC\% + AC\% + VM\%) \quad (2)$$

2.3 pH

pH of FW samples was measured according to USEPA 9045D [32]. A slurry of FW samples was made using distilled water in the ratio of 1:2 (w/v), stirred, and filtered through Whatman filter paper 1. pH of the sample was then measured immediately using a pH meter (make: Eutech Instruments, model: Ion 2700).

2.4 Ultimate analysis and higher heating value

The ultimate analysis, i.e., carbon, nitrogen, hydrogen, and sulfur content, of the FW samples was done using a CHNS analyzer (make Elementar Germany, model Vario EL). Approximately 6–8 mg of finely powdered sample was taken in small tin capsules and was placed inside the muffle and the elemental composition was noted.

The higher heating value (HHV) was calculated based on the elemental composition of the biomass samples using Eq. (3) as given by Singh et al. [31].

$$HHV = (33.5 \times C\% + 142.3 \times H\% - 15.4 \times O\% - 14.5 \times N\%) \times 10^{-2} \quad (3)$$

2.5 Elemental and morphological analyses

For estimating metals, ASTM D5198-09 (nitric acid digestion for solid waste) method was followed [33]. One gram of sample was taken into a tared 125-ml Erlenmeyer flask and 25 ml of 1 + 1 nitric acid was added. The sample was digested for 2 h at 90–95 °C. More acid was added if the sample remained colored after 2 h and digested until colorless. After digestion, the sample was cooled to room temperature, and 50 ml distilled water was added to the flask, washing down the flask walls. The contents were mixed and filtered through Whatman filter paper 40. The volume of the filtrate is made up to 200 ml and analyzed on an inductively coupled plasma–optical emission spectrophotometer (ICP-OES) (make: Thermo Fisher, Model iCAP6300 DUO) for metals, namely As, B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, and Zn.

The surface morphology of the FW samples was studied using a scanning electron microscope (SEM) (make TESCAN) operating at 10 kV.

2.6 Biochemical analysis

Cellulose, hemicellulose, and lignin contents in the FW samples were analyzed by estimating the neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) [34]. The percentage of cellulose, hemicellulose, and lignin was calculated using Eqs. 4, 5, and 6.

$$\text{Hemicellulose}(\%) = \text{NDF} - \text{ADF} \tag{4}$$

$$\text{Cellulose}(\%) = \text{ADF} - \text{ADL} \tag{5}$$

$$\text{Lignin}(\%) = \text{ADL} \tag{6}$$

Protein estimation was done according to Lowry's method [35] with bovine serum albumin as standard. The total sugar concentration was estimated according to Hedge and Hofreiter [36] using glucose as standard.

2.7 Estimation of biofuel production

For calculating the stoichiometric methane potential (SMP), volatile solids (VS) of FW were first determined according to APHA 2540-G [37].

SMP was calculated using the equation given by Choudhary et al. [38] as given in Eqs. 7 and 8.

$$\begin{aligned} CaHbOcNd + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 \\ + \left(\frac{4a-b+2c+3d}{8}\right)CO2 + dNH_3 \end{aligned} \tag{7}$$

$$SMP = \frac{1}{8}\left(\frac{4a+b-2c-3d}{12a+b+16a+14d}\right)V_m \tag{8}$$

where V_m is the molar volume of methane at STP.

Stoichiometric ethanol potential (SEP) was calculated according to Pattanaik et al. [39] who considered the conversion of hexose sugars released from cellulose and pentose sugars from hemicellulose using Eqs. 9 and 10.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO \tag{9}$$

$$3C_6H_{12}O_6 \rightarrow 5C_2H_5OH + 5CO \tag{10}$$

In Eqs. 6 and 7, 1 g of sugar produces 0.51 g ethanol and 0.489 g of CO_2.

3 Results and discussion

3.1 Proximate analysis

The proximate analysis of the FW samples is shown in Table 3. MC, one of the most critical parameters, is defined as the amount of water per unit weight of the dry sample. In biomass samples, the MC is of two types, intrinsic moisture, which is not affected by the weather conditions, and extrinsic moisture, which is affected by different weather conditions. In this study, the intrinsic MC after sun-drying the samples for 48 h was measured. From Table 2, it can be seen that the samples have a low MC ranging from 6.1 to 12.86%. MC significantly dictates the end-use of a biomass sample. High MC leads to a lower heating value of a biomass sample, and for efficient combustion and thermochemical conversion, biomass having 10–15% MC is preferred [39]. The VM was observed in the range of 79.99–88.68%, which was comparable to that of biomass samples like sawdust (83.12%), *Miscanthus* (79%), thistle (80.64%), corn cob (83%), and bamboo (83.95%) [40, 41]. The VM obtained in this study is relatively higher than that of most biomass samples reported in the literature, like most kinds of woody, herbaceous, and agricultural biomass [42]. High VM leads to higher HHV and longer flame length upon ignition [43]. According to Pattanaik et al. [39], a higher VM content also means higher organic matter content essential for anaerobic digestion and biogas production. AC forms the non-combustible inorganic part of the biomass and affects the combustion rate [44]. Additionally, AC is also inversely proportional to the HHV as it reduces the efficiency of the combustion process by acting as a heat sink. It was found the lowest in PR (4.35%) and the highest in OC (9.79%). The values obtained for AC were similar to the AC in *Matooke* peels (4.8–5.8%) [43], *Miscanthus* (9.6%), and straw (6.1%) [41]. The obtained AC was lesser than the AC of rice husk [45], rice straw [46], and potato plant waste [41]. The higher VM and lower AC values observed in the FW samples indicate that the combustion process will be easy. FC content is the part of biomass left after the release of VM and excludes moisture and AC. The FC ranged from 0.33% obtained in

