A Comparative Study of Waste to Energy Projects in India through Multi Criteria Decision Analysis

विद्यारत्नं महाधनम्

Thesis submitted in partial fulfilment
for the Award of Degree

Doctor of Philosophy

by

RADHA KRISHNA TRIPATHY

RAJIV GANDHI INSTITUTE OF PETROLEUM TECHNOLOGY
Jais, India - 229304

PM1609 **2025**

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CERTIFICATE

It is certified that the work contained in the thesis titled "***A Comparative Study of Waste to Energy Projects in India through Multi Criteria Decision Analysis***" by "***Radha Krishna Tripathy***" has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy, and SOTA.

____

Supervisor

Dr. Kavita Srivastava

DECLARATION OF THE CANDIDATE

I, “Radha Krishna Tripathy”, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of Dr. Kavita Srivastava from August 2016 to June 2025, at the Rajiv Gandhi Institute of Petroleum Technology, Jais.

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Roll No: PM1609

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Dr. Kavita Srivastava

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Dr. Jaya Srivastava

Head of Department

Department of Management Studies

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ABSTRACT

India’s urban centres generate approximately 55 million metric tonnes of municipal solid waste (MSW) on an annual basis (equating to roughly 1.5 lakh metric tonnes per day) as per data released by ministry of housing and urban affairs, Govt of India through its scheme’s portal on Swachh Bharat Mission (Urban) 2.0. In the forthcoming decades, anticipated increases in income levels alongside escalating urbanization are projected to further augment per capita waste generation, in addition to a transformation in the composition of MSW toward a greater proportion of non-biodegradable waste. The generation of MSW is forecasted to rise to 165 million metric tonnes by the year 2030 and to 436 million metric tonnes by 2050. Presently, the legacy waste, estimated at around 250 million metric tonnes, deposited at over 2300 sites (R. Singh & Budarayavalasa, 2024) throughout the nation, presents considerable public health and environmental challenges. Consequently, a status quo methodology for the management of MSW is evidently not sustainable.

India is experiencing rapid urbanization, leading to an exponential increase in Municipal Solid Waste (MSW) generation. The growing waste stream, combined with limited landfill space and environmental concerns, is driving the need for efficient waste management alternatives (BP et al., 2023). Waste-to-Energy (WtE) incineration projects present a promising solution by not only reducing landfill requirements but also recovering energy, which is essential for powering urban areas and supporting Urban Local Bodies (ULBs) in managing resources sustainably (Ram et al., 2021).

Incineration reduces the volume of waste significantly, lessening the burden on urban land and minimizing methane emissions from traditional landfill sites. It promotes cleaner urban environments by eliminating hazardous components if combined with proper emission

[1]*As per a TERI article by Dr Agnihotri dated 14 Sept 2022 , weblink : https://www.teriin.org/article/msw-management-pitiable-situation-municipal-solid-waste-management*

management systems. WtE incineration converts waste into electricity through steam generation, which can be used to power public infrastructure. This is particularly beneficial for cities with a population exceeding one million and a high daily generation of waste (around 500 TPD).This model supports the dual objective of waste disposal and sustainable energy production, turning a public nuisance into a valuable resource.

While incineration projects require a higher initial capital investment, viability is enhanced through technical innovations, proper pre-processing of waste, and complementary revenue streams like tipping fees and Power Purchase Agreements (PPAs). The adoption of financial models such as Viability Gap Funding (VGF) further supports the economic sustainability of these projects(Maniar, 2013a).

ULBs (Urban Local Bodies) play a key role in planning and strategizing effective waste management systems. They are responsible for preparing comprehensive City Solid Waste Action Plans (CSWAP) that outline the current gaps, future needs, and project proposals for waste management infrastructure. These plans help in determining the type and capacity of facilities such as waste-to-energy plants, bio-methanation plants, composting facilities, and Material Recovery Facilities (MRFs) that need to be set up based on the city's waste generation and processing requirements.

ULBs are tasked with providing suitable, encroachment-free land for the establishment of waste processing facilities. A core role of ULBs is to ensure a steady and quality supply of waste to the processing facilities. They have the responsibility to collect waste from households and commercial establishments and to ensure that waste is segregated properly at source (S, 2021).

ULBs facilitate financial viability by providing assured tipping fees or direct financing through schemes like Viability Gap Funding (VGF). They support project developers by ensuring timely payments and sometimes by setting up escrow accounts to guarantee funds for operations. This financial support gives confidence to investors and private developers, making it easier to secure loans and enter into Public-Private Partnerships (PPP) to scale up waste management infrastructure.

The central government also plays a significant role in mobilizing finances via direct grants, subsidies, and Viability Gap Funding (VGF) to support waste management projects. These funds help cover a fraction of the project costs, making projects attractive for private investors as well as public initiatives. Specific schemes and economic assistance measures such as the Swachh Bharat Mission (SBM-U 2.0) allocate funds based on project need and waste processing capacity. Moreover, support is provided through policy enablers that include loan subventions and interest rate concessions by public sector banks.

Nevertheless, the selection of an operational Waste-to-Energy (WTE) project predicated upon a specific technological framework, while considering various critical parameters, appears to be inherently complex. In the context of India, the process of decision-making becomes particularly arduous when identifying a waste-to-energy model that is optimally aligned with the unique circumstances of a given locality. The apprehension regarding potential failure inhibits the administrative bodies from undertaking the additional risks associated with the implementation of novel models. The initiation of a pilot project for evaluative purposes necessitates both financial investment and temporal commitment.

In light of time constraints and fiscal limitations, decision-makers typically gravitate towards models that have demonstrated success, are readily replicable, and can be scaled according to their specific requirements. Essentially, the administrative authorities within Urban Local Bodies (ULBs) seek a plug-and-play configuration that simplifies the decision-making process by relying on empirical output results. The Analytic Hierarchy Process (AHP), which is grounded in multi-criteria decision analysis, offers a systematic decision-making framework (Rajput & Dr.A.C.Shukla, 2012a) that can effectively aid urban local bodies in navigating these intricate choices and in identifying the most advantageous alternative available.

The principal aim of this research is to establish a systematic decision-making framework for the assessment and selection of appropriate Waste-to-Energy (WTE) operational facilities employing mixed waste or Refuse-Derived Fuel (RDF) incineration methodologies within the Indian context, utilizing the Analytic Hierarchy Process (AHP). The investigation aspires to integrate a multitude of evaluative criteria—Economical, environmental, Regulatory, operational and socio-cultural factors—to assist policymakers, planners, and stakeholders in formulating informed, transparent, and sustainable decisions concerning the implementation of WTE plants. While addressing these critical parameters, a suitable risk assessment of the selected plants will also be considered under the selected critical parameters.

Specific aims of this research are:

- To identify and delineate essential criteria and sub-criteria that significantly impact the selection of WTE facilities in India.
- To implement the Analytic Hierarchy Process (AHP) for the allocation of relative weights to these criteria, predicated upon expert evaluations.
- To assess and rank alternative WTE projects utilizing the established priority weights.
- To illustrate the applicability of AHP in addressing intricate environmental decision-making challenges within the Indian waste management domain.

The scope is confined to the appraisal of operational WTE facilities utilizing mixed waste characteristics and refuse-derived fuel (RDF) incineration, thereby excluding other technological modalities.

The research deploys Analytic Hierarchy Process (AHP) model with multi criteria decision analysis tool. AHP provides a systematic approach to decision making by breaking down complex factors such as cost, environmental impact, operational feasibility, and social considerations into simpler components. This method aids ULBs in comparing different

WtE project proposals based on weighted criteria so that the best alternative power plants can be chosen. AHP analysis ensures that the chosen incineration solutions are replicable and scalable across various urban contexts by tailoring the evaluation parameters to local waste characteristics, available infrastructure, and regional economic conditions. It helps establish best practices that can be standardized, enabling other cities to adopt similar models with confidence and minimal customization.

The study's methodology was divided into three main phases.

1st Phase:

In the first phase, a comprehensive literature study is done to explore existing knowledge and identify gaps in waste-to-energy (WtE) research particularly in the context of WTE plants that are operational in nature in India. Information was gathered in this phase from peer- reviewed journals, government reports, research articles and papers, petitions filed by the regulated entities (WTE plants) , regulatory tariff orders related to specific operational plants and the latest articles. This approach ensured that specific data points and information related to operational plants that are under research are extracted, gathered and compiled in a manner so that specific critical parameters are well established before starting the AHP modelling. It ensured to form a strong knowledge base and specific data sets related to parameters and sub parameters are established for further analysis.

2nd Phase:

After the meticulous compilation of pertinent information, four operational waste-to-energy (WTE) power plants were identified in the second phase based on critical assumptions and encompassing diverse geographical locations across India. The selected power plants were required to have achieved a minimum operational period of one year, utilizing a mixed waste incineration process (inclusive of Refuse-Derived Fuel (RDF)), and possessing a critical processing capacity of no less than 500 tonnes per day. Subsequently, the selection of these power plants was corroborated by experts and industry leaders to ensure their appropriateness for the research study.

Data were meticulously gathered from authoritative ministry websites, Lok Sabha questionnaires, orders related to tariff petitions from relevant state regulatory commissions, and scholarly articles utilizing a variety of sources, presented in both quantitative (numerical values) and qualitative (descriptive) formats. The extracted data encompassed essential parameters, including environmental considerations, economic information regarding revenue generation, environmental factors such as delays in clearance, established standards and benchmarks, regulatory provisions and obstacles, alongside socio-cultural dimensions pertaining to each selected plant. Eighteen expert interviews were conducted online utilizing survey questionnaires to solicit their insights and feedback regarding the critical parameters employed in this research, wherein they were requested to express their evaluations on a nine-point Likert scale by comparing pairs of parameters.

3rd Phase:

In the 3rd phase, data collected from experts are collated, compiled and fed to decision software that employs AHP modelling for results. It synthesizes all the weightages along with scores for all individual criteria. The consistency ratio is calculated for each individual matrix developed for checking the biasedness if any. After consistency ratio is evaluated the final score for selection of the best alternative is arrived at. The best alternative plant comes out from the analysis and accordingly all the plants are ranked. The validation is clearly established with the inputs received from the expert's judgement. The AHP modelling clearly stands out among the chosen alternatives.

Policymakers can utilize the model as a replicable framework, adapting it to different regional contexts by incorporating local waste composition, policy environments, and economic conditions. This adaptability makes it a valuable tool across various geographical locations for decision making.

The findings possess significant ramifications for Urban Local Bodies that are endeavoring to develop innovative strategies to address waste management challenges. With the Government's assistance in financial planning, including fiscal incentives such as Viability Gap Funding (VGF), it is feasible to establish a novel Public-Private Partnership (PPP) framework and craft concession agreements in a manner that fosters mutually beneficial outcomes for all involved stakeholders. This study can serve as a versatile instrument for urban local bodies, allowing them to tailor their approaches by considering various parameters that are optimally aligned with their specific local contexts, thereby enabling them to ascertain which model is most appropriate under particular circumstances and associated risk factors.

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Dedicated To

My Parents and My Saviours (Indian Army)

For their shield and protection against the internal and external threats

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(Radha Krishna Tripathy)

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

S. No.	Abbreviation	Description
1	ADB	Asian Development Bank
2	AHP	Analytical Hierarchy Process
3	AI	Artificial Intelligence
4	CA	Central Assistance
5	CBA	Cost Benefit Analysis
6	CDM	Clean Development Mechanism
7	CERC	Central Electricity Regulatory Commission
8	CR	Consistency Ratio
9	DBFOT	Design Build Finance Operate Transfer
10	DBOT	Design Build Operate Transfer
11	DISCOM	Distribution Company
12	DST	Department of Science and Technology
13	EC	Environmental Clearance
14	EIA	Environmental Impact Assessment
15	GCF	Global Climate Fund
16	GHG	Green House Gas
17	GIS	Geo Imaging
18	GOI	Govt Of India
19	HERC	Haryana Electricity Regulatory Commission
20	IRR	Internal rate of Return
21	LCA	Lifecycle Cost Analysis
22	MCDA	Multi Comparison Decision Analysis
23	MNRE	Ministry of New and Renewable Energy
24	MoEFCC	Ministry of Environment Forest and Climate Change
25	MoHUA	Ministry of housing and Urban Affairs
26	MSW	Municipal Solid Waste
27	MW	Mega Watt
28	NIMBY	Not In My Backward
29	OBI	Output Based Incentive
30	PPA	Power Purchase Agreement

S. No.	Abbreviation	Description
31	PPP	Public Private Partnership
32	RDF	Refuse - Derived Fuel
33	REC	Renewable Energy Certificate
34	RI	Random Index
35	SDG	Sustainable Development Goal
36	SLF	Sanitary Land fill
37	SPCB	State Pollution control Board
38	TPD	Tonnes per Day
39	ULB	Urban Local Body
40	UNEP	United Nations Environment Programme
41	VGF	Viability Gap Funding
42	WTE	Waste To Energy

CHAPTER 1
INTRODUCTION

Chapter 1: INTRODUCTION

1.1. Background and Context of Waste management challenge in India

India's urban centers generate approximately 55 million metric tonnes of municipal solid waste (MSW) on an annual basis (equating to roughly 1.5 lakh metric tonnes per day) as per data released by ministry of Housing and Urban Affairs, Govt of India. In the forthcoming decades, anticipated increases in income levels alongside escalating urbanization are projected to further augment per capita waste generation, in addition to a transformation in the composition of MSW toward a greater proportion of non-biodegradable waste.

The generation of MSW is forecasted to rise to 165 million metric tonnes by the year 2030 and to 436 million metric tonnes by 2050. Presently, the legacy waste, estimated at around 250 million metric tonnes, deposited at over 2300 sites throughout the nation, presents considerable public health and environmental challenges. Consequently, a status quo methodology for the management of MSW is evidently not sustainable (R. Singh & Budarayavalasa, 2024).

Therefore, an accelerated enhancement of waste processing and recycling capacities, coupled with the prompt bioremediation of legacy dumpsites, is critical for fostering sustainable MSW management within Indian cities, and is essential for the health, hygiene, and social welfare of India's urban population. The second phase of the Swachh Bharat Mission (Urban) (SBM (U) 2.0) acknowledges these pressing issues and specifically aims to address both facets, namely, (i) the establishment of MSW processing capacity and bioremediation of legacy waste, as well as the transformation of existing dumpsites into green spaces.

1.2. MSW processing capacity in India:

The designed processing capacity for Municipal Solid Waste (MSW) was reported to be 205,000 tonnes per day, which approximates to 130% of the anticipated waste generation, estimated at roughly 150,000 tonnes per day. Among this capacity, approximately 112,000 tonnes per day (55%) was allocated to composting. Alternative methodologies, including Bio-methanation (3,500 tonnes per day), Waste-to-Energy (14,200 tonnes per day), and Material Recovery Facilities (75,000 tonnes per day), constituted the remaining 45% of the processing share. The operational efficacy of these facilities ranges between 50% and 60%, equating to a throughput of 100,000 to 120,000 tonnes per day.

The total volume of waste processed stands at 76%, corresponding to 114,000 tonnes per day. Additionally, bioremediation efforts targeting legacy waste have made notable advancements in recent years, resulting in the recovery of over 3,000 acres of land following the remediation of more than 4.5 million tonnes of legacy municipal solid waste.

The proportion of processing methodologies that do not rely on composting must experience a significant and rapid increase. This is particularly imperative in light of the comparatively greater land utilization associated with composting practices and the pronounced escalation in the proportion of non-biodegradable waste. Consequently, Urban Local Bodies (ULBs) must extend their focus beyond composting and actively integrate alternative Municipal Solid Waste (MSW) processing solutions.

Furthermore, the expedited bioremediation of historical waste deposits assumes considerable importance. The Government of India acknowledges that a diverse array of waste processing methodologies and recycling technologies will be essential for addressing the complexities inherent in MSW management. Additionally, it recognizes the necessity to enhance awareness, develop competencies, and disseminate knowledge pertaining to various waste processing alternatives and their respective implementation frameworks. As ULBs persist in advancing the augmentation of MSW processing capabilities and in remediating legacy waste sites, there is a pressing need to cultivate the competencies required to devise sustainable and financially viable projects in pursuit of this objective.

1.3. Overview of Waste to Energy (WtE) Projects in India

WtE projects in India are gaining traction as viable solutions for waste management and energy generation, addressing both environmental and energy demands effectively. These projects not only help in reducing landfill waste but also contribute to renewable energy production, making them essential for sustainable urban development in India. The successful implementation of these projects requires collaboration among various stakeholders, including government bodies, private investors, and local communities. As these initiatives expand, it is crucial to address the financial, technological, and regulatory challenges that hinder their growth, ensuring a sustainable and effective waste management strategy in India. Moreover, enhancing public awareness and participation in waste segregation practices can significantly improve the efficiency of WtE projects, leading to better resource recovery and energy generation.

Additionally, fostering public-private partnerships can play a pivotal role in overcoming financial barriers and enhancing the overall effectiveness of waste-to-energy initiatives in India. Investing in research and development for innovative WtE technologies will further enhance their efficiency and sustainability, paving the way for a greener future in waste management across India. Ultimately, a comprehensive approach that integrates technological advancements, regulatory support, and community engagement is essential for the long-term success of WtE projects in India. This multifaceted strategy will not only bolster energy security but also significantly mitigate the environmental impact of waste disposal in urban areas.

