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Transforming Organic Waste in Varanasi: A Study on Decentralized Biogas Plants and Policy Recommendations

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Abstract

Varanasi, an ancient city, needs help to effectively handle its fast-growing organic garbage due to urbanisation and population expansion. Organic waste, a significant proportion of municipal solid trash, poses environmental and public health risks if poorly handled. This study examines the present condition of organic waste management in Varanasi, assessing the city's patterns of waste generation, collection methods, and treatment technology. This research highlights the importance of sustainable solutions. It emphasises the deficiencies in the current system, such as the deficient infrastructure function due to unsegregated waste and low public awareness. The article explores the functioning of 3 decentralised waste-to-energy (WTE) plants, i.e. Bhavania Pokri, IDH Khazakpura, and Paharia Mandi. This plant operates on the principle of Anaerobic Digestion Technology, viz. DRYCO-ADTM technology, apart from anaerobic digestion composting and biogas generation, is also practised as a feasible alternative to conventional waste disposal techniques. The study proposes implementing legislative interventions, conducting capacity-building initiatives, and fostering community participation to improve the practice of separating organic waste at its origin and encourage the establishment of waste processing facilities at local levels. Varanasi can transform its organic waste challenge into an opportunity for resource recovery, contributing to environmental sustainability and improved urban living conditions.

Keywords: Bio-methanation, Decentralised treatment, Municipal solid waste, Organic waste, Waste to energy.

Introduction

Solid Waste Management (SWM) is the procedure by which Solid waste can be stored, collected, transported, processed, and disposed of using a well-thought-out, environmentally responsible procedure. Due to rising population, urbanisation, economic development, and shifting production and consumption patterns, Municipal Solid Waste (MSW) has become a significant concern for growing nations like India. According to studies and literature, the SWM system in India is growing and stochastic. According to the Annual Report (CPCB) 2018, the amount of garbage generated per person per day in cities has skyrocketed from 0.24 kg in 2001 to 0.85 kg in 2018 (1). MSW generation is one of the leading environmental issues every developing nation faces now. According to a World Bank report, between 2016 and 2050, there will be a rise in the amount of MSW produced globally, from 2010 million tonnes (2). India, the world's second – most populated country, has rapidly urbanised and witnessed rapid economic growth during the past few decades. It produces 0.17 to 0.62 kg of solid trash per person daily, with an annual growth rate of 1.33% (3). Services for solid waste management are provided in urban areas by local governing authorities, specifically municipalities and municipal corporations. In most metropolitan areas, SWM was in poor condition due to low funding, outdated equipment, public awareness, and inadequate infrastructure (4).

Sources and Types of Municipal Solid Waste

Any useless materials the owner dumps after their initial usage are considered waste. Human and animal activities typically produce garbage. We classify waste into three types: a) solid waste, b) liquid waste, and c) gaseous waste. We classify it into Municipal Solid, Industrial, Agricultural, Commercial /Institutional, and Biomedical based on its nature.

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Composition of Municipal Solid Waste

In India, 51% of urban MSW is organic, 17.5% is recyclable (including paper, plastic, metal, and glass), and 31% is inert. Urban MSW has a 47% moisture content and an average calorific value of 7.3 MJ/kg (1745 kcal/kg) (5).

Organic Waste

Organic waste, defined as organic material that is readily biodegradable, constitutes a significant portion of Municipal Solid Waste (MSW) in India (6). According to the Indian council for research on international economic relations (ICRIER) report 2018, In India, the proportion of organic waste in urban MSW is between 55% and 65% (7). Organic wastes, such as livestock manure, garden trash, food waste, sewage sludge, and agricultural waste, continuously rise due to human activity, economic expansion, and the growing global population (8). The organic fraction of Municipal Solid Waste (MSW) can be composted and typically has a moisture content between 85% and 90% or less (8).Therefore, it might be recycled and used rather than losing the biodegradable component due to incorrect disposal or treatment.

Waste Management Scenario in Varanasi

Varanasi is one of the country's oldest cities. Varanasi, the name of the city formed by the combination of two rivers, Varuna and Assi, is home to several temples and ghats. Kashi Vishwanath Corridor and Rudraksha Convention Centre are the two new constructions that have contributed to the flocking of many tourists to the city. With the influx of many people and the existing population, much pressure is increasing on the cities' municipal bodies to manage waste generated at incessant levels. Solid waste management plays a vital role in the city's cultural, social and economic perspective (9).

In Swachh Survekshan's 2022 ranking, Varanasi, the electoral constituency of the honourable Prime Minister, stood at the 21st position, considered a progressive improvement as it climbed nine ladders from the previous year (10). Varanasi is one of the rapidly growing cities in Uttar Pradesh. It attracts not only national but international tourists on a large scale. However, contemplative discussions and efforts are still required in government and citizens' waste management to ensure the city's cleanliness for development and progress. The 2011 Census reports a total population of 1,198,491 for Varanasi, representing 0.115% of India's population (11). Current estimates project the population to reach 1,968,198 by 2025.

Varanasi has five zones and 14 subzones, encompassing 100 wards. With a population nearing 1.8 million, the city generates approximately 1,012 tonnes per day (TPD) of municipal solid waste, collected and transported along with other waste streams, including construction and demolition waste (12). Currently, Varanasi Nagar Nigam/ Varanasi Municipal Corporation (VMC) manages solid waste management in Varanasi. Due to the city's significant generation of vegetable, religious, and plastic waste, most of the waste produced consists of biodegradable, compostable, and recyclable materials (12). According to the 2019 Solid Waste Management (SWM) plan, nearly 41.95% of the waste is primarily organic (Figure 1).