Table 3 Proximate and ultimate analysis of different FW

		Mixed FW	Flower name										
			YC	OC	SL	RR	PR	YM	OM	PA	HR	CJ	WK
Proximate analysis	MC (%)	10.19 ± 1.1	9.63 ± 0.54	9.05 ± 0.24	12.86 ± 0.31	7.29 ± 1.08	6.27 ± 0.47	9.05 ± 0.76	9.45 ± 0.49	10.48 ± 1.25	8.41 ± 0.36	8.78 ± 0.12	6.1 ± 0.55
	VM (%)	82.68 ± 0.39	80.33 ± 0.64	80.47 ± 0.59	79.99 ± 1.91	86.14 ± 0.06	88.68 ± 0.16	82.85 ± 1.58	81.44 ± 0.41	80.73 ± 0.84	82.56 ± 0.49	83.03 ± 0.39	85.69 ± 0.38
	AC(%)	6.52 ± 0.9	9.49 ± 0.42	9.79 ± 0.36	6.82 ± 0.48	5.82 ± 0.62	4.35 ± 0.57	7.19 ± 0.89	8.28 ± 0.72	8.16 ± 0.66	8.26 ± 0.28	7.64 ± 0.36	7.7 ± 0.26
	FC (%)	0.61 ± 0.09	0.55 ± 0.15	0.69 ± 0.11	0.33 ± 0.05	0.75 ± 0.12	0.7 ± 0.24	0.91 ± 0.41	0.83 ± 0.31	0.63 ± 0.15	0.77 ± 0.59	0.55 ± 0.29	0.51 ± 0.24
pH		4.55 ± 0.04	5.39 ± 0.07	5.2 ± 0.02	4.91 ± 0.11	5.42 ± 0.06	4.43 ± 0.06	4.45 ± 0.1	4.52 ± 0.08	4.41 ± 0.09	4.26 ± 0.02	4.12 ± 0.07	3.95 ± 0.09
Ultimate analysis	N (%)	2.14 ± 0.11	2.18 ± 0.11	2.29 ± 0.06	3.56 ± 0.08	1.89 ± 0.1	1.43 ± 0.14	2.41 ± 0.01	2.35 ± 0.06	1.15 ± 0.02	2.33 ± 0.03	2.13 ± 0.04	1.64 ± 0.03
	C (%)	44.27 ± 0.15	43.36 ± 0.81	43.49 ± 0.41	42.02 ± 0.51	44.32 ± 0.62	44.35 ± 0.71	43.34 ± 0.13	42.90 ± 1.24	44.01 ± 0.63	42.27 ± 0.36	41.48 ± 0.07	42.50 ± 0.25
	O (%)	46.88 ± 0.41	47.24 ± 0.18	46.86 ± 0.42	46.98 ± 0.49	47.61 ± 0.24	47.69 ± 0.84	46.93 ± 0.31	47.72 ± 0.68	47.81 ± 0.76	48.01 ± 0.09	49.09 ± 0.24	48.59 ± 0.19
	H (%)	6.20 ± 0.03	6.97 ± 0.03	7.03 ± 0.02	7.17 ± 0.06	6.18 ± 0.22	6.43 ± 0.18	7.23 ± 0.02	6.99 ± 0.18	6.90 ± 0.12	7.28 ± 0.07	7.10 ± 0.1	7.26 ± 0.16
	S (%)	0.51 ± 0.002	0.26 ± 0.01	0.33 ± 0.04	0.28 ± 0.004	0	0.10 ± 0.02	0.11 ± 0.04	0.04 ± 0.01	0.14 ± 0.06	0.11 ± 0.03	0.21 ± 0.06	0.01 ± 0.01
Empirical formula		$C_{24}H_{40}O_{19}N$	$C_{23}H_{44}O_{19}N$	$C_{22}H_{43}O_{18}N$	$C_{14}H_{28}O_{12}N$	$C_{27}H_{45}O_{22}N$	$C_{36}H_{62}O_{29}N$	$C_{21}H_{42}O_{17}N$	$C_{21}H_{41}O_{18}N$	$C_{45}H_{83}O_{36}N$	$C_{21}H_{43}O_{18}N$	$C_{23}H_{46}O_{20}N$	$C_{30}H_{61}O_{26}N$

SL to 0.91% in YM, which was much lower than the FC observed in most biomass samples [42].

3.2 pH

The pH of a substrate plays a significant role in bio-energy production. Table 3 shows the pH of the FW samples. The highest pH value was found in RR (5.42), whereas the lowest pH was reported in WK (3.95). The pH values observed in this study were significantly lower than the pH values observed in other kinds of biomass samples like *Grewia lasiocarpa* [47] and organic waste samples like kitchen waste and farmyard waste [48]. However, other studies in the literature also reported similar values for FW samples [49–51], indicating that FW is inherently acidic in nature. Most methanogenic bacteria function at the pH range of 6.7–7.4 but optimally at a pH range of 7.0–7.2 [52]. Thus, for optimal biogas production, FW samples need to be made alkaline chemically or used as a co-substrate with feedstocks that are alkaline in nature.

3.3 Ultimate analysis

In this study, a CNHS analyzer was used to carry out the ultimate analysis of the FW samples on a dry weight basis and the data obtained are reported in Table 3. Since the carbon content in biochar causes its sequestration in the soil, biomass containing a higher carbon value is preferred for biochar production [53]. The FW samples contained a carbon concentration of 41.48–44.35%, similar to biomass like *Indigofera tinctoria* [39] and cleaning wheat [53]. The concentration of oxygen ranged from 46.86% observed in OC up to 49.09% found in CJ. The oxygen concentration was higher in the present study than that in other biomass samples [54] and the typical organic waste categories present in MSW [55, 56]. Although oxygen in samples reduces the heating value of a fuel, it also causes flame elongation, leading to lower char production [57]. The results for hydrogen in FW samples varied from 6.18 to 7.28%, which were similar to values reported in *Delonix regia* and *Sapodilla* seeds [58] but higher than sawdust, sugarcane bagasse [42], wheat straw [53], and rice husk [45]. Nitrogen is an essential macro-nutrient for plants and its high concentration is highly desirable for the production of biochar and biofertilizers. However, a higher concentration of nitrogen is also responsible for the production of NO_x upon combustion and also reduces the heating value [57]. Its concentration ranged from 1.15% found in PA to 3.56% in SL, which were comparable to most biomass samples reported in literature like hay [53] and rice straw [56], and waste categories of MSW like food waste [55, 56] and vegetable solid waste [59] but higher than most woody biomass [42]. The sulfur concentration was found to be in the range of 0–0.51% in the

FW samples tested, which was comparable to MSW (0.30%) and biomass samples like sawdust (0.16%), bagasse (0.01%), wood (0.08%), *Miscanthus* (0.15%), corn straw (0.08%), and *Matooke* peel waste [42, 43, 60].

The C/N ratio is an important parameter when a biomass sample is considered to produce compost and anaerobic digestion. The C/N ratio of FW ranges from 11.82 to 38.26 and is shown in Fig. 1. When a comparison was made with similarly published works, it was found that different kinds of vegetable wastes contained a C/N ratio ranging from 14 to 32.23 [59]. Aramrueang et al. [27] reported the C/N value of tomato (21), watermelon (31), wheat hay (38), Jose Tall wheatgrass (32), and sugar beetroot leaf (14–25), which were similar to values observed in the present study. Olupot et al. [45] determined the C/N ratio in the range of 54.73–86.81 in rice husk varieties, which was similar to values reported by Nguyen et al. [61] for dry leaves (57). Feedstock with a C/N ratio of 20–30.1 is considered optimal for efficient biogas production. A higher C/N ratio will result in faster nitrogen consumption, leading to lower gas production, whereas a lower C/N ratio will lead to ammonia accumulation and a rise in pH value resulting in toxic conditions for methanogenic bacteria [62]. The optimum C/N ratio for biogas production can be achieved by mixing feedstock of high and low C/N ratios. Kauser et al. [63] reported that an initial C/N ratio of 19–30 is considered optimal for compost production. However, many authors have reported that composting can also be achieved with a lower C/N ratio below the optimal. Zhu [64] suggested a C/N ratio of 20 for composting of swine manure and rice straw, whereas Kumar et al. [65] reported an optimal C/N ratio of 19.6 for compost production from green waste and food waste. Huang et al. [66] studied compost production from pig manure and sawdust with an initial C/N ratio of 15. The authors reported that although the lower C/N ratio reduces the requirement of bulking agents, it increases the time taken to reach the maturity of the compost.