1.4. Significance of Incineration-Based WTE Projects

Incineration represents one of the most advanced and extensively utilized waste-to-energy (WTE) technologies on a global scale. In India, the integration of incineration-centric WTE facilities has progressed slowly; however, it is currently experiencing an upward trajectory. These facilities not only facilitate waste management but also contribute significantly to the generation of renewable energy, thereby positioning themselves as integral elements of sustainable urban advancement.

Incineration-oriented WTE initiatives are particularly pertinent to India, given their potential to simultaneously mitigate two pressing urban dilemmas: waste management and energy deficiency. With the escalation of urban demographics and a corresponding rise in per capita waste production, municipal administrations are increasingly compelled to manage solid waste efficiently while also aligning with national clean energy objectives. Incineration provides a feasible technological avenue to diminish waste volume while concurrently generating electricity, thus yielding dual advantages for sustainability.

Figure1.1: Waste Management Hierarchy

Source: MNRE and own research

One of the foremost advantages of incineration is its capacity to drastically reduce the volume of waste that would otherwise end up in landfills. Typically, incineration can reduce waste volume by up to 90%, easing the burden on overfilled landfills and mitigating issues related to leachate generation and land contamination (UNEP, 2019)[3].

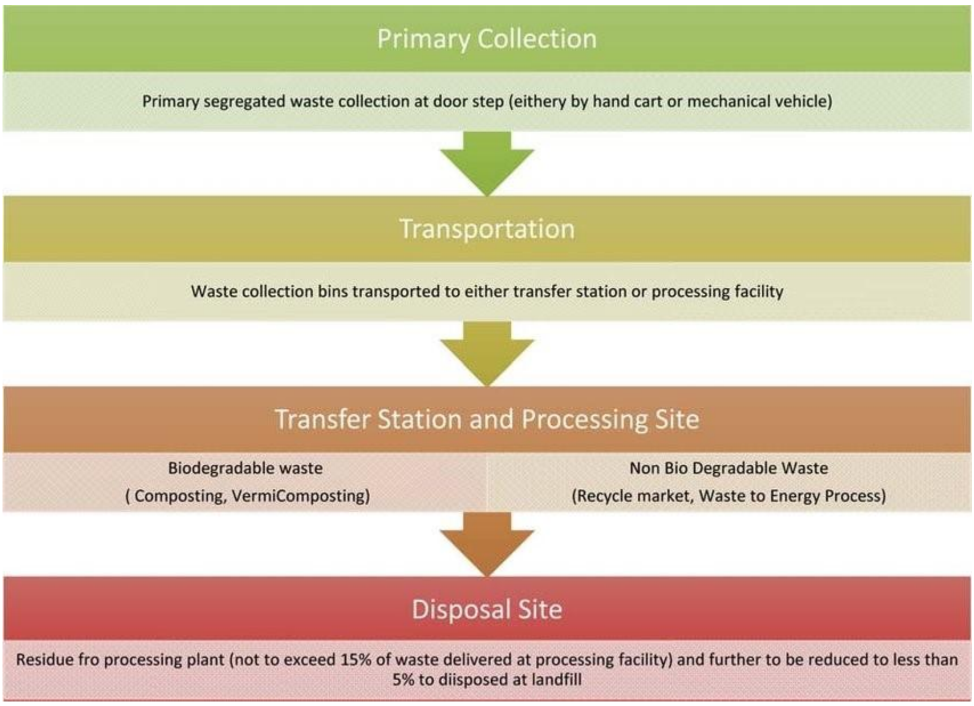
Table 1.1: Waste Volume Reduction Efficiency of Different WTE Methods

WTE Method	Volume Reduction (%)
Incineration	85–90%
Pyrolysis	70–80%
Gasification	75–85%
Landfilling	0%

Source: MNRE and industry sources

In terms of energy generation, incineration-based WTE plants can contribute significantly to the local power grid. This becomes particularly relevant in urban clusters that experience high energy demand. Cities like Delhi, Hyderabad, and Pune benefit from such plants, which feed electricity generated from waste directly into the grid.

Figure 1.2: Municipal Solid waste Value chain



Source: MNRE and own research

[3] https://www.unep.org/ietc/resources/publication/waste-energy-considerations-informed-decision-making

Economically, incineration projects can be cost-effective over the long term, particularly when externalities such as health costs from landfilling and the social cost of carbon emissions are taken into account. With proper planning, they can also become financially viable through tipping fees, power purchase agreements, carbon credits, and sale of recyclables extracted from incoming waste. Technological advancements in incineration have significantly enhanced the environmental performance of these plants. Modern incinerators are equipped with sophisticated air pollution control devices such as electrostatic precipitators, flue gas scrubbers, and baghouse filters, ensuring compliance with emission norms.

Table 1.2: Resource Recovery Potential in Incineration Plants

Resource Recovered	Potential Use
Bottom Ash	Road base material, bricks
Ferrous Metals	Steel recycling
Non-ferrous Metals	Electronics manufacturing

Source: Own research

In addition to their operational benefits, incineration plants can play an important role in fostering circular economy principles. The bottom ash generated from incineration can be processed and used in construction as aggregates or road base material, while ferrous and non-ferrous metals can be recovered and sold.

India has already developed a meaningful WtE base, with operational and under-construction projects spread across several states. The current operational status of WtE plants and the pipeline of projects under construction show that the sector is expanding, but still remains limited relative to the overall scale of waste generation. Currently, there exist 11 operational WtE facilities possessing an approximate design capacity to process ~14,200 tons per day (TPD) of waste and produce ~160 megawatts (MW) of electrical energy. Moreover, in excess of 10 projects, designed to manage 9,700 TPD of waste and yield between 130 and 140 MW, are currently in the implementation phase. The WtE processing mechanism also substantially diminishes the volume of waste relegated to landfill sites. Consequently, WtE is emerging as a practically viable and implementable solution within the Indian framework.

Table 1.3: Detail of Operational WtE plants in India (As on December 2024)

Sl. No.	State	Name of City	Designed Capacity (TPD)	Power Generation(MW)
1	AP	Guntur	1200	15
2	AP	Visakhapatnam	1200	15
3	Delhi	Ghazipur	1300	12
4	Delhi	Narela Bawana	2400	24
5	Delhi	Okhla	2000	21
6	Delhi	Tehkhand	2000	20
7	Haryana	Sonipat Cluster	800	8
8	MP	Jabalpur	600	11
9	Telangana	Hyderabad	2000	20
10	Maharashtra	PCMC	700	14
11	Gujarat	Jamnagar	650	7.5
12	MP	Rewa	350	6
13	Telangana	Hyderabad	1400	14
14	Gujarat	Ahmedabad	1000	15
Total			17,600	202

Source: MNRE and Lok Sabha Questionnaire

As per information available with MNRE , a total of 202MW of WTE plants are in operation in India as of December 2024 processing around 17,600 Tonnes per Day of waste.

Similarly, details of under-construction WTE plants are provided below for reference:

Table 1.4: Detail of under construction WTE plants in India (As of December 2024)

Sl. No.	State	Name of City	MSW (TPD)	Capacity (MW)
1	Gujarat	Ahmedabad	1000	15
2	Gujarat	Rajkot	1000	15
3	Gujarat	Vadodra	1000	15
4	Karnataka	Bengaluru	600	12
5	Maharashtra	Mumbai	600	5
6	Telengana	Hyderabad	1200	24
Total			6150	99

Source: MNRE and Lok Sabha Questionnaire

It is estimated that another 99MW of WTE powerplants are under construction having a processing facility of 6150Tonnes per Day , out of which Gujarat counts 45MW of WTE plants having a processing capacity of 3000TPD.

1.5. Overview of WTE plants as a solution

While thermal processing is associated with elevated capital expenditures, advanced technical requirements, and increased preparatory diligence, it enables urban local bodies (ULBs) to mitigate waste management challenges with a significantly reduced land footprint, rendering it an appropriate alternative for large, densely populated urban centers that face constraints in land availability and experience heightened levels of waste production(Kanhaiya Jee Gond & Dr. Mahendra Singh Khicher, 2024). In the context of thermal waste processing, the feedstock comprising potentially segregated waste, unsegregated waste, or Refuse Derived Fuel (RDF) derived from waste is subjected to thermal treatment.

Incineration, which entails the thorough combustion of municipal solid waste (MSW) possessing a calorific value exceeding 1500 kcal, or refuse-derived fuel (RDF), with the concomitant recovery of thermal energy to generate steam, subsequently utilized to produce electrical power via steam turbines (Levidow, 2016)[1].

Pyrolysis, a thermochemical process where heat facilitates the anaerobic decomposition of organic substances into combustible gaseous products (predominantly Methane, intricate hydrocarbons, Hydrogen, and Carbon Monoxide), in addition to various liquid and solid byproducts (Pandit, 2015)[2].

[1] Levidow, L. (2016). Beyond Incineration? Representing Gasification for Municipal Solid Waste (MSW) Treatment. *Dutch Crossing: Journal of Low Countries Studies*. https://isaconf.confex.com/isaconf/forum2016/webprogram/Paper76738.html

Gasification, a process wherein organic or fossil-derived materials undergo conversion into Carbon Monoxide, Hydrogen, and Carbon Dioxide under elevated thermal conditions (ranging from 500 to 1800°C) in the presence of a restricted quantity of Oxygen, typically referred to as Syngas at temperatures surpassing 900°C, in conjunction with traditional fuels such as coal for heat generation (Ayub et al., 2024).

Plasma Arc: The Plasma Arc Waste to Energy (PAWTE) technology represents an advanced method that transforms solid waste into synthetic gas (Syngas) and vitrified slag through the application of extremely high temperatures (exceeding 2000°C) generated by plasma. The produced Syngas has potential applications in electricity generation or fuel production, whereas the resultant slag may serve as a construction material or be subjected to landfilling (Sinha, 2019).

Of the various waste-to-energy (WtE) methodologies, incineration-based projects have emerged as the most prominent within the Indian context based on their ability to treat the mixed waste (Gelfand & Wong, 2000) . The inaugural WtE facility in India was established in Timarpur, Delhi, in 1987, utilizing technology sourced from Denmark; however, this facility ultimately succumbed to an array of challenges, including substantial variability in the characteristics of input waste, an inadequate calorific value of the waste for effective incineration, and an elevated proportion of inert materials, all of which are detrimental to the operational efficacy of incineration-based processing that necessitates both a high calorific value and a minimal percentage of inert waste.

[2] Pandit, A. R. (2015). Urban Waste-To-Energy by Pyrolysis Process. *International Journal of Research*, *2*(9), 669–673. https://journals.pen2print.org/index.php/ijr/article/download/2830/2716

In order to rectify this situation, it is essential to implement waste segregation practices, allowing the fraction of waste with a higher calorific value to be designated for incineration. Throughout the subsequent decade, endeavours to implement WtE technologies on a larger scale were largely thwarted, primarily due to their misalignment with the characteristics of municipal solid waste (MSW) that are prevalent in urban centers across India(Misra et al., 2018a) . In response to these challenges, the Department of Science and Technology (DST), Government of India, advocated for the conversion of the combustible fraction of MSW into Refuse Derived Fuel (RDF), thereby paving the way for a new phase of WtE facilities in India. Currently, the Solid Waste Management (SWM) Rules of 2016 in India prohibit the mass incineration of waste(Soni, 2019) and mandate that WtE plants operate exclusively utilizing either RDF or segregated/pre-processed mixed waste that possesses a calorific value exceeding 1500 Kcal/kg.

Given that a significant proportion of the available feedstock for WtE remains as mixed waste with calorific values falling below the 1500 Kcal/kg threshold, the processes of pre-processing, sorting, and enhancing the quality of the waste feed are rendered imperative for the operational success of WtE plants. Such methodologies encompass (i) the storage, blending, and preparation of mixed waste in designated pits for a duration of 10-15 days, and (ii) the employment of sorting and segregation apparatuses, including trommels, ballistic separators, shredders, and dryers. These strategies have proven effective in diminishing moisture content, augmenting homogeneity, and elevating the calorific value of the waste, thereby facilitating the operational viability of WtE plants. (Kumari et al., 2019).

The inaugural successfully functioning Waste-to-Energy (WtE) facility was established in Okhla in September 2012. Subsequently, numerous additional WtE facilities have been initiated and have commenced operations, notably in Ghazipur (2015), Jabalpur (2016), and Narela Bawana (2017). A task force established in 2014 by the Government of India evaluated the unexploited potential of WtE for municipal solid waste (MSW) processing within India and forecasted a prospective power generation capacity of 439 megawatts through the processing of an estimated 32,890 tons per day (TPD) of waste from WtE initiatives in the short term of 5 to 7 years. Furthermore, the findings of the task force recommended that urban areas with populations exceeding 2 million and generating more than 1,100 TPD of MSW were optimal for the establishment of independent WtE facilities, while urban centers with populations ranging from 1 to 2 million and producing over 500 TPD could effectively operate cluster-based WtE plants, supplemented by refuse-derived fuel (RDF) sourced from adjacent municipalities as feedstock. The significant benefits of WtE identified in this report encompassed the following:

- Waste minimization i.e., achieving the highest reduction in waste volume compared to other technologies
- Lower land requirement compared to other processing technologies
- Productive energy recovery and potentially viable business models through the sale of fuel and electricity.

Since that time, the integration of Waste-to-Energy (WtE) technologies has indeed accelerated.

1.6. Importance of structured decision making in selecting a WTE plants

In the Indian context, a significant proportion of Waste-to-Energy (WtE) processing facilities predominantly employ incineration techniques, wherein the direct combustion of Refuse-

Derived Fuel (RDF) or segregated/pre-processed mixed waste, possessing a calorific value exceeding 1500 Kcal/kg, is utilized to generate steam that subsequently facilitates electricity production. As previously articulated, WtE facilities are primarily optimized for larger scales and are particularly applicable in urban environments with populations exceeding one million.

The insights derived from the operational WtE facilities in India, concerning their scale and configuration, are succinctly encapsulated below.

- The optimal urban profile that fosters the establishment of WtE facilities is characterized by cities with populations surpassing one million, which can allocate a minimum of 500 Tons Per Day (TPD) of Municipal Solid Waste (MSW) on a dedicated basis for the operation of such facilities.

For the purposes of this research, projects with capacities exceeding 500 TPD or generating more than 7 Megawatts (MW) of power are under consideration. The Sonipat project, which has a capacity of 750 TPD and generates 8 MW, was developed in a clustered approach encompassing four Urban Local Bodies (ULBs) — Sonipat, Panipat, Samalkha, and Gannaur — to meet the requisite standard of 500 TPD and subsequently achieve both operational and financial viability.

Electricity generation from these facilities fluctuates between 1 and 1.5 MW for every 100 tons of waste processed. This variability is considerable, as the extent of energy production is influenced by a multitude of factors, including technological advancements, waste composition, and pre-treatment/segregation processes. A salient advantage of WtE facilities is their minimal land usage. A 500 TPD WtE facility (inclusive of pre-processing) necessitates approximately 5 acres to accommodate 500 TPD of waste (including pre-processing units), in contrast to the approximately 2.5 acres required for composting facilities of comparable size.

The financial outlay associated with operational projects is situated within the parameters of Rs. 15 – 25 Crores per Megawatt (MW) and Rs. 23 – 39 Crores per 100 Tons Per Day (TPD) capacity, excluding the expenditure related to land acquisition. Given the extensive diversity of technologies and configurations available for the pre-treatment of waste, there exists a significant disparity in project costs across different initiatives (Harford, 1976) . The elevated cost per MW for Waste-to-Energy (WtE) projects can also be ascribed to the incorporation of additional processing methodologies such as composting and Sanitary Land Fill (SLF), as exemplified in the cases of Narela-Bawana, Hyderabad, and Sonipat. The majority of WtE facilities have been conceptualized by Urban Local Bodies (ULBs) to accommodate mixed waste, thereby necessitating processes such as segregation, storage, blending, and homogenization for the production of Refuse-Derived Fuel (RDF), combustion, and the subsequent energy generation unit. This requirement is of paramount importance that ULBs must consider when designating land parcels for the establishment of WtE facilities.

Furthermore, it is crucial to strategize for a Sanitary Landfill, whether integrated within the project or managed separately, and to allocate land for such an entity in proximity to the WtE facility. Additionally, WtE projects are generally tendered with the objective of achieving a target Project Internal Rate of Return (IRR) in the range of 12-15% and an Equity IRR between 14-18%. However, it is imperative to acknowledge that the expectations regarding IRR fluctuate based on various project-specific factors (such as the capacity and financial robustness of counterparties, project risks, and structuring) as well as macroeconomic variables (including interest rates and the broader economic outlook).

Selecting an appropriate Waste-to-Energy (WTE) plant is a complex and multi-faceted process that involves environmental, economic, technical, operational and social considerations.