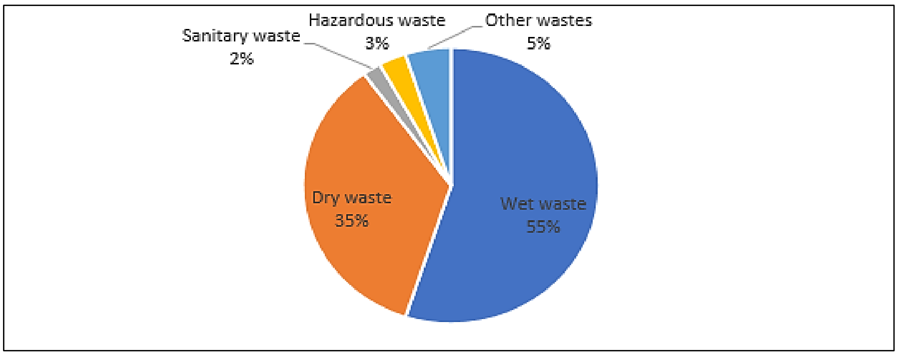

Figure 1: Varanasi City's Waste Characterization (12)

Varanasi's average waste generation rate is 0.500 kg per capita per day (Table 4). The city at present generates 1012.64 Metric Tons (MT) (Approx.) of waste per day at the rate of 0.500 Kg per capita per day and decadal population growth of 2.67 per Year (Table 4).

Table 1: Average Percent Values of Each Component of Waste in Different Zones of Varanasi (13)

Component (%)	Zones Adampur	Bhelupur	Dashashwamedh	Kotwali	Varunapar
Organic Waste	44.26	47.95	45.78	45.38	48.15
Paper	11.97	9.14	8.96	8.65	9.61
Plastic	9.97	10.11	10.67	10.34	9.82
Fabrics / Textiles	2.82	2.52	2.51	3.48	2.61
Glass	2.18	2.37	2.77	2.84	2.67
Metals	0.68	0.99	0.92	1.21	0.92
Others	28.12	26.92	28.39	28.1	26.22

Area of Focus

In India, the most significant waste stream is organic waste. In the country, the daily production of organic waste is 71,600 MT. This garbage can produce global warming gases like methane and carbon dioxide if disposed of without treatment (14). The United States Environment Protection Agency (USEPA) estimates that one tonne of legacy waste (which takes the form of a variety of municipal solid wastes disposed off in dumpsites without any prior treatment) can generate 692.5 kg of carbon dioxide and 27.7 kg of methane annually (15).

The facility near the area uses various aerobic and anaerobic composting techniques to compost the biodegradable waste. Recyclers categorise paper, plastic, metal, and other nonbiodegradable waste, then collect them for product up-cycling or down-cycling. Under anaerobic conditions, organic material undergoes a microbiological transformation into biogas in a process called biomethanation. It is highly preferred recycling option in organic waste management hierarchy (Figure 2). Anaerobic digestion is a bacterial fermentation procedure that produces biogas that contains methane (about 60%), carbon dioxide (about 40%), and other gases while operating without free oxygen. There are two advantages to biomethanation. It produces biogas and compost as its final by-product. This technology can be effectively applied in a decentralised manner to biodegrade separated organic wet waste (16).

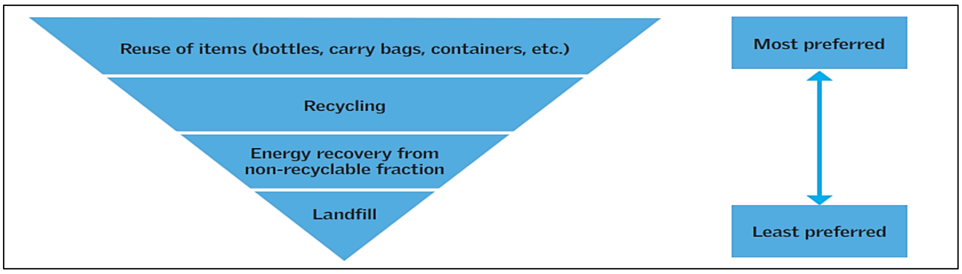

Figure 2: Hierarchy for Organic Waste Management (14)

Organic waste treatment can be done in two ways-

- Centralized method
- Decentralized method

A Centralised Method is a strategy in which all Municipal Solid Waste from the city is gathered and conveyed to a singular location for processing and treatment. A decentralised approach involves the processing and management of municipal solid waste at multiple locations, such as households, communities, wards, sub-zones, and zones, to reduce the volume of organic waste generated at the source (17).

There are three methods of Decentralized Waste Treatment: -

Aerobic Composting: It is the process by which bacteria and other microorganisms break down biodegradable organic materials into compost or manure in a controlled condition in the presence of ample oxygen. Solid waste that has been separated into its organic component is a good substrate for composting. Compost, the output product, contains vital plant nutrients and minerals that are good for plant growth (18).

Vermicomposting: Vermicomposting is a composting method that relies on earthworm for degradation of organic waste in aerobic condition. Vermicompost is the product of consumption of waste by earthworm. Vermicompost contains higher amount of nutrients than compost (19).

Anaerobic Digestion: Anaerobic digestion is also known as biomethanation. It involves the metabolic breakdown of organic materials by bacteria in an anoxic atmosphere. Methane gas and liquid fertiliser, both of which are byproducts of anaerobic digestion but may still contain pathogens, are practically stabilised. Due to the high organic and moisture content of municipal solid waste in India, using biomethanation technique for treatment of waste is a viable option (20).