HHV is the amount of energy content of a biomass sample on a dry basis and is shown in Fig. 2. HHV was calculated based on the elemental composition of FW samples and it varied from 16 to 17.2 MJ/kg in the FW samples. The obtained values were found to be higher than the HHV of different rice husk varieties [45], rice straw [46], and *Matooke* waste [67] but lower than most biomass samples like coconut shell, sawdust, different types of wood, and MSW [54]. According to Mishra and Mohanty [58], the heating value of a fuel is directly proportional to carbon and inversely proportional to the oxygen content. Considering all the parameters, using FW as fuel by combustion or biochar production can be an option for waste valorization but will require the installation of filters to reduce pollution caused by NO_x and SO_x.

3.4 Elemental and morphological analyses

The different FW samples were analyzed for various inorganic elemental concentrations using ICP-OES to study their impact on the environment and anaerobic digestion. The concentrations of these elements greatly depend on the geographical location, weather conditions, soil quality, and type of fertilizers or pesticides used for growing the biomass. According to Yusuf and Inambao [43], the emission of heavy metals from biofuel combustion is directly related to the amount of these metals in the dried biomass fuels. The elemental composition FW samples are summarized in Table 4. The dominant metals found

Fig. 1 C/N ratio of FW samples

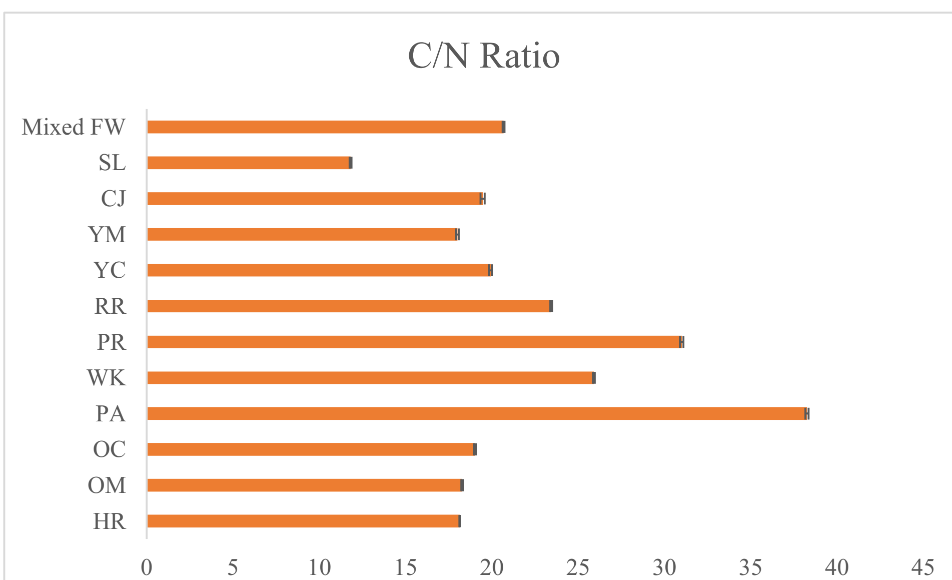
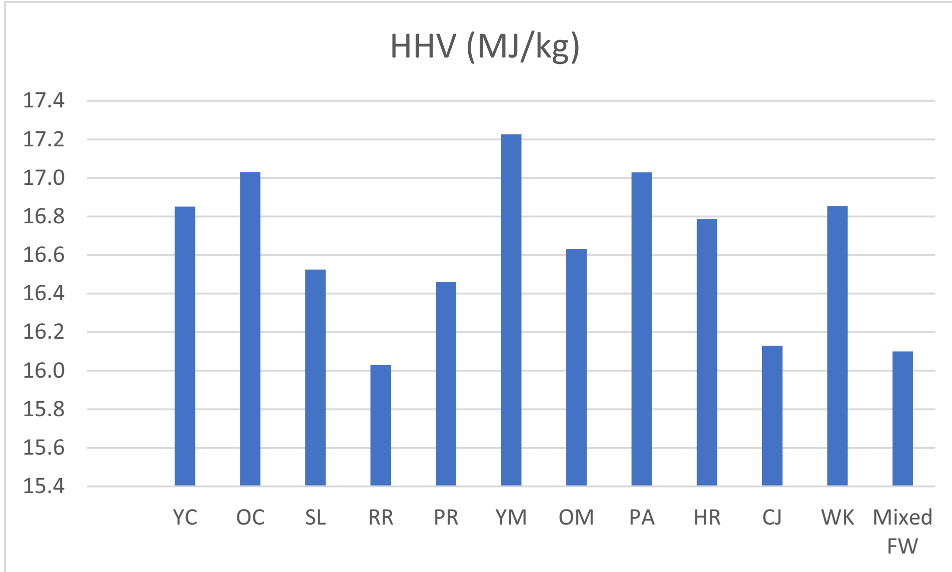


Fig. 2 Calorific value of different FW samples



were potassium (9529.13–19,184.33 mg/kg), calcium (676.25–5100 mg/kg), sodium (342–2752.50 mg/kg), phosphorus (163.36–671.32 mg/kg), iron (128.52–688.36 mg/kg), and magnesium (171.11–800 mg/kg). Kwoczynski and Čmelík [39] reported similar potassium concentrations in wheat straw (11,000 mg/kg), hay (18,100 mg/kg), and extracted rapeseed scrap (15,100 mg/kg). The same study reported higher concentrations of calcium and magnesium and lower concentrations of sodium in most samples tested than in the present study. Sharma and Yadav [49] analyzed mixed FW, sawdust, and wheat bran and reported the concentration of iron as 1760, 370, and 490 mg/kg, respectively. The same authors in a related study determined 4250 mg/kg sodium, 1250 mg/kg calcium, and 2450 mg/kg potassium in dry leaves [50]. The FW samples also contained trace concentrations of other elements like boron, cobalt, copper, manganese, molybdenum, nickel, and zinc (< 100 mg/kg). The microelements, copper and zinc, concentrations show a higher trend compared to *Matooke* peels [43]. Sharma and Yadav [49] analyzed wheat bran and determined 16.50 mg/kg copper, 110.5 mg/kg zinc, and 103 mg/kg manganese in the sample. Toxic elements like chromium, cadmium, and lead were also found in very low concentrations (< 20 mg/kg) in the analyzed biomass samples, whereas arsenic was not detected (ND) in any samples. Leng et al. [68] analyzed rice straw and sawdust and reported a higher concentration of cadmium, lead, nickel, and chromium than found in the FW samples of the present study.

The values of inorganic elements suggest that when FW is used as feedstock for biogas and bioethanol production, there is no requirement for the additional supplement of nutrients. The concentration of the various inorganic elements in FW samples is suitable for producing compost rich in various macro- and microelements necessary for plant germination and growth. The low concentration of the toxic elements implies low chances of eco-toxicity, bioaccumulation, and environmental pollution from compost produced from FW.

SEM was performed to understand the surface morphology of the different FW samples. It was studied at × 1000, which gives 20 µm. As presented in Fig. 3, the SEM images of FW samples revealed ridges and grooves, producing an uneven surface rich in organic matter. PA and RR had similar structures of about 10 µm in size, which appear in clusters. The uneven surface observed suggests that FW is low in lignin content. Pore spaces were observed in WK, HR, PR, YM, and SL samples, indicating that these flowers are better suited for biofuel and biofertilizer production due to easily decomposable surface features.