Structured decision making (SDM) plays a critical role in ensuring that the selection process is transparent, objective, and aligned with long-term sustainability goals. The following points highlight the importance of SDM in this context:

- **Multi-Criteria Evaluation:** SDM enables the integration of various quantitative and qualitative criteria—such as cost, energy efficiency, emissions, feedstock compatibility, and community acceptance—into a comprehensive decision-making framework. (Jankowski & Rinner, 2024).
- **Stakeholder Engagement:** Structured approaches encourage the involvement of key stakeholders, including government agencies, private investors, and local communities. This fosters consensus-building and increases the legitimacy of the selected solution.
- **Transparent and Repeatable Process:** A structured methodology provides a clear rationale for selecting one WTE technology over another, which is crucial for regulatory approval, funding justification, and public trust.
- **Adaptability to Local Conditions:** SDM facilitates the customization of solutions based on local waste composition, energy demands, regulatory frameworks, and socioeconomic conditions, leading to more effective and sustainable plant implementation.

In the present dissertation, four operational waste-to-energy (WtE) projects from specific Indian urban centers are examined in detail concerning the aforementioned parameters, employing the Analytical Hierarchy Process (AHP) decision-making methodology to ascertain which plant model constitutes a superior alternative for sustainability for Urban Local Bodies (ULBs) that are poised to implement such plants for their waste management practices.

1.7. Objectives of the thesis

The principal aim of this research is to establish a systematic decision-making framework for the assessment and selection of appropriate Waste-to-Energy (WTE) operational facilities employing mixed waste or Refuse-Derived Fuel (RDF) incineration methodologies within the Indian context, utilizing the Analytic Hierarchy Process (AHP). The investigation aspires to integrate a multitude of evaluative criteria—Economical, environmental, Regulatory, operational and socio-cultural factors—to assist policymakers, planners, and stakeholders in formulating informed, transparent, and sustainable decisions concerning the implementation of WTE plants. While addressing these critical parameters, a suitable risk assessment of the selected plants will also be considered under the selected critical parameters.

Specific aims of this research are:

- To identify and delineate essential criteria and sub-criteria that significantly impact the selection of WTE facilities in India.
- To implement the Analytic Hierarchy Process (AHP) for the allocation of relative weights to these criteria, predicated upon expert evaluations.
- To assess and rank alternative WTE projects utilizing the established priority weights.
- To illustrate the applicability of AHP in addressing intricate environmental decision-making challenges within the Indian waste management domain.

1.8. Scope of the Thesis

This research concentrates on the systematic assessment of Waste-to-Energy (WTE) facilities within the Indian framework, taking into account the India's distinctive waste attributes, regulatory landscape, and socio-economic factors. The parameters encompass:

- A thorough examination of operational WTE power generation facilities that utilize mixed waste, pertinent to urban and semi-urban environments in India.
- The discernment of decision-making criteria that are significant to Indian stakeholders, which encompass waste composition, financial implications, emission levels, land utilization, societal acceptance, and adherence to regulatory standards.
- The formulation and execution of an Analytic Hierarchy Process (AHP) model to assess and juxtapose selected WTE facilities for advanced analysis.
- The incorporation of expert insights (for instance, from industry professionals, academic scholars, and governmental representatives) to develop pairwise comparison matrices. A case-specific or theoretical application of the proposed framework to demonstrate its practical utility and prospective policy ramifications.

The scope is confined to the appraisal of operational WTE facilities utilizing mixed waste characteristics and refuse-derived fuel (RDF) incineration, thereby excluding other technological modalities.

While the empirical AHP model in this thesis is restricted to four operational incineration-based WtE plants (Jabalpur, Sonipat, Hyderabad and Tehkhand), this design choice might introduce a potential bias towards feasibility and sustainability. However, failed or discontinued initiatives such as Timarpur and the prolonged controversies around Okhla and Ghazipur are therefore not included as alternatives in the quantitative ranking exercise, because they do not provide a consistent data set across the full set of sustainability and risk criteria used in the AHP model. Instead, lessons from these projects are examined qualitatively in the literature review to contextualize and critically interpret the AHP findings.

CHAPTER 2
LITERATURE REVIEW

Chapter 2:
LITERATURE REVIEW

This literature review examines the evolution, technological pathways, and policy context of thermal waste-to-energy (WtE) systems, with a particular focus on their applicability in rapidly urbanizing, land-constrained settings. It synthesizes global and Indian experience on key thermal technologies such as incineration, gasification, pyrolysis, and plasma arc treatment, alongside their feedstock requirements, environmental performance, and operational challenges. In doing so, it situates WtE within broader debates on sustainable solid waste management, energy security, and urban environmental governance, while highlighting the conditions under which thermal treatment can complement, rather than undermine, waste reduction, segregation, and recycling objectives.

From a policy perspective, incineration-based WTE aligns with several national objectives. These include the Swachh Bharat Mission, National Electricity Policy, and India’s climate pledges under the Paris Agreement. However, the significance of incineration projects also hinges on addressing associated challenges. Public opposition, stemming from concerns over air pollution and health risks, remains a major hurdle. Transparent operation, third-party emissions monitoring, and community engagement are essential to gaining public trust.

Moreover, WTE plants in India often suffer from poor feedstock quality due to the lack of waste segregation at source. High moisture and organic content in Indian waste reduce the calorific value, affecting incineration efficiency. Another important factor in ensuring project success is institutional coordination. Multiple agencies—including urban local bodies, state pollution control boards, power distribution companies, and environmental ministries—need to work in a coordinated manner for smooth planning, execution, and monitoring of WTE projects.

The private sector also has a significant role to play. Many successful incineration-based WTE projects globally are developed and operated through Public-Private Partnerships (PPP). Encouraging more such collaborations can accelerate WTE deployment and ensure operational sustainability (Yu & Santoso, 2024).

International cooperation can further bolster the sector by facilitating technology transfer, access to climate finance, and benchmarking against global best practices. Countries like Sweden, Japan, and Singapore have demonstrated highly efficient and clean WTE operations, which India can emulate through knowledge exchange programs and joint ventures.

Incineration-based WTE projects are of high significance for India's urban future. They represent a pragmatic and scalable solution to the twin challenges of solid waste disposal and energy generation. When designed and managed responsibly, these projects can support environmental goals, reduce municipal expenditure, enhance urban livability, and contribute to national energy security. As India progresses toward a sustainable and inclusive urban future, incineration-based WTE systems will likely serve as critical infrastructure components in achieving these aspirations.

2.1. Policy, Regulatory, and Institutional Framework for WTE Projects in India

India's policy landscape for solid waste management and energy generation has evolved significantly over the past two decades. This chapter outlines the enabling environment for Waste to Energy (WTE) incineration projects, examining key policies, regulations, institutional roles, and financial mechanisms that impact their implementation.

National Solid Waste Management Policy Landscape

The overarching policy guiding WTE deployment is the Solid Waste Management Rules, 2016, notified under the Environment Protection Act, 1986. These rules mandate waste segregation at source, promote the use of waste for energy recovery, and encourage local authorities to adopt waste processing technologies.

Key provisions relevant to WTE include:

- Encouragement of waste processing through incineration and other technologies. Looking at the volumes of waste generated annually in India and fewer options availability, GOI has recommended for incineration technologies could be one of the alternatives for waste minimisation before it ends up in the landfills. It has directed the ULBs to explore several options to process the waste through partnership with private parties in the PPP mode and provided various financial incentives to co-opt such arrangements.
- Requirement for cities with populations over 1 million to set up processing plants. The policy has set out specifically targeting the cities and urban centres where populations cross 1 millions as it envisaged waste generation will be enough in these cities for establishment of WTE plants with a critical mass of waste input. Moreover, it advises the city administration to go for clusters centres encompassing both urban and rural

centres for waste collection and provide the same to the WTE power plants for processing.

Table 2.1: Timeline of Solid Waste Management Regulations in India

Year	Policy/Rule	Key Feature
2000	MSW Rules	First set of waste handling rules
2016	SWM Rules	Introduced WTE promotion and segregation norms
2020	Plastic Waste Rules	Linked with energy recovery

Source: own research and MNRE website

While policies such as the Solid Waste Management Rules, 2016, Swachh Bharat Mission-Urban 2.0 and various NGT directives provide a strong enabling narrative for Waste-to-Energy, their effectiveness on the ground is constrained by inconsistencies, weak enforcement and lack of accountability across institutions. Persistent gaps in source segregation, irregular tipping fee payments, delayed clearances and limited transparency in emissions monitoring indicate that formal provisions are not reliably translated into practice. In addition, the prevailing discourse often exhibits an overreliance on technological fixes, assuming that incineration-based plants will automatically deliver environmental and financial benefits even when underlying governance, contractual and operational conditions are not robust. This thesis therefore goes beyond identifying success factors at plant level to critically examine why WtE projects may underperform despite apparently strong policy support, by foregrounding risks linked to institutional capacity, regulatory oversight and stakeholder incentives in the criteria and analysis framework.

Institutional Framework and Roles

The institutional framework includes a variety of stakeholders:

- **Urban Local Bodies (ULBs):** Responsible for waste collection, segregation, and providing land for WTE facilities.

- **State Pollution Control Boards (SPCBs):** Grant environmental clearances and monitor emissions.
- **Ministry of Environment, Forest and Climate Change (MoEFCC):** Policy formulation and environmental oversight.
- **Ministry of Housing and Urban Affairs (MoHUA):** Supports project development under national urban missions.

2.2. Financial and Regulatory Incentives

To enhance the viability of WTE plants, multiple financial and regulatory incentives are available:

Viability Gap Funding (VGF):

VGF is provided under the Ministry of Finance's PPP scheme. Viability Gap Funding (VGF) plays a crucial role in enhancing the financial viability of Waste-to-Energy (WtE) plants by reducing upfront capital requirements and attracting private investment. This funding mechanism not only mitigates financial risks but also signals government commitment to project success, thereby fostering a more favorable investment climate. This support is particularly significant in regions where traditional financing options are limited, ensuring that WtE projects can be developed and sustained effectively.

Subsidies and Capital Grants:

The subsidies and capital grants are being offered by MoHUA and state governments. This support mechanism not only enhances financial viability but also fosters technological advancements, ultimately contributing to a more sustainable energy landscape. Furthermore, effective implementation of these subsidies requires careful design and coordination to maximize their impact and ensure alignment with broader environmental goals. The need for a comprehensive framework that integrates these subsidies with existing policies is essential for achieving long-term sustainability in the renewable energy sector. A well-structured subsidy framework can facilitate the transition to renewable energy while addressing the challenges posed by market distortions and environmental impacts.

Carbon Credits and Renewable Energy Certificates (RECs):

These are income streams for eligible projects. are essential components for enhancing the financial viability of waste-to-energy initiatives, providing additional revenue streams through emissions reduction and renewable energy generation. These mechanisms not only incentivize sustainable practices but also contribute to the broader goals of environmental conservation and climate change mitigation. The integration of carbon credits and Renewable Energy Certificates (RECs) can significantly improve the economic feasibility of WTE projects, aligning them with global sustainability objectives and regulatory frameworks (Raizada et al., 2006).

Priority Sector Lending:

It is recognized under infrastructure status for bank loans. It is essential to ensure that these initiatives receive necessary financial support, enabling sustainable development and enhancing the overall economic growth of the region. This approach not only fosters environmental sustainability but also addresses regional disparities in economic development, promoting a more balanced growth across different areas. Moreover, implementing effective financial strategies can significantly reduce regional disparities and promote balanced economic growth across various sectors. Such strategies are crucial for fostering equitable access to resources, ultimately leading to improved socio-economic conditions in underserved regions.

In particular, targeting investments in underdeveloped resource-rich regions can enhance the effectiveness of these financial strategies and contribute to sustainable development efforts. (Xinhua,2011)[4]

Table 2.2: Financial Incentives for WTE Projects in India

Type	Description
VGF	Up to 20% of project cost
REC Income	Issued for every MWh of energy generated
Tipping Fees	Paid by ULBs for every ton of waste processed
Tax Holidays	10-year income tax holiday under Sec 80-IA

Source: MNRE and own research

Public-Private Partnerships (PPP)

WTE projects are typically developed through PPP models, where private operators build, own, and operate plants for a fixed concession period. Successful PPPs require risk allocation, clear contractual agreements, and performance-based incentives.

[4] Xinhua, Z. (2011). Features and Functional Orientation of Underdeveloped Resource-rich Regions. *Resources Science*

Case Example: Okhla WTE Plant, Delhi

Developed under a Design-Build-Operate-Transfer (DBOT) model with a 25-year concession, the plant processes 1950 TPD of waste and generates 23 MW of electricity.

2.3. Regulatory Challenges and Bottlenecks

Addressing regulatory challenges is crucial for the successful development of Waste-to-Energy (WtE) projects in India, as these obstacles can hinder technological advancements and financial viability(Mehta et al., 2016).

While addressing regulatory challenges is often cited as essential for the success of Waste-to-Energy (WtE) projects in India, some argue that these regulations are necessary to ensure environmental protection and public health. Overly relaxed regulations could lead to subpar technologies being deployed, resulting in negative impacts on air and water quality. Furthermore, the focus should be on enhancing existing waste management practices rather than rushing WtE projects through regulatory loopholes. Instead of prioritizing regulatory easing, stakeholders should invest in comprehensive assessments and community engagement to ensure that any WtE initiatives align with sustainable development goals and truly benefit local populations. This approach may be slower but is ultimately more responsible and beneficial in the long run.

Despite the enabling framework, several challenges persist for WtE development in India such as :

- Delays in land acquisition and clearances
- Inconsistent tipping fee payments
- Lack of waste segregation affecting calorific value
- Litigation and public opposition due to environmental concerns

2.4. Role of International Frameworks and Financing

India's commitment to the Paris Agreement and the UN Sustainable Development Goals (SDGs) aligns with WTE projects that reduce methane emissions from landfills and substitute fossil fuels. International climate funds (e.g., GCF, GEF) and development banks (e.g., ADB, World Bank) have begun financing WTE projects in India.

Table 2.3: Alignment of WTE Projects with Global Goals

SDG Goal	WTE Contribution
SDG 7: Clean Energy	Electricity generation from non-fossil fuel sources
SDG 11: Sustainable Cities	Urban waste management infrastructure
SDG 13: Climate Action	GHG emissions reduction

Source: UN SDG report and authors analysis

The success of incineration-based WTE projects in India depends largely on the strength of policy enforcement, clarity in institutional roles, and availability of financial incentives. While the regulatory ecosystem has become more favorable, persistent bottlenecks need systemic intervention. A strong policy push, combined with community awareness, private sector engagement, and innovative financing, can unlock the full potential of WTE infrastructure in India.

2.5. The Emerging Model: Public-Private Partnership (PPP)

The success of Public-Private Partnership (PPP) models in Waste-to-Energy (WtE) plants in India is a multifaceted issue that involves various stakeholders, technological considerations, policy frameworks, and socio-environmental factors. This response provides a comprehensive analysis of the key factors contributing to the success of PPP models in WtE plants in India, supported by insights from relevant research papers.

2.5.1. Critical Success Factors for PPP in WtE Plants

Alignment of Stakeholder Interests

The success of PPP models in WtE projects heavily depends on the alignment of interests among stakeholders, including government agencies, private sector entities, and local communities. Research indicates that while public and private sectors share common perceptions of success factors, there are some differences in priorities (Ngullie et al., 2021). For instance, the private sector may prioritize financial returns, while the public sector may focus on environmental and social benefits. Ensuring that these interests are aligned through clear contractual frameworks and transparent communication is essential for the success of PPP projects (Kurnia Raharja et al., 2025).

Risk Management

PPP WtE projects are exposed to various risks, including financial, technical, environmental, and socio-political risks. Effective risk management is critical to mitigate these challenges. Advanced risk assessment models, such as the 2-Dimension Linguistic Environment and Cloud Model and Bayesian Analytics, have been recommended for better decision-making (Kurnia Raharja et al., 2025) . Additionally, differences in risk perceptions among stakeholders highlight the need for collaboration and transparency in managing these risks .

Technological Feasibility

The choice of technology for WtE plants is a critical success factor. Technologies such as anaerobic digestion, gasification, incineration, and landfill gas recovery are commonly used in India. However, the high organic content of municipal solid waste in India makes anaerobic digestion a more appropriate technology compared to incineration, which is widely used in developed countries(Alao et al., 2022). The feasibility of these technologies also depends on proper waste segregation and the heating value of the waste, which can be compromised if waste segregation is inadequate(Karmakar et al., 2023).

Policy and Regulatory Framework

Supportive policy and regulatory framework are essential for the success of PPP WtE projects. Policies such as the Swachh Bharat Mission and the National Policy on Biofuels have provided a foundation for WtE initiatives in India(Sati & Vats, 2024). However, the existing policy framework needs to be strengthened to address challenges such as high capital costs, operational inefficiencies, and the need for improved waste segregation at the source. Additionally, government guarantees and comprehensive risk allocation frameworks can help mitigate financial and market risks (Kurnia Raharja et al., 2025).

Stakeholder Engagement and Public-Private Collaboration

Effective stakeholder engagement is crucial for the success of PPP WtE projects. This includes collaboration between government agencies, private sector entities, and local communities. Cooperative environmental governance (CEG) has been identified as a key factor in efficient waste management and WtE generation in urban South Asia (Amin et al., 2023). Engaging local communities and addressing their concerns can help reduce public opposition, which is often a significant barrier to the success of WtE projects(Kurnia Raharja et al., 2025).