Municipal Solid Waste Treatment by Decentralized Method

A few locations, including Varanasi in Uttar Pradesh, display decentralised and centralised model. The waste is collected ward by ward and at the source, the waste is segregated into biodegradable and non-biodegradable categories. In Varanasi city there are three Waste to Energy plants operates on Decentralised Method based on DRYCO-AD™ technology and one Waste to compost plant that operates on Centralised method. Under Corporate Social Responsibility (CSR) of Indian Oil Corporation Ltd. Three Waste to Energy processing plants were established that are:

All three Waste to Energy plants are constructed and operated by YASASU EMS Pvt. Ltd. The technology used in these Decentralized Waste to Energy Plants is High Solid Thermophilic Anaerobic Digestion Technology (DRYCO-ADTM). According to Indian Biogas Association (IBA) DRYCO-ADTM Technology is an advanced biological process based on the High Solid Thermophilic Bio-methanation Process (21). The biogas generated can generate electricity using biogas engines and the slurry from Anaerobic Digester unit can further be sold as organic compost after drying. All of the three Waste to Energy processing plants work on DRYCO-AD™ Technology process (Figure 3A). This process occurs in five steps. That are:

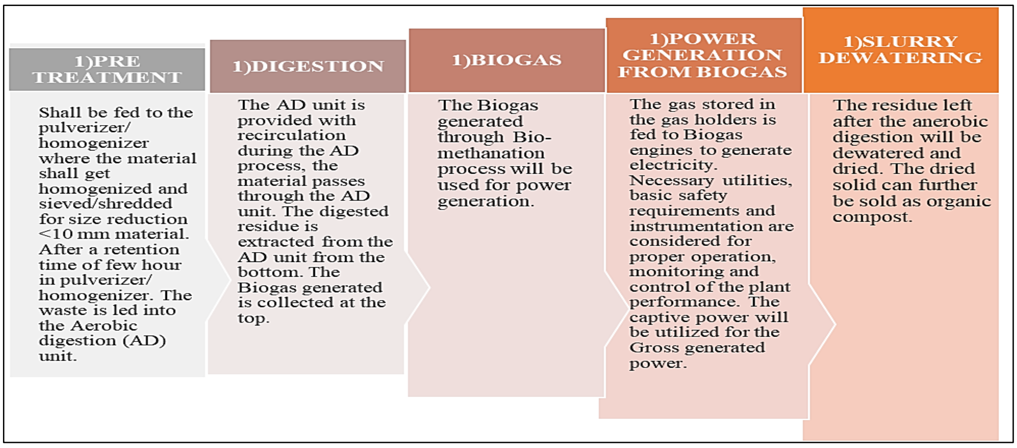

Figure 3(A): DRYCO-AD™ Technology Process (22)

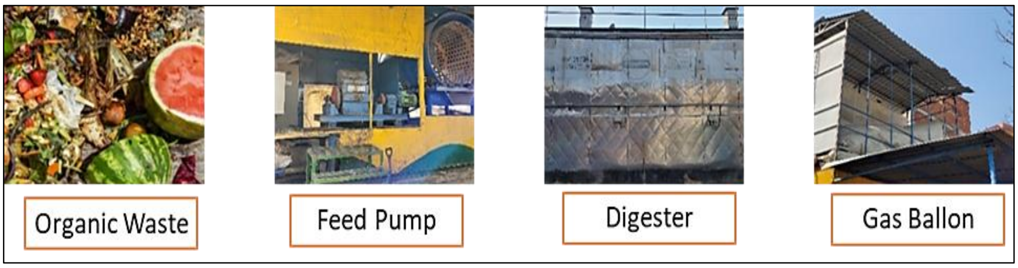

Figure 3(B): Process of Biomethanation

Bhavania Pokhari Waste to Energy Plant

The Bhavania Pokhari Waste to Energy (WTE) Plant in Varanasi was established in 2011 as part of the Corporate Social Responsibility (CSR) initiative of Indian Oil Corporation Ltd. It has been under the management of the Varanasi Municipal Corporation since 2016. This plant efficiently processes organic waste, with an impressive input capacity of 500 kg. As a result, it produces two valuable outputs: 200 kg of compost, which is eagerly utilised by the Nagar Nigam and local farmers, and a significant amount of electricity, ranging from 300 to 500 units. About 200 units of this electricity are used to power the plant itself, since it is not connected directly to the power grid. All surplus power is transmitted back to the grid. The plant has a waste processing capacity of 5 metric tonnes per day. It needs 5000 kg of organic waste to operate fully during three shifts, each lasting six hours. Unfortunately, the plant is currently operating in only one shift due to a shortage of organic waste. This is a reduction from its previous full potential, where the generated electricity was distributed to nearby areas, including street lights and the Jal Nigam. The waste processed at the plant is collected from various areas, including Lanka, Rewari Talab, Madanpura, and other nearby regions. This is done through a convenient door-to-door collection system. Waste segregation is mainly carried manually, although a trommel is used for more efficient separation when dealing with larger quantities of waste (~1000 kg). Waste generated after processing is sent to Karasada for additional treatment. This plant is managed by a small team comprising of a supervisor, an operator, and an assistant. Regular generator servicing is necessary after every 500 hours of operation, as per the guidelines provided by Mahindra Powerol (service provider). The plant also has a laboratory that is not currently in use. It is equipped with various instruments, such as a bomb calorimeter, muffle furnace, centrifuge, oven, refrigerator, and titration equipment (See Table 2).