3.5 Biochemical analysis

Cellulose, hemicellulose, and lignin are the principal constituents of biomass in addition to some small quantities of protein, lipids, simple sugars, and starch. In the present study, the concentration of cellulose, hemicellulose, lignin, protein, and total carbohydrate was estimated and is presented in Table 5. Holocellulose, which contains cellulose and hemicellulose, makes up almost two-thirds of the total dry weight and is the primary substrate for bioethanol production from such feedstock. In the present study, cellulose was the highest in OM (37.22%) and the lowest in PA (22.31%). The obtained values were similar to those for grasses (25–40%), barley straw (31–34%), nutshells (25–30%), and tea waste (30.20%) [69] but lower than those for *Indigofera tinctoria* waste (38.7–41.15%) [39], rice straw (28.5–41%) [70], sugarcane bagasse (44%), and beechwood (40.8%) [71]. The hemicellulose content was found in the range of 19.19–38.89%, which was comparable with wheat

Table 4 Concentration of inorganic elements determined by ICP-OES

Flower name	As	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	Zn
	mg/kg																
YC	ND	1 ± 0.06	2729.78 ± 145.27	1 ± 0.05	1.06 ± 0.31	6.33 ± 2.6	18.17 ± 2.4	442.7 ± 27.26	13,572.95 ± 523.36	480.39 ± 12.25	40.47 ± 11.26	2.35 ± 0.11	979 ± 51.69	5.36 ± 1.19	427.36 ± 10.36	7.56 ± 0.32	49.63 ± 4.65
OC	ND	ND	3509.27 ± 505.35	ND	0.9 ± 0.12	4.5 ± 0.93	17.57 ± 1.2	688.36 ± 48.36	17,174.74 ± 240.97	285.67 ± 26.39	42.9 ± 0.73	ND	829 ± 54	3.84 ± 0.1	418.29 ± 36.36	2.32 ± 0.12	49.43 ± 0.92
SL	ND	1 ± 0.02	1768.11 ± 210.11	ND	ND	1.87 ± 0.52	29.33 ± 0.4	128.52 ± 19.65	18,103.76 ± 369.26	447.59 ± 17.63	29.31 ± 1.63	ND	1262.5 ± 2.57	2.49 ± 0.77	671.32 ± 51.26	ND	89.32 ± 5.06
RR	ND	ND	798.54 ± 95.16	ND	0.95 ± 0.34	11.67 ± 1.52	13.21 ± 2.15	256.45 ± 59.97	10,122.3 ± 411.29	238.9 ± 23.86	46.1 ± 7.42	ND	444 ± 46.74	6.99 ± 1.64	249 ± 15.36	2.5 ± 0.86	38.07 ± 2.57
PR	ND	ND	1531.33 ± 367.25	1 ± 0.06	1 ± 0.04	6.78 ± 0.19	13.39 ± 0.59	376.01 ± 18.44	9663.91 ± 470.87	300.85 ± 37.86	68.46 ± 12.02	ND	476.93 ± 24.74	4.23 ± 0.14	163.36 ± 1.7	1.58 ± 0.15	38.59 ± 3.72
YM	ND	ND	1927.4 ± 199.74	ND	0.98 ± 0.22	9.54 ± 1.54	16.74 ± 1.12	306.39 ± 31.59	9529.13 ± 334.62	470.89 ± 32.01	40.86 ± 12.86	1.27 ± 0.26	342 ± 14.69	6.8 ± 1.75	231.96 ± 16.39	11.71 ± 0.32	48.18 ± 4.65
OM	ND	ND	2711.14 ± 653.13	ND	0.78 ± 0.04	2.35 ± 0.58	15.22 ± 1.84	305.59 ± 51.65	12,944.87 ± 264.64	452.29 ± 36.44	45.66 ± 0.74	ND	363 ± 29.12	2.06 ± 0.88	325.68 ± 39.26	ND	57.28 ± 10.01
PA	ND	ND	1980.92 ± 212.55	ND	0.55 ± 0.03	1.03 ± 0.86	10.64 ± 2.86	137.2 ± 31.95	17,462.03 ± 52.07	171.11 ± 30.53	14.07 ± 1.22	2.07 ± 0.29	380.26 ± 42	0.54 ± 0.09	235.93 ± 43.09	9.49 ± 0.55	22.24 ± 6.02
HR	ND	ND	3129.64 ± 187.82	2 ± 0.09	ND	5.8 ± 0.71	18.93 ± 1.97	400.64 ± 8.22	19,184.33 ± 370.17	626.36 ± 37.17	48.04 ± 3.88	ND	2752.5 ± 68.5	3.52 ± 0.3	312.66 ± 2.05	ND	37.18 ± 0.09
CI	ND	ND	854.92 ± 156.51	ND	1.03 ± 0.1	9.8 ± 1.21	31.52 ± 2.15	557.49 ± 15.36	15,881.86 ± 115.36	330 ± 44.29	203.86 ± 15.69	0.71 ± 0.06	446.5 ± 25.18	4.63 ± 0.24	312.06 ± 14.69	1.26 ± 0.21	58.18 ± 12.36
WK	ND	ND	676.25 ± 474.84	ND	1 ± 0.32	18.51 ± 2.76	14.78 ± 1.14	639.13 ± 31.25	16,965 ± 405.12	200.68 ± 23.09	23.29 ± 2.02	ND	441 ± 12.02	10.22 ± 2.57	374.64 ± 28.09	ND	44.87 ± 8.72
Mixed FW	ND	1 ± 0.05	5100 ± 512.31	1 ± 0.02	3 ± 0.16	5.41 ± 0.59	24.5 ± 2.12	199.44 ± 25.36	9338 ± 235.26	800 ± 39.27	36.22 ± 1.21	1.43 ± 0.31	1217 ± 21.26	5.55 ± 1.08	299.36 ± 18.69	12.69 ± 1.23	22.2 ± 2.69

straw (20–25%) [72] and corn stover (17–35%) [73]. The hemicellulose content observed in this study was higher than that in ryegrass (15.8%), banana waste (14.8%) [69], and *Miscanthus* (18%) [73]. Lignin is a group of non-fermentable phenolic compounds. The lignin concentration was low in the present study, with SL having the lowest lignin content (1.76%), whereas PA contained the maximum lignin (4.54%). The obtained lignin values were comparable with the study done by Aramrueang et al. [74], who analyzed the lignin content in various agricultural crop residues and reported < 1% in sugar beet and watermelon, 2.2% in honeydew, 1.9% in tomato, 2.5% in Jose Tall wheatgrass, and 4.4% in wheat hay. When the obtained values from the present study were compared with other published works, it was found that most biomass samples contained higher lignin content than observed in the present study. Sasmal et al. [75] determined 11.03% lignin in areca nut husk, 20.51% in bonbogori, and 22.97% in moj. Gabhane et al. [76] reported 9.66–21.80% lignin in banana waste, whereas rice straw is reported to contain 12% lignin [46]. The low lignin content observed is beneficial for biofuel production as there will be a minimal investment for lignin removal during hydrolysis of cellulose and hemicellulose. The determined protein content ranged from 2.19% in PA up to 7.33% in PR. The protein content varies according to biomass; for example, the protein content of banana waste varies from 1.9 to 8.3% [76] and 1.61% in cassava bagasse [77]. Aramrueang et al. [74] determined the protein content in sugar beetroot varieties (3.1–4.4%), wheat straw (2.8%), wheat hay (9.3%), watermelon (10.7%), and honeydew (6%). With its high cellulose and hemicellulose content and low lignin, FW can be valorized efficiently for bioethanol and biogas production with little pretreatment. Total sugar comprises different types of sugar present in a biomass sample, which is an essential parameter for determining the efficacy of a biomass sample for biofuel production. It was found in the range of 16.91–40.06%, which was similar to the total sugar concentration reported for mahula flowers (37%). Lower sugar concentration was reported by Dwivedi et al. [78], who worked with fruit and vegetable waste and reported a total sugar concentration of 3.2–14.3% in vegetable waste and 3.7–21.4% in fruit waste. Higher sugar concentration is advantageous for biogas and biofuel production.