Financial Viability

Financial viability is a critical success factor for PPP WtE projects. High capital costs and revenue uncertainty are significant challenges in the implementation of WtE projects in India (Kurnia Raharja et al., 2025) (Karmakar et al., 2023). Government incentives, such as tax breaks and subsidies, can help attract private sector investment. Additionally, the economic feasibility of WtE initiatives depends on factors such as technological innovation, political will, and revenue generation from recovered materials (Chandra, 2023).

Environmental and Social Impact

The environmental and social impact of WtE plants is a critical consideration. While WtE plants can contribute to a circular economy by reducing waste and generating energy, they also raise concerns about air pollution and health risks . The environmental impact assessment (EIA) of WtE plants is essential to justify their necessity over conventional solid waste management strategies such as landfills(Karmakar et al., 2023). Additionally, the socio-environmental impact of WtE plants, including public perception and the role of informal waste sectors, needs to be carefully managed(Sati & Vats, 2024).

Case Studies and Best Practices

Successful case studies of PPP WtE projects in India, such as the Okhla WtE plant in Delhi and the Narela-Bawana plant, provide valuable insights into the implementation of WtE initiatives (Sati & Vats, 2024). These case studies highlight the importance of integrated waste management systems, stronger regulatory frameworks, and increased public-private partnerships to foster sustainable development.

2.5.2. Challenges and Opportunities

Waste Segregation and Management

Improving waste segregation at the source is a critical challenge for WtE plants in India. The high organic content of municipal solid waste in India makes it essential to implement effective waste segregation strategies to enhance the efficiency of WtE plants . Additionally, the role of the informal waste sector, including waste pickers, needs to be formalized to ensure the smooth operation of WtE plants (Pati & Agrawal, 2025)

Public Opposition and Awareness

Public opposition to WtE plants is often driven by concerns about air pollution and health risks. Addressing these concerns through public awareness campaigns and transparent communication is essential to reduce opposition and gain community acceptance (Kurnia Raharja et al., 2025) (Karmakar et al., 2023)

Technological Innovation and Adoption

The adoption of cutting-edge technologies, such as artificial intelligence (AI) and machine learning, can enhance the efficiency of WtE plants. AI can be used for route optimization, waste composition forecasting, and process parameter optimization for energy generation (Singh et al., 2024).However, the implementation of these technologies requires significant investment and technical expertise.

Circular Economy and Sustainability

The integration of circular economy principles into WtE initiatives is essential for sustainable waste management. The circular economy approach seeks to eliminate waste by promoting the reuse and recycling of materials. WtE plants can contribute to a circular economy by recovering energy and materials from waste, reducing the need for landfills, and promoting sustainable development (Tripathy et al., 2024) (Ikponmwosa Aiguobarueghian et al., 2024).

Policy Implementation and Regulatory Reforms

The success of PPP WtE projects in India also depends on the effective implementation of policies and regulatory reforms. Strengthening the policy framework to address challenges such as high capital costs, operational inefficiencies, and inadequate waste segregation is essential for the success of WtE initiatives (Sati & Vats, 2024).

The success of PPP models in WtE plants in India is contingent upon a combination of factors, including the alignment of stakeholder interests, effective risk management, technological feasibility, supportive policy frameworks, stakeholder engagement, financial viability, and environmental and social impact(Tripathy & Tyagi, 2019). Addressing these factors through integrated approaches, such as cooperative environmental governance, circular economy principles, and technological innovation, can enhance the success of PPP WtE projects in India(Patil & Laishram, 2016). Additionally, learning from successful case studies and best practices can provide valuable insights for policymakers and practitioners to optimize waste management and energy production in India.

2.5.3. Key Factors for Success of PPP WtE Plants in India

Several key success factors for adoption of PPP in WtE projects are provided below:

Table 2.4: Key Factors for Success of PPP WtE Plants in India

Factor	Description
Stakeholder Alignment	Alignment of interests among government, private sector, and local communities.
Risk Management	Effective management of financial, technical, environmental, and socio-political risks.
Technological Feasibility	Suitability of technologies such as anaerobic digestion for high organic waste.
Policy Framework	Supportive policies and regulations for WtE initiatives.
Stakeholder Engagement	Collaboration between government, private sector, and local communities.
Financial Viability	Government incentives and revenue generation from recovered materials.
Environmental Impact	Assessment of air pollution and health risks from WtE plants.
Circular Economy	Integration of circular economy principles for sustainable waste management.
Technological Innovation	Use of AI and machine learning for optimizing WtE plant operations.
Waste Segregation	Improving waste segregation at the source for efficient WtE operations.
Public Awareness	Addressing public concerns through awareness campaigns.

Source: Secondary research and author's analysis.

2.6. Comparative Analysis of Select Operational Incineration-Based WTE Plants in India

This chapter presents an in-depth comparative analysis of four selected Waste-to-Energy (WTE) incineration projects operating in India that are the main focus of our research and these are selected for further analysis through Analytical Hierarchy Process model. The four plants that are selected for the study are Jabalpur in Madhya Pradesh, Sonepat in Haryana, Hyderabad in Andhra Pradesh and Tehkhand in New Delhi.

2.6.1. Salient features of select operational WTE projects

For the research purpose, these plants are selected based on the waste type (mixed type of waste) with a minimum waste processing capacity of 500 tonnes per day. They either employ mass incineration technology or integrated with RDF combustion process so as to make the research technology agnostic. This consideration comes from the fact that in India, most of the Urban Local Bodies (ULBs) generate huge waste and are eager to employ such technologies that can process a large volume of waste with minimum percentage for landfilling disposal. To make the research independent of any particular geographical locations, selection of these plants is based on a pan India profile where the plants are under operation for at least 1 year and considerable data is available with secondary domains or regulatory filings.

Table 2.5: Basic features of selected WTE plants

Parameter	**WTE Plants**			
	Jabalpur	**Sonipat**	**Hyderabad**	**Tehkhand**
Technology type	Mass Incineration	Integrated Project including Collection and Transportation (C&T) (RDF based Incineration)	Integrated project including secondary transportation RDF based Incineration	RDF based Incinera tion
Waste type	Mixed	Mixed	Mixed	Mixed
Waste processed (TPD)	600	750	6000	2000
Power generated (MW)	11.5	8	24	25

Source: Secondary research and state regulatory commission's orders

Other operational parameters like land availability , project cost of these plants are provided below for information.

Table 2.6: Processing capacity and Project Cost of selected WTE plants

Parameter	Jabalpur	Sonipat	Hyderabad	Tehkhand
Land Available (Acres)	10	39	14	15
Project cost (Rs Crore)	178	200	468	460
Power generation (MW/100 TPD)	1.9	1	2	1.25
Project cost (Rs. cr. / MW)	~15.5	~25	19.5	~18.5
*Project cost (Rs. cr. /100 TPD)	29.6	26.6	39	23

Source: Secondary research, regulatory commission orders

*Project cost varies according to designed capacity WtE projects based on technology, scope, availability of water, suitability of land (soil strength), cost of power evacuation, and emission standards.

2.6.2. Project Structuring and bidding parameters of selected projects

Most operational WtE projects in Indian cities have been set up on Public-Private partnership (PPP) mode, where the developer is typically selected by the ULB through a competitive bidding process(van den Hurk et al., 2016). Key findings from operational projects on PPP implementation mode are summarized below.

These WtE projects have been structured in their concession agreement either with **Integrated** or **Processing-only** as scope (i.e) the project scope covers all intermediate steps from waste collection to disposal as an integrated way and complete responsibility falls on the project developers, or it can only process the waste as supplied by the ULBs based on a gate fee. In processing only scoping, ULBs have complete responsibility to provide the designed waste inputs to the wte plants.

In Integrated WtE projects at Narela-Bawana, Hyderabad, and Sonipat, the developer's scope covers waste collection & transportation, processing, and disposal of inert rejects in a sanitary landfill. Here, the selected developer is responsible for waste collection and transportation within an earmarked area (either covering the whole city or part of the city) apart from being responsible for setting up the processing and SLF.

In Processing-only WtE projects, the developer is not responsible for collection and transportation but only for handling and managing waste at the WtE facility while the ULB / authority is responsible for delivering a pre-committed quantity and quality of waste at the facility run by the operator. In many cases, a tipping fee will be provided by the ULB to the developer per tonne of waste provided by the ULB (Ummatin & Faria, 2021) .(Tipping fee is a fee that is paid by those entities that dispose off waste either at a processing facility or a landfill).

For instance, in WtE projects at Okhla, Ghazipur, Pimpri Chinchwad, Jabalpur and Tehkhand, the WtE developer is responsible only for waste processing and ensuring that residual waste to be sent to landfill does not exceed the target cap (typically 20%) set as per the Concession Agreement. Landfill operation is not in scope of the developer in these specific projects mentioned.

Project Type of select plants

Projects	**Scoping**
Sonipat and Hyderabad	Integrated operations
Jabalpur and Tehkhand	Processing only

Integrated WtE projects are typically conceptualized in cities where (i) waste generation is more than 500 TPD, (ii) waste collection / segregation practices are weak and (iii) pre-processing is needed to separate wet and dry waste (Kalogirou, 2024) .

2.6.3. Bid Variable in Concession Agreements

Preferred bid variable in integrated projects is Output based incentives (OBI)/ tipping fee/processing fee/tariff or combination of any of the two. In a processing only WtE PPP, the ULB takes the responsibility for providing a pre-specified quantity and quality of waste (Misra et al., 2018b) .The Preferred bid variable in processing projects is Output based incentives (OBI)/processing fee/tariff or combination of any of the two. In processing only there will not be any tipping fees but in some cases, the operator may give royalty to ULB for providing guaranteed quantum of acceptable waste as per the contractual obligations (Mendis et al., 2015) .The choice between integrated or processing only projects therefore is contingent on the ULB's waste segregation, collection, and transport infrastructure.

Most WtE projects have been bid competitively on PPP mode by respective ULBs or the competent authorities(Nayyer & Annamalai, 2024) . Although a multitude of Public-Private Partnership (PPP) formats are deemed acceptable, Waste-to-Energy (WtE) projects have predominantly been procured through a Design-Build-Finance-Operate-Transfer (DBFOT) or a Design-Build-Finance-Operate (DBFO) framework. The duration of WtE concessions typically exceeds 20 years, which corresponds with the operational lifespan of WtE facilities (surpassing 25 years), with the appointed developer customarily establishing a special purpose vehicle (SPV) for the execution of the project.

Given the technology-intensive nature of Waste-to-Energy (WtE) projects, it is imperative for a private developer possessing commendable sectoral credentials and pertinent prior experience to oversee the management of technology, construction, and operational risks. In the majority of WtE projects, the performance of private developers is subjected to rigorous monitoring and evaluation via a performance monitoring mechanism, which is intricately linked to their compensation; thus, corresponding incentives are awarded, or penalties imposed based on performance outcomes(Mohamed Salleh et al., 2022) . For example, numerous WtE projects stipulate (i) a designated timeframe for the completion of construction, (ii) adherence to emission standards consistent with those established by the Central Pollution Control Board or as delineated in the Concession Agreement, (iii) criteria for plant availability, and (iv) a limitation on the volume of residual waste disposed of in landfills.

Given the capital-intensive nature and operational complexities associated with Waste-to-Energy (WtE) projects, the economic feasibility of such initiatives necessitates supplementary financial assistance(De La Cruz & Bernal, 2024) .This support has traditionally been rendered through mechanisms such as Viability Gap Funding, which serves as a governmental grant aimed at alleviating the financial burden related to capital expenditures necessary for return on investment, or by establishing revenue certainty via a processing or tipping fee assessed per tonne of waste processed, alongside the income generated from energy production (Ery & Isrochmani, 2022).

Bid variable in WtE projects

In India, WtE projects are structured to be bid out using a variety of bid variables, most commonly with tariff-based bidding (Chen & Chiu, 2011) . Other approaches would depend upon ULB’s preference, financial prowess and infrastructure availability. Most of the ULBs prefer to go for tariff-based bidding approach as they are concerned about the sale of power that is being generated from the WtE projects and generally, they would like to save on power purchase cost. The thinking beyond this concept comes from the fact that the input material (waste) is already being supplied by the ULBs to the WtE developers.

Various bid variables are as follows-

1. **Tariff-based bidding:** Tariff (quoted as Rs/kilowatt hour [KWH]) is the price at which power is generated by the WtE. In this type of bid, other terms such as power generation and waste handling capacity, viability gap funding (VGF) available or tipping fee/processing fee payable are fixed and known in advance. The developer quoting the lowest tariff for selling power is selected and enters into a power purchase agreement (PPA) with the respective electricity distribution company (DISCOM). The Tehkhand WtE project in Delhi has been bid on this model without providing for a tipping fee. The State/ULB helps the developer in obtaining the approval of draft PPA and facilitates in obtaining the approval of levelized tariff for the project, along with the signing of PPA with DISCOM/ State Electricity Regulatory Commission (SERC). This kind of model is unique to India as the state distribution companies are bound to enter into long term agreement with power suppliers to alleviate the supply side risk arising out from the non-supply of power at a preferred rate. In case of WTE projects, the private developers would also like to get a buyer for a long term for the power produced from the facility. (McConnell, 2014).

2. **Processing/Tipping fee:** Tipping fee, quoted by the developer, as rupees/ton of waste received at WtE plant. Jabalpur and Bawana WtE projects have been bid based on processing/tipping fees as the bid variables and in addition to this, the developer gets its revenue from sale of power as well (H. Singh et al., 2011) . Tipping fee works as an additional revenue generation for the WtE developer along with the revenue it gets from selling the power to the local distribution company or outside. Tipping fees

act as a cushion for any revenue risks generated out of non-sale of power produced from the waste.

3. **Viability Gap funding (VGF):** Also referred to as grant-centric bidding, the bidder proposing the minimal viability gap grant payable by the governing authority is designated as the favoured bidder. The city of Patna is in the process of implementing a Waste-to-Energy (WtE) project, where the Viability Gap Funding (VGF) serves as a bid variable, concurrently allowing revenue from the sale of electricity to be accessible to the project developer(Maniar, 2013).

4. **Output-Based Incentive (OBI):** In the context of the OBI framework, it is required that bidders submit an extensive OBI amount that is payable per kilowatt-hour (KWH) of electricity generated. The OBI is typically set at a rate that exceeds the tariff authorized by the electricity regulatory authority for the sale of electricity. Revenue assessments are based on the sanctioned tariff that the Distribution Companies (DISCOMs) are mandated to pay for the electricity sold, whereas the remaining differential between the OBI and the tariff is reimbursed by the Urban Local Body (ULB). The portion of the OBI that is attributable to the ULB is modified in accordance with prevailing inflationary trends.

   This methodology delineates a direct relationship between the disbursements from Urban Local Bodies (ULB) and the actual production of energy, thereby incentivizing the developer to augment power generation outputs. The Waste-to-Energy (WtE) initiative situated within the Sonipat cluster is being acquired under this framework, which alleviates uncertainties for the developer concerning tariff evaluations by the regulatory authority, as the disparity is assured and financed by the ULB. The tariff is uniform over a duration of 20 years, remaining unchanged without any variances. A significant advantage of the Outcome-Based Incentive (OBI) framework is that the developer secures revenue from electricity sales that surpass the standardized tariff, thus enabling the coverage of operational expenses and assuring the long-term sustainability of the projects (Garg & Misra, 2023) . It is essential to elucidate that the tariff may not exceed the OBI, as the tariff regulated by the Central Electricity Regulatory Commission (CERC) is made available to bidders during the tendering process; should the tariff surpass this threshold, the ULB is not compelled to make any payments to the developer, who will derive revenues solely from the sale of electricity to Distribution Companies (DISCOMs).

The OBI framework thus provides recompense for expenditures related to power generation, encompassing the costs associated with collection, transportation, and profit margins. In contrast, tariff-based bidding incorporates solely the production costs of electricity and corresponding profit margins. Tariff-based bidding proves efficacious when there is a clear regulatory framework and the DISCOMs exhibit an inclination to support the arrangement. The OBI model functions to alleviate tariff-related risks for an operator by necessitating that the ULB addresses the differential costs. In circumstances where VGF is allocated, it must be determined through competitive processes in alignment with PPP policy, thereby establishing it as the implicit bidding variable. As a result, the bidding variable must possess contextual relevance and should be finalized by considering project-specific and ULB-specific factors during the preparatory phase of the project.

2.6.4. Case of Pimpri-Chinchwad Municipal Corporation

Given the reliance on the commercialization of electrical energy, Waste-to-Energy (WtE) initiatives are profoundly influenced by the fluctuations associated with tariff approvals by the electricity regulatory authority, coupled with the financial and counterparty risks that emanate from the electricity Distribution Companies (DISCOM), with whom a Power Purchase Agreement (PPA) is established. In a significant deviation from standard practices, the Pimpri-Chinchwad Municipal Corporation (PCMC) invited proposals for their WtE initiative predicated on a tipping fee or processing fee as the variable component, while simultaneously ensuring a committed viability gap funding (VGF) and the acquisition of power at a fixed tariff of approximately INR 5 per kilowatt-hour (KWH) for its internal utilization. In this manner, the endeavor proficiently dissociated the WtE project from the imperative of interfacing with numerous stakeholders, including the Urban Local Body (ULB), DISCOM, and the Electricity Regulatory Commission, thereby streamlining the process and mitigating risks related to tariff fixation and the attainment of requisite approvals(Chatrath, 2017).