Paharia Mandi Waste to Energy Plant

The Paharia Mandi Waste to Energy (WTE) Plant in Varanasi was established in 2012 as part of the Corporate Social Responsibility (CSR) initiative of Indian Oil Corporation Ltd., and was initially operated by Organic Recycling System Pvt. Ltd. Since 2017, the management of Varanasi Municipal Corporation (VMC) has been under new leadership. This plant efficiently handles organic waste, with a daily input capacity that can range from 3 to 5 tonnes per day (TPD), and sometimes even up to 10 TPD. The organic waste undergoes a transformation, resulting in two primary outcomes. Firstly, it produces 300-500 kg of compost, which is utilised in the hands of the Nagar Nigam and local farmers. Secondly, it generates 400-600 units of electricity, with approximately 300 units being utilised on-site due to the plant's lacks, a direct connection to the power grid. The facility has a waste processing capacity of 5 metric tonnes per day (MTD), requiring 5000 kg of organic waste for continuous operation across three shifts of six hours each (Figure 3B). Unfortunately, like many other plants, a shortage of organic waste has resulted in limited operations to just one shift. In the past, the plant was fully operational and the electricity it generated was distributed to nearby areas, including street lights and the Jal Nigam. Waste collection focuses primarily in Paharia Mandi, with additional collections from Sarnath, Pandeypur, and nearby areas. The waste is collected through a door-to-door method, with 3-4 trips made daily by Waste to Solution Pvt. Ltd. The amount of waste collected typically grows up during the winter season. Waste segregation is usually carried out by hand, but for larger quantities (~1000 kg), trommel machinery is used to enhance the efficiency of the separation process. Rejected materials are sent to Karasara for additional treatment. The plant's generator needs regular servicing every 500 hours, which is taken care of by Mahindra Powerol (service provider). The plant operator is responsible for handling additional maintenance tasks such as servicing the feed pump and bio crusher. A small team consisting of a supervisor, an operator, and an assistant is tasked with managing the plant's operations (See Table 2).

IDH Kazzakpura Waste to Energy Plant

The IDH Kazzakpura Waste to Energy (WTE) Plant in Varanasi was established in 2013 as part of the Corporate Social Responsibility (CSR) initiative of Indian Oil Corporation Ltd. It was initially operated by Organic Recycling System Pvt. Ltd. In 2018, the plant's management was handed over to the Varanasi Municipal Corporation (Varanasi Nagar Nigam). This plant efficiently processes organic waste, with a remarkable input capacity that ranges from 4 to 5 tonnes per day (TPD), and on certain occasions, it can even handle up to 10 TPD. The plant produces 400-500 kg of compost, which is utilised by the Nagar Nigam and local farmers. Additionally, it generates 500-600 units of electricity, with approximately 350 units being consumed on-site due to the plant's absence of connection to the power grid. being a facility with a capacity of 5 metric tonnes per day, it requires 5000 kg of organic waste for full operation across three shifts of six hours each. The plant used to run two shifts, but now it only runs one shift due to a lack of organic waste. When it was fully operating, electricity generated was delivered to the Jal Nigam, street lights, and surrounding regions. for this plant, Waste is collected from Kazzakpura, Adampur, Konia, Golgadda, and surrounding areas through a door-to-door collection method. it operates 3-4 trippers daily for this purpose. During the winter season, there is a noticeable increase in the volume of waste collection. Waste segregation is usually carried out by manpower, but for larger quantities (~1000 kg), a trommel is employed to enhance the efficiency of sorting. Excess materials are directed to Karasara, Waste to Solution Pvt. Ltd. for additional processing. The plant's engine needs regular servicing every 500 hours, which is taken care of by Mahindra Powerol (service provider). The plant is run by a small team consisting of a supervisor, an operator, and two assistants (See Table 2).

This research systematically analyses waste generation patterns and organic waste management practices in Varanasi City while evaluating decentralised waste treatment facilities' functionality and operational status in the region.

Table 2: Comparative Study between Three Existing Decentraised Waste Treatment Plant in Varanasi

	Bhavaniya Pokhari	**Paharia Mandi**	**IDH Kazzakpura**
Governing Body	Municipal Corporation	Municipal Corporation	Municipal Corporation
Established By	Indian Oil	Indian Oil	Indian Oil
Capacity	5 MTD	5 MTD	5 MTD
Type of Waste	Organic Waste	Organic Waste	Organic Waste
Segregation Method	● Manual ● Trommel	● Manual ● Trommel	● Manual ● Trommel
Collection Method	Door to door (by Tripper)	Door to door (by Tripper)	Door to door (by Tripper)
Collection Area	▪ Lanka, ▪ Rewari Talab ▪ Madanpura	▪ Paharia Mandi ▪ Sarnath ▪ Pandeypur	▪ Kazzakpura ▪ Adampur ▪ Konia ▪ Golgadda
Waste Input	3-4 TDP	3-5 TPD	4-5 TPD
Compost Output	200-300 kg	400-500 Kg	300-500 Kg
Electricity Output	300-500 unit	500-600 unit	400-600 unit
Reject Produced	Transferred to Karasara plant	Transferred to Karasara plant	Transferred to Karasara plant
Current Status	Partially operational (1 shift)	Partially operational (1 shift)	Partially operational (1 shift)
Previous Status	Fully operational (3 shifts)	Fully operational (3 shifts)	Fully operational (3 shifts)
No. of person appointed	● In charge (1) ● Operator (1) ● Helper (1)	● In charge (1) ● Operator (1) ● Helper (1)	● In charge (1) ● Operator (1) ● Helper (2)
Laboratory	Not Functional	________	________
Engine Running Capacity	500 hrs	500 hrs	500 hrs

Varanasi was chosen as the case study location because of its elevated population density, which results in substantial waste production, and its persistent waste management issues, including inadequate infrastructure and ineffective segregation practices. The city's implementation of decentralised waste-to-energy plants through government initiatives provides a significant framework for examining sustainable waste management solutions.

Methodology

This study investigated the state of Varanasi's organic waste management, its impact on the environment and public health, and the possibility of implementing better methods of disposing of organic waste. The data collected include Waste to Energy (WTE), Waste to Compost (WTC) and Bio-methanation; this study includes a six-month period of investigation that involved data gathered from the literature, in-depth fieldwork, and correspondence with authorities, locals, and urban local bodies.