3.6 Assessment for biofuel production

Biofuel can be broadly divided into gaseous and liquid biofuels. Methane is considered the most common biofuel among gaseous biofuels, whereas bioethanol is the most common liquid biofuel. SMP and SEP give an approximate idea of biofuel production from a biomass sample. Based on the empirical formula, SMP of FW was found to be in the range of 0.170–0.434 L CH_4 g^{-1} VS, whereas SEP was found the lowest in OM

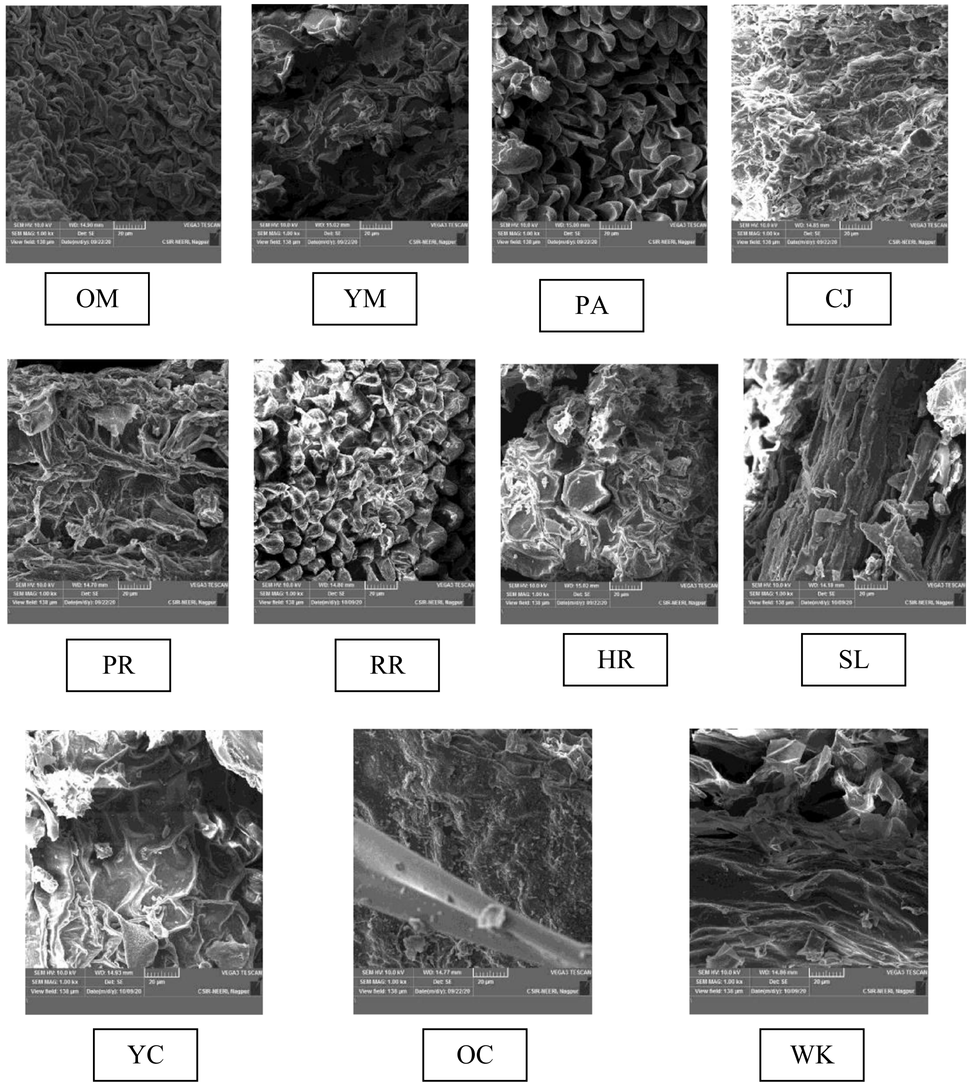


Fig. 3 SEM images of different FW samples at × 1000

Table 5 Biochemical analysis of FW

Flower name	Cellulose %	Hemicellulose	Lignin	Protein	Total carbohydrate
YC	28.08 ± 1.24	29.81 ± 1.05	3.67 ± 0.15	4.13 ± 0.29	16.91 ± 1.05
OC	29.56 ± 0.85	30.52 ± 1.25	2.57 ± 0.24	4.98 ± 0.16	20.59 ± 1.09
SL	28.23 ± 1.61	19.19 ± 0.53	1.76 ± 0.11	5.29 ± 0.26	28.55 ± 0.95
RR	31.92 ± 1.21	37.62 ± 0.66	3.99 ± 0.36	5.69 ± 0.22	19.53 ± 0.56
PR	28.02 ± 1.01	34.08 ± 0.81	4.18 ± 0.2	7.33 ± 0.15	28.69 ± 1.11
YM	36.43 ± 0.51	36.15 ± 1.59	2.08 ± 0.19	3.26 ± 0.09	27.26 ± 1.26
OM	37.22 ± 0.36	29.00 ± 1.66	3.22 ± 0.21	4.39 ± 0.11	30.98 ± 0.68
PA	22.31 ± 0.95	37.13 ± 1.83	4.54 ± 0.33	2.19 ± 0.25	38.84 ± 0.51
HR	28.44 ± 0.22	29.61 ± 1.16	3.14 ± 0.36	3.22 ± 0.19	25.95 ± 0.39
CJ	23.32 ± 1.09	20.17 ± 1.63	2.88 ± 0.0.09	2.91 ± 0.18	26.11 ± 0.77
WK	32.59 ± 1.22	33.57 ± 0.62	2.15 ± 0.16	2.55 ± 0.24	40.06 ± 0.58
Mixed FW	28.41 ± 0.66	38.89 ± 0.69	2.99 ± 0.22	5.94 ± 0.26	37.75 ± 1.15

Table 6 SMP and SEP of different FW

Flowers	SMP (L CH_4 g^{-1} VS)	SEP (Lg^{-1})
Mixed FW	0.412	0.435
YC	0.417	0.573
OC	0.423	0.570
SL	0.170	0.530
RR	0.404	0.472
PR	0.418	0.500
YM	0.430	0.533
OM	0.405	0.433
PA	0.434	0.515
HR	0.413	0.522
CJ	0.405	0.582
WK	0.415	0.566