Table 2.7: WtE scope, implementation mode and bid variable for select operational projects

Parameter	Tehkhand	Sonipat	Jabalpur	Hyderabad
Project scope	Processing, Disposal	Collection, Transportation, Processing & Disposal	Processing, Disposal	Integrated - secondary transportation, pre- processing, disposal
Implementation mode	PPP-DBFOT	PPP-DBFOT	PPP-DBFOT	PPP-DBFOT
Capacity (Waste TPD)	2000	750	600	6000 (Mixed waste) & 1200 RDF is recoverable
Concession period	25 years	22 years	20 years	25 years
Duration operational	1 year	2 years	7 years	3 years
Bid variable	Tariff	OBI	Processing Fee	Tipping Fee + Levelized Tariff at Rs 7.84 per

				unit
PPA Tariff (per KWH)	Rs. 5.13 (Levelized)	Rs. 6.84	Rs. 6.39	Rs.7.84
Tariff escalation % YoY	Levelized	Levelized	Levelized	Levelized
Processing / Tipping fee	No tipping fees	OBI Rs. 3.44 / KWH power Rs. 333 per tonne (4% YoY escalation)	Not available	Rs. 1,400 Per tonne
Land Lease cost	Yr. 1-12: Rs. 25 Lakh/acre Yr. 13-25: Rs. 30 Lakh/ acre	Rs. 4000 per acre per annum	Not available	Not available
Royalty Paid by Operator	(No Royalty being paid)	(No Royalty being paid)	~ Rs. 20.7 per tonne	(No Royalty being paid)
Cost for Disposal of Inert	~Rs 350 per tonne	Covered in the project cost	Not Applicable	Rs 350 to 400 per tonne

Source: Secondary research, Interactions with ULBs / developers

2.7. WTE financial sustainability Vis-à-vis ULB options

Waste-to-Energy (WtE) programs are distinguished by significant upfront capital investments and often face substantial unpredictability concerning the actualization of revenue derived from electricity generation, which is dependent on the imperative to negotiate a Power Purchase Agreement (PPA) with a relevant counterparty, specifically the Distribution Company (DISCOM), alongside the necessity for obtaining tariff authorization from the electricity regulatory body.

Consequently, the formulation and organization of a financially sustainable Waste-to-Energy (WtE) initiative require a comprehensive examination of the alternatives accessible to the Urban Local Body (ULB), in conjunction with proactive collaboration with the electricity Distribution Company (DISCOM) and the electricity regulatory authority throughout the preparatory stage of the initiative. From a financial standpoint, the economic viability of the undertaking is shaped by three pivotal factors.

First, the allocation of Viability Gap Funding functions to mitigate the imperative for the recoupment of project expenditures via revenue generation (which must be secured by the developer through an amalgamation of equity and debt financing). Second, the revenues derived from the commercialization of electricity generated from the processed waste. Third, ancillary revenue streams, such as tipping or processing fees, are available to the project. Collectively, these three mechanisms are utilized in varying degrees to augment the financial viability of the project.

2.7.1. Viability Gap Funding (VGF) grants

The Viability Gap Fund (VGF) grants function as a pivotal mechanism for augmenting the financial viability and overall feasibility of Waste-to-Energy (WtE) projects. Numerous WtE initiatives, including those situated in Tehkhand, Sonipat, and Jabalpur, have reaped varying degrees of advantage from the allocations of VGF. In particular, the Tehkhand initiative was conferred a VGF allocation totaling Rs. 105 Crores (which represents 23% of the aggregate project expenditure), while Sonipat and Okhla received VGF contributions of 19.8% and 2.9% of their respective project outlays. The availability of VGF serves as a proficient de-risking strategy and is often perceived as a testament to the commitment of the concessioning authority and the government towards the effective realization of the project.

2.7.2. Revenue from sale of power:

One of the primary avenues for generating revenue within Waste-to-Energy (WtE) initiatives is the commercial exchange of electricity with Distribution Companies (DISCOMs). The electricity produced can be transacted to utility organizations via Power Purchase Agreements (PPAs) or designated to the Urban Local Body (ULB) as a captive consumer, thereby creating revenue based on the electricity contributed to the grid. The tariff levels available, in conjunction with the assurance and reliability concerning the realization of this revenue stream, are critical for the economic sustainability of WtE projects. A scrutiny of operational projects in India reveals that the tariff rates for WtE endeavours have varied between Rs. 5 per KWH and Rs. 7.84 per KWH. This fluctuation highlights the diversity among projects not only in terms of technological and waste characteristics but also in structural aspects, which encompass the provision of Viability Gap Funding (VGF) and the degree of supplementary revenue sources such as processing or tipping fees, as regulatory commissions consider these elements when assessing and/or approving the tariff for electricity sales.

2.7.3. Revenue from processing fee/tipping fee

A multitude of Waste-to-Energy (WtE) initiatives have sought to establish processing fees or tipping fees in order to augment the financial resources available for WtE projects. The tipping fee represents a crucial component in projects that include solely collection and transportation functions. For instance, in the case of Narela-Bawana, Delhi, where both collection and transportation fall within the project's parameters, the tipping fee is designated at Rs. 1950 per tonne; conversely, in Pimpri Chinchwad, where the project is confined to processing activities, the tipping fee amounts to Rs. 500 per tonne. This fee is typically allocated from the overarching budget of the Urban Local Body (ULB).

2.7.4. Other revenue streams

WtE initiatives frequently yield by-products as a matter of course. For example, the ash or residues produced as a result of combustion possess prospective applications in the realm of construction materials, the development of road infrastructure, or as a supplementary component in the manufacture of cement. Ash-derived bricks hold commercial viability in the marketplace. WtE initiatives that contribute to the mitigation of greenhouse gas emissions qualify for carbon credits through the Clean Development Mechanism (CDM) framework. Moreover, WtE projects have the capacity to generate Renewable Energy Certificates (RECs), which can be marketed to organizations aiming to fulfill renewable energy objectives or sustainability initiatives. Certain projects, such as Timarpur Okhla, have successfully obtained carbon credits.

In scenarios where only models are processed, the entirety of the associated costs will be encapsulated within the tariff; conversely, in the context of integrated projects, additional components of waste management, such as collection and transportation (C&T) and disposal, are linked to tipping fees that fluctuate based on the specifics of the projects. Notwithstanding, a substantial proportion of the revenue accrued by Waste-to-Energy (WtE) facilities—exceeding 95%—for project developers operating under Public-Private Partnership (PPP) frameworks is derived from processing or tipping fees in conjunction with the sale of generated power.

Table 2.8: Financing mix and revenue drivers for select WtE projects

Parameter	Tehkhand	Sonipat	Jabalpur
Capacity (TPD)	2,000	750	600
Project Cost (Rs. cr.)	460	200	178
VGF (Rs. cr.) (% of project cost)	105 Cr. (23%)	39.6 Cr. (19.8%)	No VGF
Private (Rs. cr.) (% of project cost)	355 (73%)	160.4 (80.2%)	544 (100%)
Sale of Power (Rs./KWH)	5.13*	6.84*	6.39*
Tipping/Processing fee (Rs./ton)	No tipping fee	333	Not available
Sale of by-products (Rs./ton)	Not Applicable	Not Applicable	Not Applicable

Source: Secondary research

* Levelized Tariff. ** BSES Rajdhani Power Limited (BRPL) (60 MUs): Rs. 2.49 Per unit with 2% escalation for 1-10 Years, & 1% for 11-25 Years; TPDDL (6 MW – Long Term Open Access (LTOA)) and Rs. 5.83 Per unit (Levelized).

In consideration of the expansive breadth and complex characteristics of Waste-to-Energy (WtE) initiatives, Urban Local Bodies (ULBs) are required to devote significant attention towards the systematic organization of projects in a manner that comprehensively alleviates financial risks while concurrently ensuring a considerable level of revenue assurance and transparency. Preliminary consultations involving a heterogeneous spectrum of stakeholders, inclusive of Distribution Companies (DISCOMs) and regulatory authorities, along with market engagement discussions with prospective investors and debt financiers, should constitute a critical element in the project structuring phase to promote reliability and predictability during the bidding process. The ensuing section articulates vital structuring considerations and contextual factors imperative for the proficient preparation, implementation, and management of WtE projects.

2.8. Critical success factors for WtE sustainability

While financial sustainability is one of the major critical factor for the WtE developers there are other considerations that should not be ignored while selecting a WtE project. Critical considerations for preparing and structuring bankable WtE projects are summarized below:

2.8.1. Waste Assurance and Critical Size of Plant

The currently operational Waste-to-Energy (WtE) initiatives substantiate the findings articulated by the Government of India Taskforce regarding the necessity for a minimum threshold scale for WtE projects to achieve financial and operational sustainability. An input waste quantity of 500 tonnes per day (TPD) or greater appears to delineate a critical minimum threshold. Urban centers with populations exceeding one million or clusters of urban areas with a combined population of one million or more seem to represent viable candidates for the implementation of WtE projects (Linzner & Lange, 2013) . The Urban Local Body (ULB) or the corresponding urban region must assure a consistent supply of waste for the successful execution of the project. Fluctuations in the composition of waste, including variations in moisture content, calorific value, and the presence of contaminants, can significantly influence the efficacy and performance of the waste conversion methodologies. (Namuli et al., 2013).

The majority of functioning facilities seem to have successfully secured and processed the requisite threshold quantity of waste and have developed the capacity to render the waste suitable (in terms of required quality) to maintain ongoing operations. Among the more recent undertakings, Jabalpur has inaugurated a WtE project with a designed capacity of 600 TPD; however, its suboptimal performance regarding waste availability (projected to be less than 400 TPD) has adversely affected both the operational and financial viability of the initiative(Cucchiella et al., 2016).

2.8.2. Ease of Land and Sanitary Landfill Availability

In the context of any waste processing initiative, the provision of encumbrance-free land, inclusive of land title or leasehold rights, alongside essential infrastructural facilities, while complying with permissible limits established by regulatory authorities concerning habitation, aquatic ecosystems, airports, etc., for the entire duration of the project, constitutes a critical prerequisite for Waste-to-Energy (WtE) projects. Should the responsibilities of the operator encompass the management of residual waste, it is imperative that land designated for the establishment and operation of such facilities, which includes the development of an ash processing facility and a disposal site, such as a landfill, is allocated and made available in advance. (Wang & Zhang, 2017).

The spatial requirements for WtE projects are to be approximated at around 1 acre for the management of 100 tons per day (TPD) of waste. For capacities up to 10 megawatts per 1000 TPD, the land requirement can be assessed at 1 acre per 100 TPD. Beyond the threshold of 10 acres or 1000 TPD, the land requirement is anticipated to be less than the established rule of thumb.

The availability of land has posed significant challenges even for projects that are currently operational. The Tehkhand project, designed for 2000 TPD, was envisioned on a tract of 15 acres with an annual lease rental of 25 lakh per acre for an initial duration of 12 years. Although this arrangement does not strictly conform to the 1 acre per 100 TPD standard, the availability of land is expected to be adequate, taking into account economies of scale. In Ghazipur, a plant with a capacity of 1300 TPD has been proposed on a severely constrained land parcel of 5.7 acres, with an annual lease cost of Rs. 4080 per acre. This scenario results in elevated civil work costs relative to industry peers, attributable to the heightened automation required for optimizing waste handling efficiency(Themelis, 2023).

2.8.3. Timely Approvals and Compliance to standards

Waste-to-Energy (WtE) initiatives that involve Sanitary Landfills necessitate obtaining Environmental Clearance (EC) along with various approvals from regulatory bodies at local, regional, and national echelons (Y. Wang et al., 2022).The social ramifications of such projects are encapsulated within the concluding report of the project's EC. The process of obtaining these approvals is protracted, and any delays in acquisition can be mitigated through support from Urban Local Bodies (ULBs) or state authorities. ULBs are mandated to adhere to prescribed standards for air emissions and wastewater discharge quality in accordance with the norms set by the Central Pollution Control Board (CPCB) as well as international standards(Tan et al., 2014).

Before June 2017, EC was a prerequisite for all WtE facilities, typically requiring a duration of 1 to 2 years for procurement. This stipulation has since been relaxed, such that EC is now only mandated for projects with a capacity exceeding 25 MW or those developed in conjunction with a Sanitary Landfill (SLF). While this differential requirement is somewhat advantageous for independent WtE initiatives, it concurrently introduces a risk that ULBs may proceed to prepare and implement WtE projects without adequately addressing the requisite capacities for sanitary landfills.

The management and regulation of emissions to meet stipulated standards are influenced by the variability in the characteristics of the waste received. The developer, who typically assumes this risk, must establish a design and system capable of accommodating a broad spectrum of variations in waste quality and characteristics. The installation of flue-gas treatment systems and continuous emission monitoring systems (CEMS) to ensure compliance with emission norms that align with national standards—which are progressively harmonized with global best practices—should be regarded as an obligatory requirement *("Flue Gas Desulfurization Systems," 2025)*.

Waste-to-Energy projects frequently encounter resistance from local communities, primarily due to apprehensions regarding health and environmental hazards. Gaining public acceptance is vital for the effective execution of WtE projects, and it necessitates community engagement, education, and transparency to adequately address concerns, foster trust, and garner support from relevant stakeholders(Y. Wang et al., 2022).

2.8.4. Timely Government Assistance and Revenue Commitments

Waste-to-Energy (WtE) projects necessitate considerable initial capital investment; owing to a historical precedent of project failures and the ambiguity surrounding revenue streams, financial institutions persist in perceiving WtE projects as ventures fraught with high risk. Consequently, the demonstration of robust governmental commitment—manifested through mechanisms such as Viability Gap Funding (VGF) in instances of diminished financial viability, alongside other analogous initiatives—becomes pivotal to the financial viability of these projects.

In addition to the availability of land and requisite infrastructure, a definitive commitment regarding the provision of waste, coupled with assurances for facilitating the acquisition of essential approvals (particularly concerning environmental clearances and associated issues), is crucial; furthermore, guarantees pertaining to the punctuality of payments are integral to enhancing project bankability.

A preliminary Power Purchase Agreement (PPA), delineating the stipulations governing the sale of electricity—including pricing, contract duration, delivery conditions, and payment modalities—should be incorporated within the bid documentation, subsequent to reaching an accord with the Distribution Company (DISCOM). The execution of a PPA must be contingent upon the prompt completion of feasibility analyses, selection of technology, engineering design, environmental evaluations, and the attainment of requisite permits and approvals.

The following three aspects can contribute substantially to the success or failure of a project:

Availability of Viability Gap funding:

The provision of Viability Gap Funds for Waste-to-Energy initiatives assists in diminishing the requisite effective return-generating capital (both equity and debt) and serves as a direct mechanism to enhance project viability. Furthermore, this initiative conveys a robust governmental commitment to the project from the perspective of potential investors. The Tehkhand and Sonipat projects derived approximately 23% of their total project expenditures from Viability Gap Funds, thereby augmenting their bankability.

Revenue assurance:

Power purchase agreements (whether established with Distribution Companies or Urban Local Bodies) necessitate a foundation of unequivocal tariff certainty, along with well-defined processes and timelines for regulatory endorsement. In instances where it is practicable, the assurance of power off-take enhances the efficacy of the contracting framework. Recent initiatives, such as those in the Pimpri-Chinchwad Municipal Corporation, have witnessed Urban Local Bodies, as opposed to Distribution Companies, step forward to offer off-take commitments and tariff certainty, representing a noteworthy advancement with potential for broader application. In the Tehkhand Waste-to-Energy project, both the signing of the Power Purchase Agreement and the determination of tariff were executed expeditiously, thereby facilitating the unhindered construction and commissioning of the project.

Payment security from ULBs:

The implementation of escrow mechanisms, wherein certain identifiable revenue streams (such as property taxes) are specifically allocated for the disbursement of processing or tipping fees, can significantly enhance payment assurance for developers. A majority of operational projects have been afforded various forms of payment guarantees.

2.8.5. Project Accountability: Incentives based on performance

Ultimately, the attainment of effective operational outcomes is contingent upon the formulation of pragmatic yet efficient linkages between compensation incentives and penalties, as they pertain to performance metrics and adherence to contractual obligations by all participating entities. From the standpoint of the developer, concession agreements must articulate clear objectives, which include (i) timelines for the initiation of projects, (ii) restrictions on the volume of residual and inert waste allocated to landfills, and (iii) compliance with air emission and water/wastewater discharge standards as prescribed in the concession agreement (CA).

In a similar vein, the obligations of Urban Local Bodies (ULBs) consist of (i) the provision of a predetermined quantity and quality of waste, (ii) the guarantee of designated land and infrastructure availability, and (iii) the adherence to financial covenants, which encompass viability gap funds, revenue assurance, and payment security.