Initially key stakeholders were identified, their respective roles delineated, and participation obstacles outlined; a power–interest matrix was then constructed to provide analytical clarity on stakeholder dynamics. Quantitative data were obtained from secondary records provided by the VMC and plant operators—specifically waste generation rates, compost output, biogas production, and electricity yields—to enable a rigorous numerical assessment of plant efficiency. Complementing this, qualitative insights were gathered through fieldwork, which included site visits to decentralised waste-to-energy plants and a centralised composting facility, as well as surveys and interviews with municipal authorities' officials and 50 local residents to identify operational challenges such as feedstock shortages.

Study Area

Varanasi, a city of historical and cultural importance in Uttar Pradesh, India, covers an area of 1,535 square kilometres and has an estimated population of 3,676,841 people. Varanasi is located on the banks of the sacred Ganges River at 25.3176° N latitude and 82.9739° E longitude. The city is around 80.71 meters (265 feet) above sea level, giving it a unique climate and topography. Varanasi experiences a humid subtropical climate, marked by three distinct seasons: summer, monsoon, and winter (23). Summers span from March to June and are generally characterised by scorching heat and arid conditions, with temperatures frequently surpassing 40°C (104°F). The city receives an average of approximately 1,100 millimetres (43 inches) of precipitation during the monsoon season, which spans from July to September. Most of the annual rainfall occurs during this period, with elevated humidity and sporadic flooding. Winters are comfortable compared to the hot summers, lasting from December to February. The average temperature during the winter months is between 5°C (41°F) and 15°C (59°F).

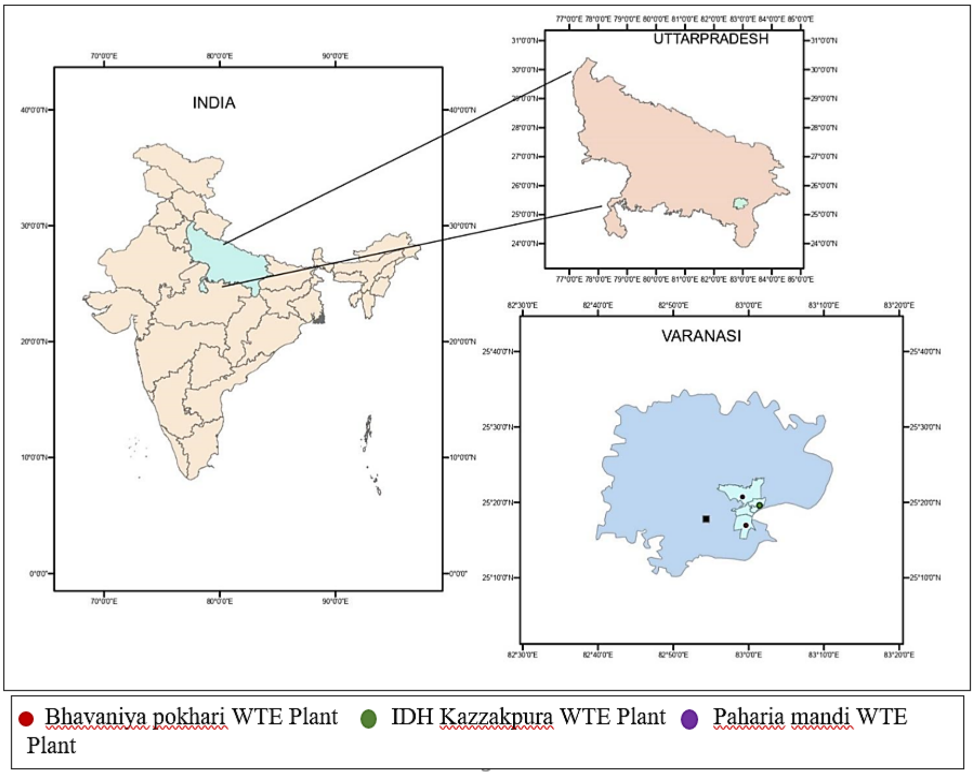

Figure 4: Map of the Study Area

The Varanasi Municipal Corporation, responsible for municipal administration and infrastructure development, is in command of governance in Varanasi. The municipal corporation has divided the city into five zones, each with 14 sub-zones and 100 wards (Table 1) (24). The efficient governance provided by this administrative framework enables the provision of public health, sanitation, water supply, waste management, and other services methodically throughout the crowded, diverse metropolitan area (25). Structured division into zones and wards facilitates targeted interventions and localised governance, enabling municipal authorities to address the specific needs of different parts of the city (Figure 4) (26).

Results and Discussion

Current MSW Management in Varanasi City

As per the estimate, waste generation rate estimated by the municipal corporation is 1012.64 Tons per Day (TPD), out of which approximately 850 TPD waste is collected each day and approximately 750 TPD waste is processed (See Table 3).

Table 3: Current MSW Management in Varanasi City

1.	Current MSW total generation in TPD	**1012.64**	
2.	Per Capita generation	**550 gms**	
3.	Total waste collected (TPD)	**850**	
4.	No. of Wards practicing 100% door to door waste collection	**90**	
5.	Total quantity transported in TPD to:	Processing Plants	**750**
		SLF	**100**
		Dumpsites	**162.64**
6.	Total no. of Secondary collection points/ Transfer Stations (TS)	Wet Waste	**0**
		Dry Waste	**23**
7.	Total quantity of MSW currently processed	**750 TPD**	

Table 4: Decadal Growth and Projection of Waste Generation in Varanasi City (12)

Years	Population	Waste Per capita per day	Generation Based on Population MT/Day (approx.)
2011	1198491	0.400	479.39
2021	1559805	0.400	623.92
2031	2030047	0.450	889.74

Stakeholder Analysis

Key Stakeholders and Roles:

- Varanasi Municipal Corporation (VMC): Manages waste disposal, operates decentralised waste-to-energy (WTE) facilities, and partners with private organisations.
- Private companies, such as YASASU EMS Pvt. Ltd. and Waste to Solution Pvt. Ltd., offer technological expertise, construct and operate waste-to-energy plants, and oversee waste collection.
- Community Organisations: Local farmers and residents employ composting and electricity, aiding in waste segregation.
- NGOs: Prospective collaborators for public awareness (role implied, to be elaborated with data).