Table 7 Calculation for SMP and SEP of mixed FW

Specifications	Value	Remarks
Average mixed FW generation from Ganesh Tekdi (kg)	500	From field survey
Total VS production (kg)	467.4	Considering 93.48% VS content in mixed FW
SMP (L CH_4 g^{-1} VS)	0.412	Calculated using Eq. 8
Total methane production (L)	192569	-
SEP (Lg^{-1})	0.435	Calculated using Eqs. 9 and 10
Total SEP (L)	217.44	-

(0.433 Lg^{-1}) and highest in CJ (0.582 Lg^{-1}), as shown in Table 6. The SMP values were similar to values obtained from onion and okra waste [59] but lower than indigo dye waste [39], different *Chlorella* species biomass [79], banana plantain, potato, broad beans, and mixed vegetable waste [59]. The SEP observed in this study was higher than the SEP observed from indigo biomass [39]. The total SMP and SEP were estimated to be around 192,569 L of CH_4 and 217 L of bioethanol from 500 kg of mixed FW as shown in Table 7. However, SMP and SEP generally overestimate biofuel production since, in practice, some of the sugars are required for cell growth and maintenance. Biofuel production also depends on biomass pretreatment, hydrolysis of sugars, microbial strain used, and culture conditions.

4 Conclusion

The biomass samples included in this study are the commonly found flowers in FW from religious places in India. The present work explores the potential of FW for its valorization via the production of biofuel and compost. The presence of high VM (79.99–88.68%), cellulose (22.31–37.22%), hemicellulose (19.19–38.89%), total carbohydrates (16.91–40.06%), and low lignin (1.76–4.54%) content suggests that FW can be an excellent feedstock for biofuel production. The biofuel potential of FW is comparable to various other kinds of biological waste materials and thus can be considered a potential non-food source for second-generation biofuel production. However, due to the inherent acidic nature of FW (3.8–5.47), the feedstock needs to undergo alkaline treatment to maintain the optimum pH levels required for biofuel production. Low lignin content also suggests that the deconstruction of FW to fermentable sugars might be easier than traditional biomass samples. High NPK levels and other trace metals observed in the studied biomass samples suggest that FW can be an excellent candidate for compost production.

Acknowledgements We are thankful to the Director of CSIR-National Environmental Engineering Research Institute, Nagpur, India, for providing the necessary facilities and funds.

Author contribution M. Suresh Kumar conceived and supervised the study whereas Smita Dutta collected the data, performed the analysis, and wrote the original manuscript. All the authors discussed and commented on the manuscript.

Data availability All data generated during this study are included in this manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Yusuf AA, Inambao FL (2019) Bioethanol production from different Matooke peels species: a surprising source for alternative fuel. Case Stud Therm Eng 13:100357. https://doi.org/10.1016/j.csite.2018.11.008
2. Barampouti EM, Mai S, Moustakas K et al (2021) CHAPTER 3 - Status and perspectives of agricultural residues in a circular and resource-efficient context. In: Tyagi V, Aboudi KBT-CE and RR (eds) Clean energy and resources recovery. Elsevier, pp 49–102
3. Panigrahi S, Dubey BK (2019) A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew Energy 143:779–797. https://doi.org/10.1016/J.RENENE.2019.05.040
4. Sarsaiya S, Jain A, Kumar Awasthi S et al (2019) Microbial dynamics for lignocellulosic waste bioconversion and its importance with modern circular economy, challenges and future perspectives. Bioresour Technol 291:121905. https://doi.org/10.1016/j.biortech.2019.121905
5. Kumar V, Kumari S, Kumar P (2020) Management and sustainable energy production using flower waste generated from temples. Environ Degrad Causes Remediat Strateg 154–165. https://doi.org/10.26832/aesa-2020-edcrs-011