2.8.6. Case Study: Sonipat Cluster Model

The Sonipat Waste-to-Energy (WtE) initiative represents a cluster-based, integrated waste management endeavor that encompasses four Urban Local Bodies (ULBs) situated in the state of Haryana, specifically Sonipat, Panipat, Samalkha, and Gannaur. The waste generation within these four ULBs is projected to be approximately 700-750 Tons Per Day (TPD). Given that Sonipat's own waste generation was recorded at only 300-350 TPD, which falls below the requisite threshold of 500 TPD necessary for a sustainable WtE project, neighboring municipalities within a 50-kilometer radius were amalgamated to ensure a sufficient waste supply for the WtE project.

Formulated in 2017 and tendered under a Public-Private Partnership (PPP) Design, Build, Finance, Operate, and Transfer (DBFOT) framework with a concession period spanning 20 years, the Sonipat WtE project was conferred in August 2019 and became operational in August 2021. Currently, the facility operates at its planned capacity of 700-750 TPD, generating between 7 to 8 Megawatts (MW) of energy.

M/s JBM Environment Management Private Limited was identified as the successful bidder and has since developed and is managing the facility. The variable in the bidding process for the project was the Operating Benefit Incentive (OBI) payable per Kilowatt Hour (KWH) of electricity generated. The project's scope encompasses the collection and transportation of waste from all four ULBs, including the establishment and operation of transfer stations along the route to the WtE plant located in Murthal, Sonipat.

The WtE project functions as an integrated facility where the operator is responsible for the segregation of mixed waste, utilizing the combustible dry waste fraction as Refuse-Derived Fuel (RDF) for incineration within the WtE unit, while the wet waste is directed towards composting. Additionally, the development and management of the Sanitary Landfill (SLF) falls within the purview of the developer's responsibilities.

Project Snapshot

Technology type	**RDF based Incineration**
Waste type	Mixed
Design capacity	750 TPD
RDF generated	375 - 400 TPD
Power generated	8 MW
Land available	39 Acres (19 Acres for WtE + 20 acres for SLF)
Project cost	Rs 200 Cr. | ~ Rs 25 Cr./MW | Rs. 26.6 Cr./100 TPD
Power generation	2 MW/100 TPD of RDF
Project scope	Collection, Transportation, Processing & Disposal
Implementation mode	PPP-DBFOT
Concession period	20 years
Duration operational	2 years
Bid variable	OBI (Output-Based Incentive)
Land lease cost	Rs 4000/Acre per annum
VGF Rs. cr. (% of project cost)	Rs 39.6 Cr. (22.5% of estimated project cost Rs. 176 Cr.)
Private Rs. cr. (% of project cost)	Rs 160.4 Cr (80%)
Sale of Power Rs./KWH	Rs 6.84 per unit (Levelized tariff for 20 years)
Processing fee	Rs 3.44 Per Unit Power (Differential amount of OBI, i.e. Total price quoted – Levelized Tariff) Rs 333 per Ton (4% YoY escalation on both the fees)
Reported revenue Rs. cr. (Fin. year)	Rs 60 Cr

Source: Interactions with ULBs / developers, KPMG report and authors' analysis

Replicable project features of Sonipat Cluster Model

Rigor in project preparation: The project was conceived by the Urban Development Department of Haryana and was substantiated by a comprehensive Technical Feasibility Report, which included an exhaustive analysis of the project area (ULB cluster), encompassing waste generation and projection trends over a design horizon of 20 years, as well as variations in waste characteristics and associated parameters. Additionally, the report outlined the infrastructural necessities for the project, detailing the number of collection and transport (C&T) vehicles required, the establishment of transfer stations, and a preliminary cost estimation for the project's execution.

Land availability: Land that was free of encumbrances was identified prior to the bidding process for the project, and the Environmental Clearance (EC) for the initiative was concurrently initiated by the Urban Local Bodies (ULBs) Department.

Balanced risk-sharing and payment security: To ensure equitable risk-sharing between the ULB and the Developer, a levelized tariff was determined and communicated to bidders prior to the submission of bids, while the draft Power Purchase Agreement (PPA) received prior approval from the Haryana Electricity Regulatory Commission (HERC) before the bid submission. An Escrow account was established for payments to the Developer, incorporating a provision to maintain three months of advance operational costs within the escrow to address any potential delays in payment from the ULB.

State Government commitment and support to facilitate collaboration among multiple ULBs for the development of a cluster-based project: The project was executed under a Public-Private Partnership (PPP) framework, employing an open tendering process to ensure participation from all qualified entities. The bid documents were meticulously structured and evaluated from a legal standpoint, culminating in a Tripartite Agreement signed by the Department of Urban Local Bodies, Haryana (acting as project administrator), the ULBs, and the Developer. Furthermore, the Department of ULBs facilitated the creation of an inter-ULB agreement among the participating ULBs, delineating the responsibilities of each ULB and conferring rights to the project developer regarding the waste collected from these ULBs. Absent the intervention of the state department, the realization of this project would likely have been unattainable.

OBI as bid variable to optimize waste processing: The project's bid variable was established as OBI per KWH generated, which effectively links ULB payments to actual energy production, thereby incentivizing the Developer to enhance power generation and mitigating uncertainty for the Developer concerning tariff determination by the Regulator, as the differential is guaranteed and funded by the ULB.

Cluster-based projects encounter shared challenges, including land accessibility and coordination among ULBs. In this initiative, Sonipat served as the lead ULB, entrusted with the provision of land, waste collection, and financial remuneration to the operator. Each ULB appointed a designated individual to manage the day-to-day operations of the project. This model possesses the potential for replication in other regions of various States where individual ULBs may not generate sufficient waste (a minimum of 500 TPD) to sustain a waste-to-energy (WtE) facility, yet where land is available and ULBs are situated within a 40-50 km radius of one another, thereby enabling collaborative efforts to establish a sustainable project. The cluster model can effectively divert waste from landfills, consequently conserving land resources.

CHAPTER 3

RESEARCH METHODOLGY

Chapter 3:
RESEARCH METHODOLOGY

3.1. AHP Model

The Analytic Hierarchy Process (AHP) is a structured decision-making methodology developed by Thomas L. Saaty in the 1970s. It is widely used for complex decision problems that involve multiple, often conflicting criteria(Rajput & Dr.A.C.Shukla, 2012b). AHP helps decision-makers arrive at a rational and justifiable choice by breaking down the decision problem into a hierarchy of more manageable sub-problems (Terzi, 2019).

At its core, AHP involves the following key steps:

- **Problem Structuring:** The decision problem is decomposed into a hierarchical structure consisting of the overall goal at the top, followed by multiple levels of criteria, sub-criteria (if necessary), and alternative options at the bottom.
- **Pairwise Comparisons:** Decision-makers conduct pairwise comparisons of the elements at each level of the hierarchy with respect to their importance or contribution to the element above them. These comparisons are usually made using a standardized 1–9 scale to reflect the intensity of preference.
- **Priority Weight Calculation:** The pairwise comparison matrices are used to derive relative weights (or priorities) for the elements, typically through eigenvalue computation or approximation methods.
- **Consistency Check:** AHP includes a mechanism to evaluate the consistency of the decision-maker's judgments, ensuring logical coherence throughout the process. A consistency ratio (CR) is calculated, and values under 0.1 are generally considered acceptable.

- **Synthesis and Ranking:** Finally, the priorities of all criteria and alternatives are aggregated to determine an overall ranking of the decision alternatives, leading to a recommended choice.

AHP is especially useful in the context of Waste-to-Energy (WTE) plant selection because it accommodates both quantitative data (e.g., cost, energy output) and qualitative judgments (e.g., social acceptability, environmental impact)(Delmonico et al., 2018). Its flexibility and logical rigor make it a preferred tool in multi-criteria decision analysis (MCDA) for environmental and infrastructure planning(Tapia et al., 2023).

The Analytic Hierarchy Process (AHP) has been widely adopted in diverse fields of research around the world due to its ability to handle complex decision-making scenarios involving multiple criteria. Its flexibility, ease of implementation, and structured approach make it a preferred choice across sectors such as energy planning, environmental management, urban development, and more(Siekelova et al., 2021).

3.1.1. AHP in Global Research Context

Below are some notable examples of how AHP has been applied in various global research contexts:

1. **Waste Management and Waste-to-Energy (WTE) Planning**

- **India:** Researchers have used AHP to evaluate and rank suitable WTE technologies (e.g., incineration, pyrolysis, gasification) for Indian cities based on criteria such as energy efficiency, emissions, and economic viability. For example, a study in Delhi applied AHP to select the most appropriate WTE method, favoring incineration due to high compatibility with the local waste composition(Sankalp & Sahoo, 2023).
- **Malaysia:** AHP was used to determine optimal sites for WTE plants by incorporating environmental, economic, and social factors. The method helped prioritize locations

that minimized transportation costs and environmental risks while maximizing community acceptance.

2. Renewable Energy Resource Selection

- **Turkey:** AHP has been employed to evaluate and rank renewable energy alternatives—solar, wind, hydro, and biomass—based on factors like investment cost, sustainability, and policy support. In one study, wind energy emerged as the top choice due to favourable local wind patterns and lower environmental impact(Karakas & Yildiran, 2019).
- **Iran:** Researchers used AHP to compare solar photovoltaic, geothermal, and biomass energy systems. Criteria such as land use, energy output, and environmental impact led to the selection of solar PV as the most viable solution.

3. Urban and Transportation Planning

- **China:** In urban transportation research, AHP has been used to assess the sustainability of various public transport modes. It allowed city planners to prioritize investments in metro systems over buses or light rail due to higher efficiency and lower emissions.
- **Italy:** AHP was applied to evaluate alternative urban redevelopment strategies, balancing economic benefits, environmental improvements, and social impacts. This facilitated more transparent, stakeholder-driven decision-making.

4. Environmental Impact Assessment

- **Indonesia:** AHP has supported environmental impact assessments (EIA) of industrial projects, helping decision-makers weigh potential effects on air, water, biodiversity, and public health.
- **Greece:** In coastal zone management, AHP has guided the selection of eco-friendly tourism development strategies, ensuring sustainable use of natural resources. Disaster

Risk Management

- **Japan:** AHP has been used to prioritize risk reduction strategies for earthquake-prone regions, incorporating criteria like infrastructure resilience, population density, and economic recovery capacity.
- **Nepal:** In the aftermath of the 2015 earthquake, AHP helped identify the most critical factors for rebuilding strategies, aiding international aid agencies and government bodies in efficient resource allocation.

AHP's global application across multiple research areas illustrates its power as a versatile and practical decision-support tool. Whether in energy, environment, or urban development, AHP aids in structuring complex problems, engaging stakeholders, and arriving at justifiable and optimal decisions.

3.1.2. Overview of decision-making frameworks used in infrastructure projects

Infrastructure initiatives—including transportation networks, energy generation facilities, water purification plants, and waste management systems—constitute extensive, capital-intensive projects that yield enduring repercussions for society, the environment, and the economy. Given their inherent complexity and the diverse array of stakeholders engaged, the efficacy of decision-making processes is paramount to fostering sustainability, operational efficiency, and public endorsement.

Throughout the years, a variety of decision-making frameworks have been devised and implemented to facilitate systematic assessment and selection among alternative solutions in the realm of infrastructure development. Some of the decision making frameworks are provided below:

1. Traditional Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis represents one of the most venerable and extensively utilized methodologies for decision-making within the realm of infrastructure planning (Crandall, 1981) .This analytical framework entails the quantification and comparative assessment of the economic costs and benefits associated with a project throughout its entire lifecycle (Singer, 1977)[5].

Advantages: It is characterized by its straightforward nature, the capability to monetize various impacts, and its broad acceptance within policy-making spheres.
Limitations: This approach notably overlooks non-monetary considerations such as environmental and social ramifications, and it may exhibit bias stemming from the assumptions made regarding the discounting of future benefits.

2. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) systematically analyses the environmental repercussions of a project or system throughout its complete lifecycle—encompassing the phases of raw material extraction, construction, operational activities, and eventual disposal(El Haouat et al., 2024).

- Application: LCA is commonly employed within the domains of energy and waste management projects to evaluate carbon emissions, energy consumption, and ecological ramifications(Emmanuel et al., 2024).
- Strength: It offers a comprehensive perspective on environmental sustainability.
- Limitation: It fails to directly consider economic or social dimensions.

[5] Singer, S. F. (1977). Cost-Benefit Analysis in Environmental Decision Making. *The Journal of College Science Teaching*, *7*(2), 79–84. https://eric.ed.gov/?id=EJ196759

3. Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) represents a systematic methodology that facilitates the integration of both qualitative and quantitative dimensions within the decision-making framework (Shrivastava et al., 2018) .This approach is particularly advantageous when it becomes necessary to navigate trade-offs among competing objectives (Kheybari, 2021).

Commonly Employed MCDA Methodologies:

1. Analytic Hierarchy Process (AHP): it deconstructs intricate decisions into a hierarchical structure and employs pairwise comparisons to allocate weights.
2. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS): It evaluates alternatives by assessing their geometric proximity to an ideal solution.
3. Elimination and Choice Expressing Reality (ELECTRE): It analyzes alternatives by examining outranking relationships.
4. Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE): It applies preference functions to assess the superiority of alternatives.

These MCDA methodologies support participatory decision making , accommodates multiple participants with conflicting criteria. Major challenges include subjectivity judgements, requires expert input and sensitivity to weight assignments. Despite certain shortcoming, this method is used widely for decision making choices.

4. Risk Assessment and Scenario Planning

These frameworks are used to assess the potential uncertainties and risks associated with infrastructure projects.

- Application: Often used in conjunction with other methods to assess climate risks, economic volatility, and operational failures.

- Tools: Monte Carlo simulations, decision trees, and fault tree analysis are commonly used.

5. Public-Private Partnership (PPP) Evaluation Models

In PPP projects, decision-making frameworks often integrate risk-sharing models, value-for-money assessments, and financial viability analyses to determine feasibility (Volden, 2019).

- Examples: The UK's Green Book framework, India's PPP Appraisal Committee (PPPAC) model.

6. Geographic Information Systems (GIS) in Spatial Decision-Making

GIS-based decision support systems (DSS) are increasingly used to integrate spatial data in infrastructure planning, especially for site selection of plants, roads, and utilities (Schröder & Geldermann, 2019).It is often combined with AHP or other MCDA techniques for location-based analysis.

3.2. Detailed exploration of AHP and its applications in decision-making

The Analytic Hierarchy Process (AHP) serves as a structured and systematic methodology for decision-making, particularly pertinent to the resolution of intricate, multi-criteria dilemmas(Rajput & Dr.A.C.Shukla, 2012c) . AHP holds significant merit in the realms of infrastructure decision-making, whereby alternatives necessitate assessment according to a combination of quantitative and qualitative criteria. This methodology disaggregates a complex decision into a hierarchical framework, thereby facilitating decision-makers in the independent analysis of each constituent element through pairwise comparisons(Carpitella et al., 2022).

3.2.1. Structure of AHP

AHP organizes decision problems into a three-level hierarchical structure:

- Level 1: The overall goal of the decision (e.g., selecting the best Waste-to-Energy operational plant among alternatives).

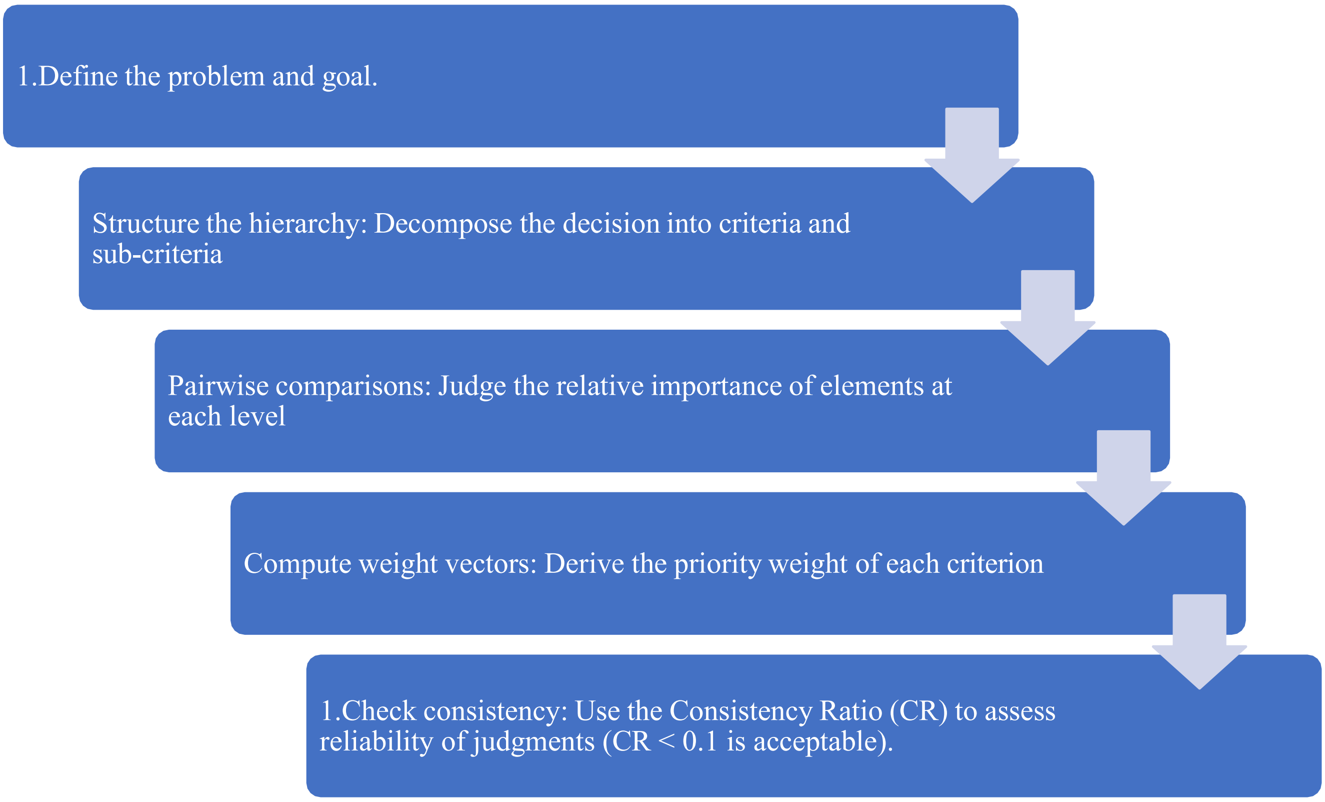
- Level 2: Criteria and sub-criteria influencing the decision (e.g., risk elements, revenue , regulatory hurdles, emission control, land use, social acceptance).
- Level 3: Alternatives or options to be evaluated

Each criterion is compared pairwise in terms of its relative importance using a standardized 1–9 Saaty scale, where 1 indicates equal importance and 9 indicates extreme importance of one element over another. These comparisons are used to compute priority vectors (weights) and consistency ratios to ensure logical coherence in judgments.