Challenges / Obstacles

- VMC: Insufficient infrastructure and minimal public awareness.
- Private companies: experience operational disruptions due to fluctuating waste supply.
- Communities: Inadequate incentives and awareness hinders engagement.

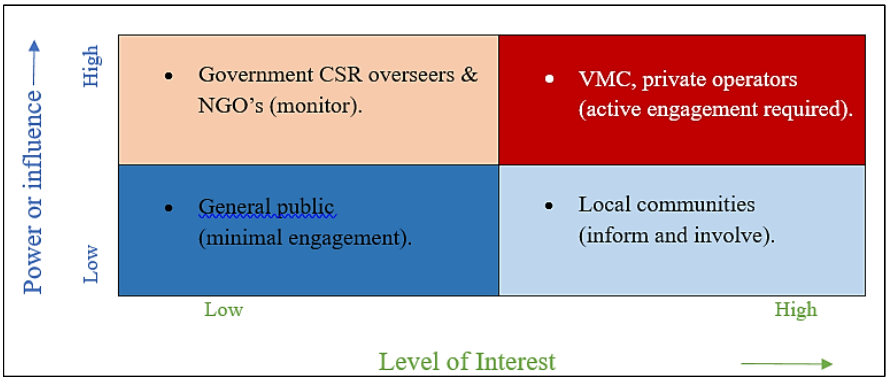

Figure 5: Stakeholder Power Interest Matrix

A stakeholder analysis identified the VMC and private entities such as YASASU EMS Pvt. Ltd. as influential and highly invested participants essential to Varanasi's waste-to-energy ecosystem. The VMC oversees waste and plant operations but encounters infrastructure deficiencies, whereas private companies offer technology but face challenges with waste supply reliability. Local communities, identified as low-power, high-interest stakeholders, derive advantages from outputs but necessitate enhanced awareness. A power-interest matrix clarifies these relationships, informing focused engagement strategies (Figure 5).

Monthly Performance Waste to Energy Plant

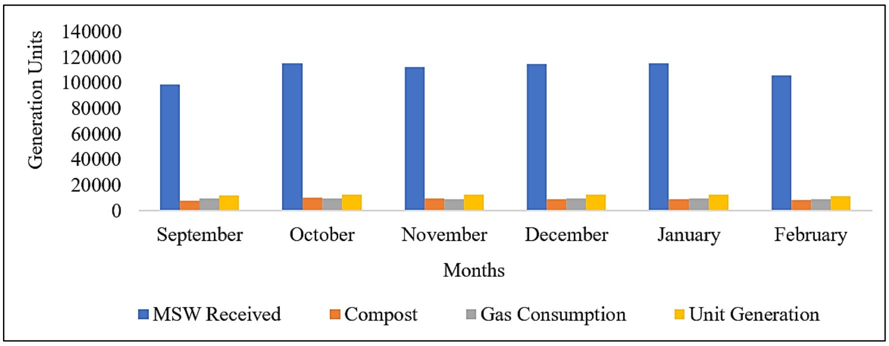

Figure 6: Monthly Performance of Bhavaniya Pokhari WTE Plant

The below graph (Figure 6) shows the monthly report of Bhavania pokhari WTE plant that operates on decentralised method (27). The study of six month collected data shows that an average of 110 TPD of Municipal Solid Waste is received from which an average of 9 TPD compost is generated. An average of 9465 m^3 gas consumption occur for generation of 12330 unit electricity in six month. The graph illustrates notable patterns in the management of Municipal Solid Waste (MSW) and energy generation, which are mostly driven by seasonal activity. The month of October experiences the greatest increase in municipal solid waste (MSW) due to the festival season, leading to a substantial production of compost (28). In contrast, September has the lowest levels in both categories. Fuel (gas) consumption shows a notable increase in January, perhaps attributed to the colder climate, and subsequently declines to its minimum level in February. December is notable for its significant power generation, as it produces the most considerable amount of units. This reflects the enhanced energy consumption that occurs during the winter months. The seasonal trends highlight the complex relationship between waste management and energy generation throughout the year.

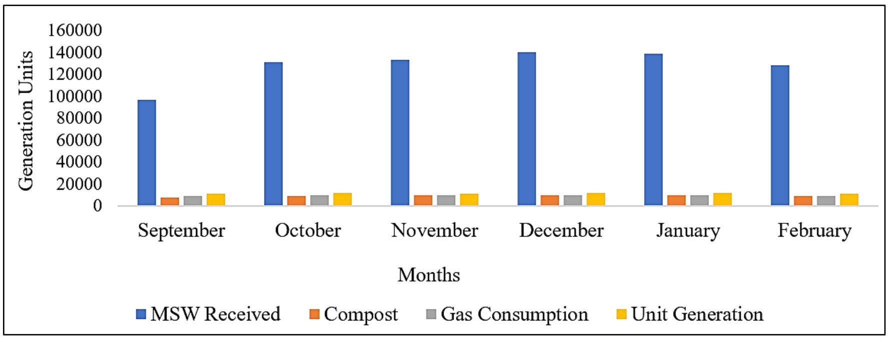

Figure 7: Monthly Performance of Paharia Mandi WTE Plant

The above graph (Figure 7) shows the monthly report of Paharia Mandi WTE plant that operates on decentralised method. The study of six month collected data shows that an average of 141 TPD of Municipal Solid Waste is received from which an average of 10.5 TPD compost is generated. An average of 9776.66 m^3 gas consumption occur for generation of 11902.66 unit electricity in six month. The graph offers a fascinating insight into the seasonal fluctuations of Municipal Solid Waste (MSW) management and energy generation. December is the month with the enormous amount of municipal solid waste (MSW) received and also the month with the most compost output. In contrast, September has the lowest amount of MSW received and the lowest compost production. October experiences the highest level of fuel (Gas) consumption, which is in strong contrast to February, when fuel (Gas) usage is at its lowest. In December, electricity generation reaches its peak, producing the maximum number of units, while October sees the lowest output. The oscillations highlight the complex and interconnected relationship between waste processing, resource utilisation, and energy generation throughout the year (28).