6. Dutta S, Kumar MS (2021) Potential of value-added chemicals extracted from floral waste: a review. J Clean Prod 294:126280. https://doi.org/10.1016/j.jclepro.2021.126280
7. Nguyen DTC, Le HTN, Nguyen TT et al (2021) Engineering conversion of Asteraceae plants into biochars for exploring potential applications: a review. Sci Total Environ 797:149195. https://doi.org/10.1016/j.scitotenv.2021.149195
8. Sharma D, Yadav KD, Kumar S (2018) Role of sawdust and cow dung on compost maturity during rotary drum composting of flower waste. Bioresour Technol 264:285–289. https://doi.org/10.1016/j.biortech.2018.05.091
9. Sharma D, Yadav KD, Kumar S (2018) Biotransformation of flower waste composting: optimization of waste combinations using response surface methodology. Bioresour Technol 270:198–207. https://doi.org/10.1016/j.biortech.2018.09.036
10. Mozhiarasi V, Speier CJ, Rose PMB et al (2019) Variations in generation of vegetable, fruit and flower market waste and effects on biogas production, exergy and energy contents. J Mater Cycles Waste Manag 21:713–728. https://doi.org/10.1007/s10163-019-00828-2
11. Raghu S (2019) A holy mess. In: New Indian Express, https://www.newindianexpress.com/magazine/2019/jul/07/a-holy-mess-1999557.html. Accessed 20 Aug 2021
12. Samadhiya H, Pradesh M, Pradesh M (2017) Disposal and management of temple waste: current status and possibility of vermicomposting. Int J Adv Res Dev 2:359–366
13. Aich A, Ghosh SK (2019) Conceptual framework for municipal solid waste processing and disposal system in India. In: Ghosh S (ed) Waste management and resource efficiency. Springer Singapore. https://doi.org/10.1007/978-981-10-7290-1_9
14. Desai K (2018) How these temples give a new life to old flowers. In: The Times of India. https://timesofindia.indiatimes.com/india/how-these-temples-give-a-new-life-to-old-flowers/articleshow/65762167.cms. Accessed 15 Aug 2021
15. Das D (2018) Red roses at Ajmer Dargah will be now converted to organic compost. In: Life Beyond Numbers. https://lifebeyondnumbers.com/red-roses-at-ajmer-dargah-will-be-now-converted-to-organic-compost/. Accessed 15 Aug 2021
16. Perumal K, Moorthy S, Savitha JS (2012) Characterization of essential oil from offered temple flower Rosa damascena mill. Asian J Exp Biol Sci 3:330–334
17. Goswami S (2018) In these temples, offerings do not go waste. In: Down To Earth. https://www.downtoearth.org.in/news/waste/in-these-temples-offerings-do-not-go-waste-60758. Accessed 6 Aug 2021
18. Solanke A, Wadar S, Telang S et al (2018) Study of Nirmalya solid waste treatment by artificial and natural aeration vermicomposting. Int J Sci Res Dev 6:296–300
19. Vankar PS, Shanker R, Wijayapala S (2009) Utilization of temple waste flower Tagetus erecta for dyeing of cotton, wool and silk on industrial scale. J Text Apparel Technol Manag 6:1–15
20. Pervaiz S, Mughal TA, Khan FZ et al (2017) Environmental friendly leather dyeing using Tagetes erecta L. (Marigold) waste flowers. Int J Biosci 10:382–390. https://doi.org/10.12692/ijb/10.1.382-390
21. Adlakha N (2018) Recycling temple waste along the Ganges with Help Us Green. In: The Hindu. https://www.thehindu.com/life-and-style/the-worlds-first-biodegradable-thermocol-and-flower-leather-by-ankit-agarwals-kanpur-based-organisation-help-us-green/article25013953.ece. Accessed 16 Aug 2021
22. Nguyen DTC, Nguyen TT, Le HTN et al (2021) The sunflower plant family for bioenergy, environmental remediation, nanotechnology, medicine, food and agriculture: a review. Environ Chem Lett 19:3701–3726. https://doi.org/10.1007/s10311-021-01266-z
23. Yusuf AA, Inambao FL (2019) Bioethanol production techniques from lignocellulosic biomass as alternative fuel: a review. Int J Adv Res Eng Technol 10:259–288
24. Moreno AD, Magdalena JA, Oliva JM et al (2021) Sequential bioethanol and methane production from municipal solid waste: an integrated biorefinery strategy towards cost-effectiveness. Process Saf Environ Prot 146:424–431. https://doi.org/10.1016/j.psep.2020.09.022
25. Shahbaz M, Ammar M, Zou D et al (2019) An insight into the anaerobic co-digestion of municipal solid waste and food waste: influence of co-substrate mixture ratio and substrate to inoculum ratio on biogas production. Appl Biochem Biotechnol 187:1356–1370. https://doi.org/10.1007/s12010-018-2891-3
26. Gómez X, Cuetos MJ, Cara J et al (2006) Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes: conditions for mixing and evaluation of the organic loading rate. Renew Energy 31:2017–2024. https://doi.org/10.1016/j.renene.2005.09.029
27. Zhu H, Parker W, Conidi D et al (2011) Eliminating methanogenic activity in hydrogen reactor to improve biogas production in a two-stage anaerobic digestion process co-digesting municipal food waste and sewage sludge. Bioresour Technol 102:7086–7092. https://doi.org/10.1016/j.biortech.2011.04.047
28. American Society for Testing and Materials (2015) ASTM E1756 - 08: Standard test method for determination of total solids in biomass. In: Annual Book of ASTM Standards. ASTM International, Philadelphia, PA
29. American Society for Testing and Materials (2007) ASTM E1755–01: Standard test method for ash in biomass. In: Annual Book of ASTM Standards. ASTM International, Philadelphia, PA
30. American Society for Testing and Materials (2019) ASTM E872–82: Standard test method for volatile matter in the analysis of particulate wood fuels. In: Annual Book of ASTM Standards. ASTM International, Philadelphia, PA
31. Singh YD, Mahanta P, Bora U (2017) Comprehensive characterization of lignocellulosic biomass through proximate, ultimate and compositional analysis for bioenergy production. Renew Energy 103:490–500. https://doi.org/10.1016/j.renene.2016.11.039
32. United States Environmental Protection Agency (2004) USEPA Method 9045D: Soil and Waste pH. 1–5. https://www.epa.gov/sites/default/files/2015-12/documents/9045d.pdf
33. American Society for Testing and Materials (2009) ASTM D5198–09: standard practice for nitric acid digestion of solid waste. In: Annual Book of ASTM Standards. ASTM International, Philadelphia, PA
34. Goering HK, Van Soest PJ (1970) Forage fiber analysis (apparatus, reagents, procedures, and some applications). In: Agriculture Handbook No. 379. Agricultural Research Service, United States Department of Agriculture, Washington, DC
35. Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (1951) Protein measurement with the folin phenol reagent. J Biol Chem 193:265–275. https://doi.org/10.1016/S0021-9258(19)52451-6
36. Hedge JE, Hofreiter BT (1962) Estimation of carbohydrate. In: Carbohydrate chemistry. Academic Press, New York
37. American Public Health Association (2012) APHA 2540-G. In: Standard methods for the examination of water and wastewater, 22nd ed. American Public Health Association, Washington, DC
38. Choudhary P, Prajapati SK, Malik A (2016) Screening native microalgal consortia for biomass production and nutrient removal from rural wastewaters for bioenergy applications. Ecol Eng 91:221–230. https://doi.org/10.1016/j.ecoleng.2015.11.056
39. Pattanaik L, Naik SN, Hariprasad P (2019) Valorization of waste Indigofera tinctoria L. biomass generated from indigo dye extraction process—potential towards biofuels and compost. Biomass Convers Biorefinery 9:445–457. https://doi.org/10.1007/s13399-018-0354-2