3.2.2. Steps Involved in AHP

There are several steps involved in AHP modelling. This is being illustrated with the diagram below:

Figure 3.1: Steps involved in AHP process



Source: Secondary Research and Authors' own analysis

3.2.3. Consensus Mechanisms and Prioritization in AHP

In the Analytic Hierarchy Process, the consistency check serves a dual purpose: it not only verifies the mathematical reliability of pairwise comparisons but also functions as a mechanism for ensuring judgment coherence and convergence of expert preferences across multiple stakeholders. Once the consistency ratio (CR) is computed and found to be within acceptable limits (typically $CR < 0.10$), the comparison matrix is deemed sufficiently coherent to proceed to the synthesis phase, wherein priority weights are derived and aggregated to produce the final ranking of alternatives.

AHP achieves consensus not by forcing unanimous agreement among decision-makers, but by systematically transforming diverse individual judgments into a normalized aggregate preference structure. This is particularly valuable in multi-stakeholder contexts such as Waste-to-Energy (WtE) plant selection, where stakeholders may include policymakers, municipal authorities, environmental experts, project developers, and community representatives, each bringing distinct perspectives and priorities to the decision-making process.

The prioritization operation in AHP proceeds through the following logical sequence:

- Pairwise Comparison Aggregation: When multiple experts provide judgments, their individual pairwise comparison matrices are aggregated using geometric mean methods to produce a single consolidated matrix that represents the collective preference. This approach reduces the influence of extreme individual opinions while preserving the essence of majority judgment.
- Eigenvalue Computation: The principal eigenvalue (λ_max) of the consolidated comparison matrix is computed, and the corresponding eigenvector is normalized to derive the priority vector, which assigns relative weights to each criterion or alternative under consideration.
- Consistency Validation: The consistency index (CI) and consistency ratio (CR) are

calculated to verify that the aggregated judgments exhibit logical coherence. An acceptable CR value indicates that the collective judgments are sufficiently transitive and can be relied upon for decision-making.

- Hierarchical Synthesis: Priority vectors computed at each level of the hierarchy are synthesized through weighted aggregation, whereby the local priorities of alternatives with respect to each criterion are multiplied by the global priority weights of those criteria, and the products are summed to yield the overall priority score for each alternative.

This mechanism ensures that the final prioritization outcome reflects a balanced integration of multiple criteria and stakeholder perspectives, while maintaining transparency and mathematical rigor throughout the process. In the present study, this consensus-driven prioritization approach is applied to evaluate four operational WtE plants—Tehkhand, Sonipat, Jabalpur, and Hyderabad—across five critical dimensions: economic, environmental, regulatory, operational, and socio-cultural considerations.

The strength of AHP's consensus mechanism lies in its ability to accommodate subjective judgments within a structured framework, thereby transforming qualitative assessments into quantitative priority rankings that can guide Urban Local Bodies (ULBs) in selecting sustainable and replicable WtE plant models for their waste management strategies

3.3. Advantages of AHP in Decision-Making

The Analytic Hierarchy Process (AHP) offers several advantages in decision-making, including structured problem-solving, enhanced clarity in evaluating alternatives, and improved stakeholder engagement through transparent methodologies. Additionally, AHP facilitates the incorporation of both qualitative and quantitative criteria, enabling a comprehensive analysis that reflects the complexities of real-world decision-making scenarios(Ramík, 2020).

Moreover, AHP's hierarchical structure allows for systematic evaluation and prioritization of alternatives, ensuring that decisions are made based on a thorough understanding of the criteria involved. This systematic approach not only aids in addressing complex problems but also enhances the reliability of the decision-making process by providing a clear framework for analysis. Furthermore, AHP's flexibility allows it to be applied across various fields, including project selection, supply chain management, and environmental sustainability, demonstrating its broad applicability in complex decision-making scenarios(Bugingo et al., 2024).

3.4. Limitations of AHP and Mitigations

The limitations of Analytical Hierarchy Process (AHP) in risk assessment can hinder effective decision-making and mitigation strategies in various contexts. These limitations can lead to misjudgements in prioritizing risks and implementing appropriate mitigation measures, ultimately affecting the overall effectiveness of risk management. To enhance decision-making, it is crucial to address these limitations by integrating more comprehensive risk assessment frameworks that account for diverse variables and stakeholder perspectives. By incorporating stakeholder-centric frameworks, organizations can better align their risk assessment processes with actual needs, improving both decision-making and mitigation outcomes. Addressing these limitations not only improves the accuracy of risk prioritization but also fosters collaboration among stakeholders, leading to more effective and sustainable mitigation strategies.

Table 3.1: Limitations of AHP process and its mitigation strategy

Limitation	Mitigation
Subjectivity in judgment	Involve multiple experts to average out biases
Inconsistency in comparisons	Use consistency ratio (CR) to validate matrices
Scalability issues in large problems	Use automated software (e.g., Expert Choice, Super Decisions)

Sensitivity to input changes	Conduct sensitivity analysis to test robustness

Source: Secondary Research and authors' analysis

3.5. Software Tools for AHP

Several tools support the implementation of AHP in decision-making:

- Expert Choice
- Super Decisions
- Microsoft Excel (with custom AHP templates)
- MATLAB or Python (for large-scale problems or integration with GIS)

Table 3.2: Comparison of Multi-Criteria Decision-Making Tools

Method	Handles Subjectivity	Pairwise Comparison	Application to WTE
AHP	Yes	Yes	Widely used
TOPSIS	Limited	No	Moderate use
DEA	No	No	Low use

Source: Secondary Research and authors' analysis

The selection of criteria was based on literature review and expert consultation. The criteria can be increased based on the location, local issues, risk and reward and other factors also. However, for this research purpose, we have selected 5 major criteria that are distinctive , useful in present situation at Indian context and often cited as main reasons for any decision regarding implementation of waste to energy plant.

Table 3.3: AHP Criteria and Indicators used for selection

Dimension	Criteria	Description
Environment	Time delay in Clearance	Projects getting environmental clearance in 2 years affect project viability and cost
	Benchmark standards and Norms to be adhered to	Stringent benchmarks standards and norms increase project cost

	Emissions Compliance and penalty	Compliance with CPCB norms, Nox, COx emission limits
Economic	CapEx & OpEx	Cost of building and operating the plant
	Revenue Risks and Potential	Tipping fees, power sales, VGF availability, payment security
Regulatory	PPA approval, scrutiny, data validation	PPA approval requires rigorous follow up and data validation
	Tariff determination	Benchmark tariff may render project unviable
	Flexibility and deviation	Regulation may not allow for extension and strictly adhere to regulations
Operational	Waste Quantity and Quality	A minimum size of waste requirement for plant operation with quality characteristics
	Landfill requirement	Ash disposal requires landfills and minimum ash generation to maintain the landfill
	Pre Processing facilities and advanced technologies	Advanced technologies requirement for pre-processing facilities like segregation, sorting, drying etc to maintain calorific value
Socio Cultural	Public Acceptance	Local community and political support
	NIMBY syndrome	Distance from the local population from health point of view
	Job opportunities	Job opportunities for local population , means for livelihood
	Political buy in	Strong support required from local political establishments

Source: Secondary research and authors analysis

3.6. Limitations and Sensitivity Analysis in AHP model

There are certain limitations to the AHP model that are described below:

- **Subjectivity:** While pairwise comparisons bring structure, the process can still reflect personal biases.
- **Consistency Dependence:** If judgments are inconsistent, results can be skewed.
- **Static Weights:** AHP weights are fixed unless re-evaluated through stakeholder engagement.

Sensitivity analysis can be used to test how changes in weights impact the final ranking of alternatives.

In the context of our research, as the Waste-to-Energy (WTE) sector advances, a sufficient number of data points are available regarding operational characteristics owing to the annual submission of petitions by the generators to the state regulators for tariff determination process. Though, normally, it is very difficult to gather operational and financial data from the operating plants, these data can be sourced from the petitions and orders of the state regulatory commissions. By gathering data from the regulatory authorities and secondary research through expert interviews, the research becomes relevant as all essential datasets are compiled, analysed and models can be derived pertinent to the projects, which will then be analysed to yield a comparative dataset that can assist other Urban Local Bodies (ULBs) in adopting optimal alternatives or models for their waste management methodologies. As the power plants ages, more and more operational datasets are available which can be used for further benchmarking and decision-making process. This can also be useful for the plants under study to make amendments accordingly to make the system more robust and sustainable in the long run.

3.7. Identification of gaps in existing research

Despite increasing attention toward sustainable waste management and the adoption of incineration-based Waste-to-Energy (WTE) in India, several critical gaps remain in the existing body of literature. A review of studies on decision-making, WTE technologies, and the application of multi-criteria decision analysis (MCDA) reveals significant areas that require further investigation and methodological advancement. While majority of studies either focus upon the current technologies to be adopted within WTE and primarily concentrate on a location specific subject, it fails to address and study the operational plants that are already under operation and specific data available with the authorities. The limitations that this study addresses are:

3.7.1. Lack of Structured, Context-Specific Evaluation Models

Many studies on Waste to Energy selection apply general decision-making frameworks without tailoring them to the socio-economic, environmental, and technical context of India. While global frameworks exist, their effectiveness is limited when applied directly to Indian cities due to:

- Heterogeneous waste composition
- Varying policy environments
- Urban infrastructure disparities

This thesis addresses this gap by developing a structured decision-making framework based on the Analytic Hierarchy Process (AHP) customized for the Indian context, incorporating locally relevant criteria such as economic cost, revenue generation, life cycle assessment, risk factors , community acceptance, and policy incentives along with possible regulatory hurdles.

3.7.2. Limited Stakeholder-Inclusive Decision Models

Few studies incorporate the perspectives of all relevant stakeholders (e.g., policymakers, municipal authorities, environmental experts, and prominent citizens) when evaluating WTE. As a result, the decisions made are often technocratic and fail to gain public acceptance or implementation traction.

This thesis incorporates stakeholder engagement through expert-based pairwise comparisons in the AHP model, ensuring the decision-making process is inclusive and reflects diverse priorities. Also, the research comprises feedbacks from industry experts, project developers, regulatory bodies and ULBs personnels, thus comprising the whole gamut of stakeholders.

3.7.3. Absence of Comparative Analysis of WTE Technologies Using MCDA in India

Although MCDA methods like AHP, TOPSIS, and PROMETHEE are used internationally for evaluating WTE projects, there is a dearth of comparative studies that evaluate multiple WTE plants based on similar technology systematically in the Indian context using these tools.

This thesis fills this research gap by applying AHP to compare common WTE plants across environmental, economic, technical, and social criteria specific to Indian urban centres.

3.7.4. Inadequate Integration of Technical and Social Criteria

Existing literature often emphasizes technical and economic feasibility (e.g., energy recovery, cost) while underrepresenting social and environmental considerations such as public health impact, emissions, and social acceptance.

This thesis ensures a balanced evaluation by integrating both hard (operational, economic) and soft (social, environmental) criteria into the AHP framework, enabling a holistic assessment of alternatives.

3.7.5. Scarcity of Region-Specific Case Applications

Many studies remain theoretical and lack practical demonstration of decision-making tools on real-world scenarios or city-specific case studies in India.

This thesis applies the developed AHP model to various case studies based on different parts of India for mixed waste, thereby offering practical insights into the application and policy implications of structured decision-making tools for WTE selection.

3.7.6. Insufficient Methodological Transparency

Some past research lacks detailed explanations of weight assignment, consistency checks, and sensitivity analysis, which are essential for the credibility and replicability of AHP-based studies.(Sharma & Jain, 2020).

This thesis provides a transparent methodology, including detailed documentation of pairwise comparison matrices, consistency ratio checks, and sensitivity analyses to enhance robustness and reproducibility.

3.8. Research Methodology Applied

- The study's methodology was divided into three main phases, starting with a comprehensive literature study to explore existing knowledge and identify gaps in waste-to-energy (WtE) research particularly in the context of WTE plants that are operational in nature in India.

1st Phase:

- In this first phase, information was gathered from peer-reviewed journals, government reports, research articles and papers, petitions filed by the regulated entities (WTE plants) , regulatory tariff orders related to specific operational plants and the latest articles.
- This approach ensured that specific data points and information related to operational plants that are under research are extracted, gathered and compiled in a manner so that specific critical parameters are well established before starting the AHP modelling. It ensured to form a strong knowledge base and specific data sets related to parameters and sub parameters are established for further analysis.
- After gathering the information, four operational WTE power plants are selected based on certain critical assumptions and covering pan India geographical locations. The power plants are selected such that they have completed at least 2 year of operation based on mixed waste incineration (along with RDF) having a critical processing facility of at least 500 tonnes per day. The power plants were then validated from the experts and industry stalwarts for their selection for the research study. Four WTE power plants namely Tehkhand in Delhi, Sonipat in Haryana, Jabalpur in Madhya Pradesh and Hyderabad in Telangana are selected for this research.

2nd Phase:

- The next phase focused on systematic data extraction and preparation for analysis .
  - Data were collected from relevant ministry websites, Lok Sabha questionnaires, orders pertaining to tariff petitions from relevant state regulator commissions, research articles using various sources and represented in both quantitative (numerical values) and qualitative (descriptive) forms.
  - The extracted data included key parameters such as environmental details, economic information pertaining to revenue generation, environmental factors such as time delay in clearance, standards set and benchmarks, regulatory provisions and hurdles and socio-cultural aspects of each selected plants.
  - 18 number of Expert (from a pool of relevant stakeholders) interviews were done online with survey questionnaires for their opinions and feedbacks about the critical parameters used for this research and they were asked to provide their opinions in a satty scale (from 1 to 9) comparing 2 parameters at a time.
  - The collected data were then normalized and organized into structured tables in excel making it easier to compare and analyse in perspective of the 4 operational WtE plants for long term sustainability and replicability from decision making in ULBs.
- The core of the methodology utilizes the Analytic Hierarchy Process (AHP) for Multi-criteria Decision Analysis (MCDA) .
  - The datasets thus gathered were fed into "SuperDecisions" software for results. This software performed pair-wise comparisons between different criteria, ensuring that each factor was weighed appropriately.

    - In simple terms, each selected WtE plants was compared with 5 critical parameters step by step, using a scale (from 1 to 9, as defined by Saaty's nine-point scale). These comparisons helped in assigning relative weights to the criteria.

- A consistency check was then carried out to verify that the comparisons made in the decision matrices were reasonable.
    - The consistency ratio (CR) was calculated to ensure that the judgments in the pairwise comparison matrix were logically consistent. An acceptable CR value indicated that the judgments could be trusted and that there were no large anomalies in the input data.

3rd Phase:

- Finally, the AHP model was used to derive the final priority order for the WtE plants.
    - The aggregated priority vectors across all criteria led to the final ranking of the plants. This method helped in identifying the most viable WtE plants that can be replicated by way of designing the concession agreement in a such way that it becomes viable for long term for the ULBs and a win-win proposition for both ULB and project developers.
    - Complementary to this, sensitivity analysis was performed to test the robustness of the model against changes in criteria weights. This "what if" scenario testing assured that the final rankings were reliable even when adjustments were made to input priorities.

By following these systematic steps—from literature review and data extraction to constructing and validating the AHP model—the paper offers a structured, transparent, and replicable approach for selecting the best alternative plant based on incineration, mixed waste processing facilities. This method ensures that various aspects are comprehensively analyzed and weighed before coming to a final decision, making it accessible even to those without extensive prior knowledge on the topic.