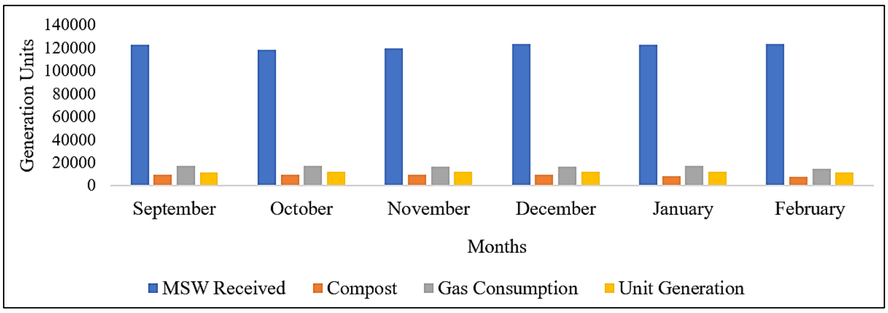

Figure 8: Monthly Performance of IDH Kazzakpura WTE Plant

The above graph (Figure 8) shows the monthly report of IDH Kazzakpura WTE plant that operates on decentralised method. The study of six month collected data shows that an average of 114 TPD of Municipal Solid Waste is received from which an average of 10.1 TPD compost is generated. An average of 16672.16 m^3 gas consumption occur for generation of 11977.33 unit electricity in six month.The graph displays notable patterns in the management of Municipal Solid Waste (MSW) and energy generation throughout the course of the year. February is particularly notable for having the highest amount of municipal solid waste (MSW). Although trash processing reaches its highest point in February, gas use is at its lowest, in sharp contrast to October, when gas usage hits its highest level. In addition, November is the month with the highest electricity generation, while September consistently has the lowest electricity production. These variations highlight the dynamic interplay between waste intake, resource utilization, and energy production across different seasons.

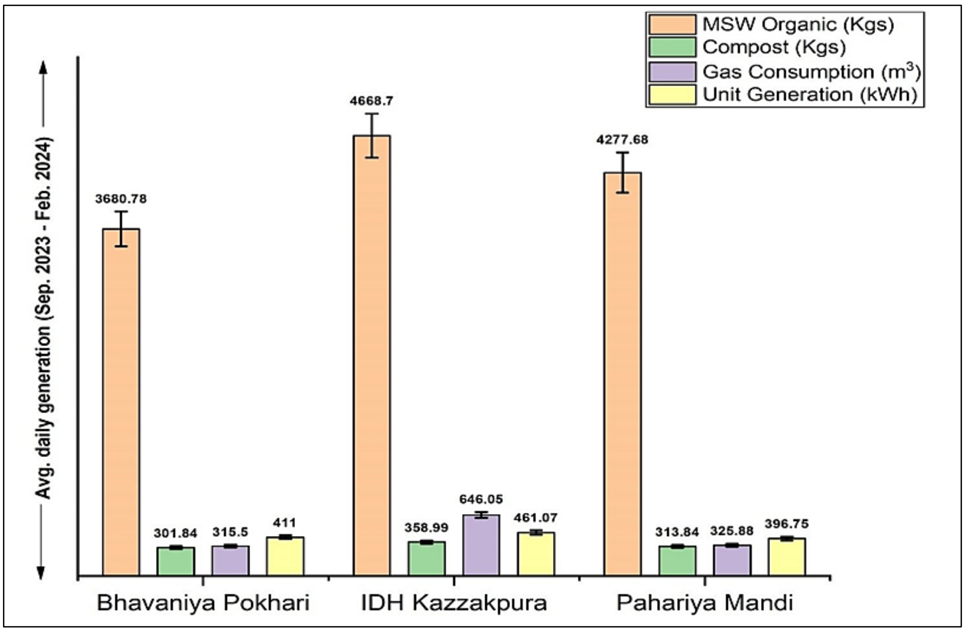

Figure 9: Average Daily Performances of All Three WTE Plants

Average Daily Performance

Organic to Compost

- Bhavaniya Pokhari WTE Plant: 301.8 kg ÷ 3 680.8 kg ≈ 8.2 %
- IDH Kazzakpura WTE Plant: 359.0 kg ÷ 4 668.7 kg ≈ 7.7 %
- Pahariya Mandi WTE Plant: 313.8 kg ÷ 4 277.7 kg ≈ 7.3 %

Bhavaniya pokri plant attains the highest compost conversion ratio, whereas Pahariya records the lowest although its location is close to vegetable market hence a huge chunk of vegetable reject or green matter rich in nitrogen as major proportion of waste and low brown matter or carbon content disturbing the suitable C/N ratio while Bhavaniya pokhari plant attributable to superior carbon-nitrogen balance or processing control leading to best compost production among others (Figure 9).