40. Oyedun AO, Tee CZ, Hanson S, Hui CW (2014) Thermogravimetric analysis of the pyrolysis characteristics and kinetics of plastics and biomass blends. Fuel Process Technol 128:471–481. https://doi.org/10.1016/j.fuproc.2014.08.010
41. García R, Pizarro C, Lavín AG, Bueno JL (2012) Characterization of Spanish biomass wastes for energy use. Bioresour Technol 103:249–258. https://doi.org/10.1016/j.biortech.2011.10.004
42. Vassilev SV, Baxter D, Andersen LK, Vassileva CG (2010) An overview of the chemical composition of biomass. Fuel 89:913–933. https://doi.org/10.1016/j.fuel.2009.10.022
43. Yusuf AA, Inambao FL (2020) Characterization of Ugandan biomass wastes as the potential candidates towards bioenergy production. Renew Sustain Energy Rev 117:109477. https://doi.org/10.1016/j.rser.2019.109477
44. Ahmed A, Hidayat S, Abu Bakar MS et al (2021) Thermochemical characterisation of Acacia auriculiformis tree parts via proximate, ultimate, TGA, DTG, calorific value and FTIR spectroscopy analyses to evaluate their potential as a biofuel resource. Biofuels 12:9–20. https://doi.org/10.1080/17597269.2018.1442663
45. Olupot PW, Candia A, Menya E, Walozi R (2016) Characterization of rice husk varieties in Uganda for biofuels and their techno-economic feasibility in gasification. Chem Eng Res Des 107:63–72. https://doi.org/10.1016/j.cherd.2015.11.010
46. Van Hung N, Maguyon-Detras MC, Migo MV et al (2020) Rice straw overview: availability, properties, and management practices BT - sustainable rice straw management. In: Van HN, Chivenge P, Douthwaite B (eds) Gummert M. Springer International Publishing, Cham, pp 1–13
47. Akwu NA, Naidoo Y, Singh M (2019) A comparative study of the proximate, FTIR analysis and mineral elements of the leaves and stem bark oF Grewia lasiocarpa E.Mey. ex Harv.: an indigenous southern African plant. South African J Bot 123:9–19. https://doi.org/10.1016/j.sajb.2019.01.028
48. Singh A, Jain A, Sarma BK et al (2013) Solid waste management of temple floral offerings by vermicomposting using Eisenia fetida. Waste Manag 33:1113–1118. https://doi.org/10.1016/j.wasman.2013.01.022
49. Sharma D, Yadav KD (2018) Application of rotary in-vessel composting and analytical hierarchy process for the selection of a suitable combination of flower waste. Geol Ecol Landscapes 9508:1–11. https://doi.org/10.1080/24749508.2018.1456851
50. Sharma D, Yadav KD (2017) Bioconversion of flowers waste : composting using dry leaves as bulking agent. Environ Eng Res 22:237–244
51. Swain MR, Kar S, Sahoo AK, Ray RC (2007) Ethanol fermentation of mahula (Madhuca latifolia L.) flowers using free and immobilized yeast Saccharomyces cerevisiae. Microbiol Res 162:93–98. https://doi.org/10.1016/j.micres.2006.01.009
52. Lay J-J, Li Y-Y, Noike T (1997) Influences of pH and moisture content on the methane production in high-solids sludge digestion. Water Res 31:1518–1524. https://doi.org/10.1016/S0043-1354(96)00413-7
53. Kwoczynski Z, Čmelík J (2021) Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process. J Clean Prod 280:124302. https://doi.org/10.1016/j.jclepro.2020.124302
54. Parikh J, Channiwala SA, Ghosal GK (2007) A correlation for calculating elemental composition from proximate analysis of biomass materials. Fuel 86:1710–1719. https://doi.org/10.1016/j.fuel.2006.12.029
55. Abdul Samad NAF, Jamin NA, Saleh S (2017) Torrefaction of municipal solid waste in Malaysia. Energy Procedia 138:313–318. https://doi.org/10.1016/j.egypro.2017.10.106
56. Baawain M, Al-Mamun A, Omidvarborna H, Al-Amri W (2017) Ultimate composition analysis of municipal solid waste in Muscat. J Clean Prod 148:355–362. https://doi.org/10.1016/j.jclepro.2017.02.013
57. Voca N, Grubor M, Peter A, Kricka T (2019) Evaluation of Posidonia oceanica waste as a biomass source for energy generation. BioEnergy Res 12:1104–1112. https://doi.org/10.1007/s12155-019-10032-7
58. Mishra RK, Mohanty K (2018) Characterization of non-edible lignocellulosic biomass in terms of their candidacy towards alternative renewable fuels. Biomass Convers Biorefinery 8:799–812. https://doi.org/10.1007/s13399-018-0332-8
59. Pas C, P. S, (2021) Correlation between empirical formulae based stoichiometric and experimental methane potential and calorific energy values for vegetable solid wastes. Energy Rep 7:19–31. https://doi.org/10.1016/j.egyr.2020.10.071
60. Channiwala SA, Parikh PP (2002) A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 81:1051–1063. https://doi.org/10.1016/S0016-2361(01)00131-4
61. Nguyen V-T, Le T-H, Bui X-T et al (2020) Effects of C/N ratios and turning frequencies on the composting process of food waste and dry leaves. Bioresour Technol Rep 11:100527. https://doi.org/10.1016/j.biteb.2020.100527
62. Barik D (2019) Chapter 3 - Energy extraction from toxic waste originating from food processing industries. In: Barik DBT-E from TOW for H and PG (ed) Woodhead Publishing Series in Energy. Woodhead Publishing, pp 17–42
63. Kauser H, Pal S, Haq I, Khwairakpam M (2020) Evaluation of rotary drum composting for the management of invasive weed Mikania micrantha Kunth and its toxicity assessment. Bioresour Technol 313:123678. https://doi.org/10.1016/j.biortech.2020.123678
64. Zhu N (2007) Effect of low initial C/N ratio on aerobic composting of swine manure with rice straw. Bioresour Technol 98:9–13. https://doi.org/10.1016/j.biortech.2005.12.003
65. Kumar M, Ou Y-L, Lin J-G (2010) Co-composting of green waste and food waste at low C/N ratio. Waste Manag 30:602–609. https://doi.org/10.1016/j.wasman.2009.11.023
66. Huang GF, Wong JWC, Wu QT, Nagar BB (2004) Effect of C/N on composting of pig manure with sawdust. Waste Manag 24:805–813. https://doi.org/10.1016/j.wasman.2004.03.011
67. Yusuf AA, Inambao FL, Hassan AS et al (2020) Comparative study on pyrolysis and combustion behavior of untreated Matooke biomass wastes in East Africa via TGA, SEM, and EDXS. Int J Energy Environ Eng 11:265–273. https://doi.org/10.1007/s40095-019-00331-2
68. Leng L, Leng S, Chen J et al (2018) The migration and transformation behavior of heavy metals during co-liquefaction of municipal sewage sludge and lignocellulosic biomass. Bioresour Technol 259:156–163. https://doi.org/10.1016/j.biortech.2018.03.019
69. Saidur R, Abdelaziz EA, Demirbas A et al (2011) A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 15:2262–2289. https://doi.org/10.1016/j.rser.2011.02.015
70. Bhattacharyya P, Bhaduri D, Adak T et al (2020) Characterization of rice straw from major cultivars for best alternative industrial uses to cutoff the menace of straw burning. Ind Crops Prod 143:111919. https://doi.org/10.1016/j.indcrop.2019.111919
71. Hameed Z, Aslam M, Khan Z et al (2021) Gasification of municipal solid waste blends with biomass for energy production and resources recovery: current status, hybrid technologies and innovative prospects. Renew Sustain Energy Rev 136:110375. https://doi.org/10.1016/j.rser.2020.110375

72. Prasad RK, Chatterjee S, Mazumder PB et al (2019) Bioethanol production from waste lignocelluloses: a review on microbial degradation potential. Chemosphere 231:588–606. https://doi.org/10.1016/j.chemosphere.2019.05.142
73. Cheng JJ, Timilsina GR (2011) Status and barriers of advanced biofuel technologies: a review. Renew Energy 36:3541–3549. https://doi.org/10.1016/j.renene.2011.04.031
74. Aramrueang N, Zicari SM, Zhang R (2017) Characterization and compositional analysis of agricultural crops and residues for ethanol production in California. Biomass Bioenerg 105:288–297. https://doi.org/10.1016/j.biombioe.2017.07.013
75. Sasmal S, Goud VV, Mohanty K (2012) Characterization of biomasses available in the region of North-East India for production of biofuels. Biomass Bioenerg 45:212–220. https://doi.org/10.1016/j.biombioe.2012.06.008
76. Gabhane J, Prince William SPM, Gadhe A et al (2014) Pretreatment of banana agricultural waste for bio-ethanol production: individual and interactive effects of acid and alkali pretreatments with autoclaving, microwave heating and ultrasonication. Waste Manag 34:498–503. https://doi.org/10.1016/j.wasman.2013.10.013
77. Ricardo Soccol C, Faraco V, Karp S et al (2011) Chapter 5 - Lignocellulosic bioethanol: current status and future perspectives. In: Larroche C, Ricke SC et al (eds) Pandey A. Academic Press, Amsterdam, pp 101–122
78. Dwivedi A, Vaidya AN, Kumar MS (2018) Characterisation of selected fruit and vegetable solid waste (FVSW) to determine their potential use as a substrate for biohydrogen production. Asian J Microbiol Biotechnol Environ Sci Pap 20:1259–1263
79. Prajapati SK, Malik A, Vijay VK (2014) Comparative evaluation of biomass production and bioenergy generation potential of Chlorella spp. through anaerobic digestion. Appl Energy 114:790–797. https://doi.org/10.1016/j.apenergy.2013.08.021