Biogas Production and Consumption (Gas per kg of Organic Feedstock)

- Bhavaniya Pokhari WTE Plant: 315.5 m^3 ÷ 3 680.8 kg ≈ 0.086 m^3/kg
- IDH Kazzakpura WTE Plant: 646.1 m^3 ÷ 4 668.7 kg ≈ 0.138 m^3/kg
- Pahariya Mandi WTE Plant: 325.9 m^3 ÷ 4 277.7 kg ≈ 0.076 m^3/kg

Biogas production in the plant depends on proper availability of segregated feedstock. Bhavaniya pokhari plant recived its waste from the residential area of population with low socio-economic status where chance of mixed waste is common that hinder its productivity. Though the C/N ratio is found optimim.in the case of pahariya mandi plant the waste received totally segregated organic waste because a lot of reject from vegetable market beside it. The green matter (leafy vegetable residue) is too much which reflect nitrogen richness of organic while the carbon content i.e. brown matter is low which change C/N ratio and leads to low biogas product. The brown matter is sometimes maintained externally but usually the problem persist. IDH's gas yield per kilogram is highest likely reflecting more readily digestible feedstock. Efficient digester design can be a factor but all three digestor are designed a common manufacture and operates on same technology.

Energy Production (kWh per m^3 of Biogas)

- Bhavaniya Pokhari WTE Plant: 411.0 kWh ÷ 315.5 m^3 ≈ 1.30 kWh/m^3
- IDH Kazzakpura WTE Plant: 461.1 kWh ÷ 646.1 m^3 ≈ 0.71 kWh/m^3
- Pahariya Mandi WTE Plant: 396.8 kWh ÷ 325.9 m^3 ≈ 1.22 kWh/m^3

Bhavaniya pokhari plant and Pahariya plant exhibit very similar gas-to-electricity conversion efficiencies of approximately 1.25 kWh/m^3, while IDH Kazzakpura plant's efficiency is about half the amount of gas consumed. This discrepancy indicates potential higher losses in either the generator or gas-cleaning processes, or a reduced methane concentration in its biogas (Figure 9).

Overall Energy Efficiency (kWh per kg of Organic Feedstock)

- Bhavaniya Pokhari WTE Plant: 411.0 kWh ÷ 3 680.8 kg ≈ 0.11 kWh/kg
- IDH Kazzakpura WTE Plant: 461.1 kWh ÷ 4 668.7 kg ≈ 0.099 kWh/kg
- Pahariya Mandi WTE Plant: 396.8 kWh ÷ 4 277.7 kg ≈ 0.093 kWh/kg

We have found in overall energy efficiency, Bhavaniya pokhari plant leads (0.11 kWh/kg of organic feedstock), followed by IDH (0.099 kWh/kg of organic feedstock) and Pahariya (0.093 kWh/kg of organic feedstock).

Economic and Social Implications

Decentralised waste-to-energy plants involve significant capital expenditures for technology and infrastructure and ongoing operational costs for labour and maintenance. Revenue generated from compost 200–500 kg/day (1 ton compost costs 5000rs) that is 400-1000 Rs /day and electricity 300–600 units /day (1 unit = 1kwh costs proximately 7 Rs /unit in urban area) that is 2100-4200 Rs / day sustain operations by each plant (29, 30). However, dependence on CSR subsidies indicates constrained profitability without external funding. The erratic supply of waste presents an economic risk, requiring additional cost-benefit analysis. The plants create jobs and improve urban cleanliness; however, the broader effects on community well-being necessitate further examination.

Community Perceptions

Community perceptions of waste-to-energy plants indicate a balance of advantages and disadvantages. A survey of 50 households adjacent to the Bhavania Pokhari plant revealed that 70% prioritised diminished waste and employment prospects, whereas (15) 30% expressed odour concerns. Trade-offs encompass land allocation for vegetation versus alternative applications and aesthetic consequences. These initial findings highlight the necessity for odour mitigation and formal surveys to confirm community sentiments, thereby enhancing policy formulation.

Conclusion

This study highlights the potential of decentralized biogas plants in Varanasi to transform organic waste into energy and compost, mitigating urban waste challenges. However, operational success is constrained by inconsistent waste supply and inadequate segregation, needing robust policy interventions. Economically, profitability without subsidies remains uncertain, while socially, benefits like job creation and capacity-building programmes are evident yet underexplored. We recommend future research to conduct cost-benefit analyses assessing unsubsidized viability and pilot projects to test odour control technologies and community engagement strategies, enhancing the scalability and acceptance of such initiatives.

Recommendations

- Urban local bodies should implement effective measures for segregation of MSW at source.
- Optimize C / N ratio to around 15–30: 1 for balanced composting and gas yields.
- Enforce a hydraulic retention time of 20–30 days to maximize conversion.
- For maintenance and operation of treatment facilities PPP (Public Private Partnership) model should be promoted.
- Several Awareness programs and campaign about waste segregation should be conducted regularly on various level like Schools, hospitals, religious places, institutional and commercial places.

Abbreviations

CSR: Corporate Social Responsibility, CSWAP: City Solid Waste Action Plan, DRYCO-ADTM: Decentralized Waste to Energy Plants is High Solid Thermophilic Anaerobic Digestion Technology, IBA: Indian Biogas Association, ICRIER: Indian council for research on international economic relations, IDH: Indira Development Housing, MSW: Municipal Solid Waste, NEERI: National Environmental Engineering Research Institute, SWM: Solid Waste Management, USEPA: United States Environment Protection Agency, WTC: Waste to Compost, WTE: Waste-to-Energy.

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Author contributions

Ravikant Dubey: conception, designing, collecting data, analysing and interpreting the results, preparing the manuscript, Shyamli Gupta:

conception, analysis, and interpretation of results, Amrita Dwivedi: editing, final proof reading.

Conflict of Interest

The authors declared no potential conflicts of interest.

Ethics Approval

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