3.9. Steps Involved

1. **Identification of plants**
    - The basis for plant identification is already covered in earlier chapters. To compare a set of plants, similar type of plants is considered (incineration-based plants that take mixed waste as input, a critical size of 500 tonnes per day processing capacity and at least 1 year of continuing operational). On this basis, 4 plants are selected. These plants are
        - Tehkhand in Delhi
        - Sonipat in Haryana
        - Jabalpur in Madhya Pradesh
        - Hyderabad in Telangana
    - The technical details of these plants are already covered in earlier chapter.
2. **Goal Setting**
    - The prime objective of the study is the selection of the best WtE plants among four alternatives that is sustainable for long term in terms of competing criteria established and which can be replicable in nature in terms of adoption by the ULBs both financially and operationally taking onto consideration the PPP structure and risks associated.

3. **Identification of critical criteria for evaluation purpose**

- 5 major critical criteria are established for this research study among various alternatives. These are:
    - Economic criteria
    - Operational criteria
    - Regulatory criteria
    - Environmental criteria
    - Socio Cultural criteria

3.10. Description of the Selected Critical Criteria

3.10.1. Economic Criteria:

Economic considerations for waste-to-energy incineration plants are crucial, particularly regarding revenue generation through gate fees, tariffs, and payment security. Gate fees, or tipping fees, serve as a primary income source, incentivizing waste disposal over landfilling. When set competitively, these fees can attract more waste, enhancing profitability. Additionally, securing payment mechanisms ensures that revenue flows remain stable, allowing for consistent operational funding. Ultimately, a well-structured financial model that incorporates these elements can significantly improve the economic viability of waste-to-energy projects.

Furthermore, the integration of variable tariffs based on waste volume can further optimize revenue streams, enabling facilities to adjust pricing in response to market dynamics and operational costs. This adaptability not only enhances financial sustainability but also aligns with regulatory requirements and market conditions, thereby promoting a more effective waste management strategy.

Moreover, the implementation of Viability Gap Funding (VGF) can provide essential financial support, reducing the capital burden on developers and enhancing project feasibility. By ensuring that tipping fees are set appropriately, operators can maximize their revenue potential while complying with environmental regulations, ultimately fostering a sustainable waste management ecosystem. Apart from this, the capital cost and the O&M cost of each plant is also considered. In this research, we explore these parameters within economic considerations for the selected power plants to know where they stand currently as far as their plant economy is considered and the results are astounding.

3.10.2. Environmental Criteria:

Environmental hurdles for waste-to-energy incineration plants in India often arise from protracted time delays in obtaining necessary clearances and approvals. The complex procedures involved can hinder project initiation, while stringent emission standards necessitate advanced flue gas treatment systems to mitigate air pollutants. Additionally, the imposition of penalties and fines for non-compliance with these standards can further complicate operations, making it essential for stakeholders to navigate these environmental challenges effectively.

These hurdles can significantly impact project timelines and operational costs, ultimately affecting the feasibility of waste-to-energy initiatives in urban areas across India. Moreover, the lack of streamlined processes for obtaining environmental clearances often leads to significant project delays, discouraging potential investors in the waste-to-energy sector. In our research, due considerations are provided to these environmental factors while discussing the selected plants in particular to find out how these plants fair on these criteria comparing to other criteria.

3.10.3. Regulatory criteria

Regulatory parameters for waste-to-energy incineration plants in India encompass various aspects, including Power Purchase Agreements (PPAs), tariff determination, and operating benchmark requirements. The tariff structure is crucial, as it influences the financial viability of projects, and must align with the guidelines set by the Central Electricity Regulatory Commission (CERC). Additionally, plant extensions and concession agreements must adhere to the regulations outlined in the Solid Waste Management Rules of 2016, which emphasize the need for pre-processing waste to achieve the necessary calorific value for efficient incineration. Furthermore, navigating regulatory hurdles, such as securing environmental clearances and ensuring compliance with emission standards, remains a significant challenge for developers in this sector.

Though, WTE plants in India enjoys a preferential tariff over other conventional fuel, it depends on plant-to-plant considerations. There is no specific benchmark on the tariffs provided by the regulator. Waste to Energy plants is now covered under renewable energy and the discoms are mandated to buy power from these plants whenever available. That gives a lot of comfort to the generators. However, there are other several challenges related to power offtake, auxiliary consumption, power plant extension that often face the regulatory hurdles affecting the operation of the plant. In our research study, we evaluate regulatory hurdles for each of the power plants and data gathered. The questionnaire also emphasized on these parameters while asking for a choice selection from the experts.

3.10.4. Operational Criteria:

Operational parameters for a waste-to-energy incineration plant are influenced by several factors, including the quantity of waste processed, the critical size of the facility, and the availability of waste materials. Additionally, the infrastructure of urban local bodies (ULBs) plays a significant role, as does the presence of pre-processing facilities that can enhance efficiency. Landfill availability is also crucial, as it affects the overall waste management strategy and the integration of incineration within the local waste disposal framework. These operational parameters must be carefully evaluated to optimize the performance of waste-to-energy systems, ensuring both environmental sustainability and economic viability. Moreover, understanding the interplay between these parameters can lead to more effective waste management strategies that align with municipal regulations and community needs.

Effective management of these operational parameters can significantly enhance the efficiency of waste-to-energy plants, ultimately contributing to reduced environmental impact and improved resource recovery. Furthermore, integrating advanced technologies for monitoring and optimizing these parameters can lead to better decision-making and operational efficiency in waste-to-energy incineration plants. This integration not only improves energy recovery but also minimizes emissions, aligning with the goals of waste management and environmental protection(Fordham et al., 2003) (Petridis & Dey, 2018)while simultaneously addressing the challenges posed by increasing waste generation and stricter regulatory requirements. Addressing these operational parameters effectively can lead to significant advancements in waste management practices, ensuring that incineration plants operate within environmental constraints while maximizing energy recovery and minimizing waste disposal costs.

3.10.5. Socio Cultural criteria:

Public opposition to waste-to-energy incineration plants in India often stems from socio-cultural factors like NIMBY syndrome, where communities resist local projects due to perceived health risks and environmental concerns. This resistance can lead to significant drops in real estate prices and limit livelihood opportunities for those who could benefit from employment in the facility. Furthermore, issues such as odour leakages and health considerations exacerbate public sentiment against these plants, complicating their acceptance and implementation. Researchers have conducted extensive studies on public acceptance towards the NIMBY effect together with the coupling effect between cognition and emotion in individual behaviour and decision-making mechanism for WtE plants(Huang et al., 2015).

Table 3.4: Identification of Criteria and type of data

Selected Criteria	Considerations	Descriptions	Type of Data
Economy	Considerations: VGF, Tipping fees, Payment Security , Capex and Opex of the plant	The amount of VGF, tipping fees required for financial sustainability of the plant. The risk factor that arises due to non-payment of tariff by the discoms/ULBs	Quantitative and Qualitative
Operational	quantity of waste processed, the critical size of the facility, and the availability of waste materials, landfills, pre-processing operations	Whether proper quantity and quality of waste is available or not, whether it is occupied with right design of pre-processing facilities or not, whether sufficient landfills available for ash disposal	Quantitative and Qualitative
Regulatory	Power Purchase agreements, disputes related to PPA and concession agreements, controllable and uncontrollable factors regarding benchmark criteria etc	Whether PPA is approved from regulator or not, Is there any disputes related to power offtake and sale of power, Whether open access is provided to the plant or not, whether plants operate within the defined controllable factors or not	Qualitative
Environmental	Time delay in clearance, fulfilment of emission standards, penalties and fines	Whether the plant gets clearance in defined time, whether all emission d=standards as mentioned are maintained by the plant or not, all technological interventions are placed or not, is there any kind oof penalties the plant faced and how that affects its operations	Qualitative
Socio Cultural	NIMBY syndrome, health impacts, employment opportunities, social acceptance	Whether there is public opposition to the plants or not, what are the negative health impacts on the local population and whether livelihood opportunities are there from the plant or not	Qualitative

Source: Authors own analysis

3.11. Principles of AHP

All calculations are based on the main principles that were written by Thomas Saaty as follows:

1. Homogeneity - The parameters constituting a group should exhibit homogeneity and be comparable amongst themselves. For instance, the significance of criterion A in relation to criterion B cannot be quantified as either zero or infinity.
2. Dependence - Each sub-criterion may exhibit a reliance on its primary criteria and the overarching objective situated at the pinnacle of the hierarchical framework.
3. Invariance - In the context of a pairwise evaluation, should the importance of criterion A relative to criterion B be quantified as n, then the importance of criterion B relative to criterion A is represented as 1/n.
4. Expectations - Should there be an alteration in the ranking of criteria within the hierarchical framework, it is imperative that the calculations be recalibrated accordingly.
5. Construct Structure
   - Structure the problem in a hierarchy, which breaks down the goal, main criteria and WtE plant alternatives in descending order
6. Pairwise Comparisons
   - Each plant is compared against the others using pairwise comparisons. This means that each parameter is evaluated by asking simple questions like: “Is economical considerations impact more important than environment factors ?” or “Is Socio cultural aspects more significant than operational performance?”

- Respondents use a standardized scale (the nine-point scale developed by Saaty) to rate how much one parameter outweighs another. This process assigns weight to each parameter according to its relative importance

- After the comparisons, the weights are normalized so that they add up to one, making it easier to compare the influence of each parameter fairly

- These normalized weights form priority vectors that reflect the relative importance of each criterion and sub-criterion

7. Consistency Check

   - To ensure that the judgments made during the pairwise comparisons are logical and consistent, a consistency ratio (CR) is calculated. A low CR indicates that the ratings are reliable, which makes the final evaluation more trustworthy
   - To check that the pairwise comparison judgements are consistent by calculating the consistency ratio (CR). To compute CR, the principal eigenvalue (λmax) for each matrix is calculated with Eq. (1).

     $$Aw = \lambda\mathbf{max} * w \qquad (1)$$

     Where A is the comparison matrix, w is the normalized priority vector (obtained from 'SuperDecisions'). Next, the consistency index is obtained for each matrix with the dimension of the matrix (n) by Eq. (2).

     $$CI = (\lambda\mathbf{max} - n/n - 1) \qquad (2)$$

     Finally, CR is calculated by Eq. (3)

     $$CR = CI/RI \qquad (3)$$

Where RI is the random index. The values for RI are obtained from the table based on the dimension of the matrix (n). The allowable cap for CR value depends on the size of the matrix.

To apply the AHP techniques to the problem described in this study, the goal is positioned on the top of the hierarchy structure connected to five main criteria connected to the alternatives at the bottom of the hierarchy. In the model structure, criteria are considered as a cluster. Hence, the top cluster consists of parental nodes of the main criteria. . This linking of clusters generates feedback or interdependence.

CHAPTER 4

DATA ANALYSIS AND RESULTS

Chapter 4:
DATA ANALYSIS AND RESULTS

4.1. Data Analysis

The judgements are entered using Saaty's nine-point scale and the principles. For example, the judgement on the importance of economy criteria over sociocultural criteria is given in the first row and sixth column in the above table with a value of 2 according to the data from the expert interviews. In other words, economy criteria are considered strongly important over socio-cultural criteria. The priority vector values for criteria were obtained from the 'SuperDecisions' software. The pairwise comparison matrix has positive numerical values and their entries sum to one. In the second stage, a normalized priority matrix is generated with the values of the priority vector collected from the 'SuperDecisions' software.

Table 4.1: Sattys 9-point scale for pairwise comparison

Numerical Scale	Definition	Description (Judgement between criteria A and Criteria B)
1	Equal Importance	A Contributes equally as B
3	Slightly more important	A is slightly more favourable than B
5	Strongly important	A is strongly favourable compared to B
7	Demonstrated Importance	A has demonstrated strong [practice over B
9	Absolutely important	A providing very strong affirmation over B
2,4,6,8	Intermediate values	When compromise is needed between A and B between the points

Source: secondary research.

To perform a consistency check on the given judgements the following manual method is adopted.

First, to find the principal eigenvalue λ**ma ,** criteria weights were computed by a normalized pairwise matrix from the pairwise comparison matrix . Further, the weighted value matrix was calculated by multiplying criteria weights and initial judgements. The average of the ratio of the weighted value sum and criteria weight is equal to the principal eigenvalue. So,

λ**max** = (Average Weighted Values ⁄ CW ratio)/ n where, n is the matrix size (in this case , it is 5)

Table 4.2: Allowable Values of random index (RI)

Matrix Size	1	2	3	4	5	6	7	8	9	10
RI Value	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Source: Secondary Research

For a matrix of 5x5 size, **the RI is 1.12**

In this case, The 5 × 5 matrix of pairwise comparison judgements for the main criteria listed in this study is shown below:

For a 5 x 5 matrix, we have number of comparisons = n (n-1)/2 = 5 (5-1)/2 = 10

Number of comparisons = 10

For this research, the maximum eigenvalue λ**max = 5.321** (calculated from super decisions software)

Consistency Check (CI) = (λ**max**-n)/ (n-1)

= (5.321-5)/(5-1)

= 0.321/4

=0.8025

Hence, the consistency ratio will be

CI = CI/RI

= 0.8025/1.12

=0.071

The CR value of 0.071 < 0.01

The RI value of 1.12 was selected from Table 16 for the 5 × 5 matrix. As the value of CR is less than 0.1 (maximum allowable limit), the judgments given in the matrix are satisfactory and consistent. If the CR value was more than 0.1, the judgements would be inconsistent and the decision makers would have to revise the judgements until they found consistency in it . The CR value obtained from the 'SuperDecisions' software is the same as the value obtained from manual calculations.

Table 4.3: Prioritisation Matrix of Main Criteria

Priortization Matrix	Economy	Environmental	Regulatory	Operational	Socio Cultural	Priority Vector
Economy	1	2	3	5	2	0.388
Environmental	0.5	1	2	2	5	0.266
Regulatory	0.3333	0.5	1	2	2	0.150
Operational	0.2	0.5	0.5	1	2	0.106
Socio Cultural	0.5	0.2	0.5	0.5	1	0.089
	2.5333	4.2	7	10.5	12	1.000

Source: From Superdecision software

In this study, the priority vector is calculated using the Analytic Hierarchy Process (AHP) method, which provides a structured way to make decisions by comparing alternatives pairwise.

4.2. The matrix design and Analysis

4.2.1. Constructing the Pairwise Comparison Matrix

- First, experts compare each pair of criteria or sub-criteria using a standardized rating scale (Saaty's nine-point scale).
- This gives us a matrix where each element represents how much more one alternative is favored over another for a specific parameter.

4.2.2. Normalising the Matrix:

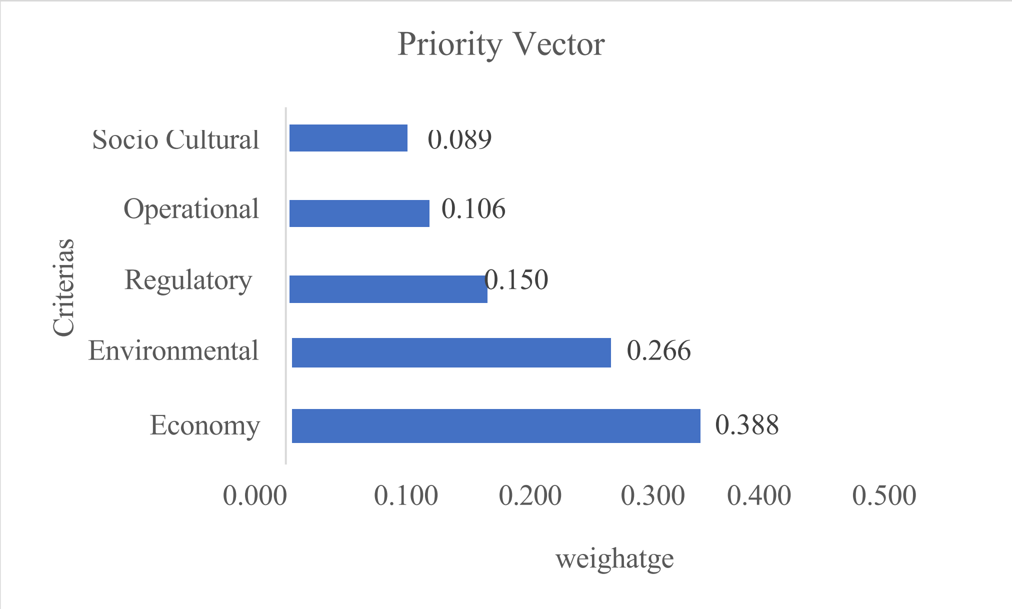
- The next step involves adding the values in each column of the matrix
- Then, each element in the column is divided by the respective column total. This ensures that all the columns sum to one, meaning every comparison is properly scaled to be comparable

4.2.3. Calculating the Row Averages (Priority Vector)

- Once the matrix is normalized, the priority vector is determined by calculating the average of the numbers in each row
- Each row corresponds to one of the criteria being assessed. The average of each row gives a single number—the priority vector—which represents the weight or relative importance of that alternative.

In this case, we find that economic factor is the highest weightage factor among all the criteria selected for the study.

Figure 4.1: Priority Vector for main criteria



Source: Authors analysis

If the priority vector for main criteria is plotted, the rankings according to the weightages are formed. Clearly, it can be seen that from the expert's judgement, while Economy weights (around 38.8%) most weightage among the 5 alternatives, socio cultural criteria have least weightage (around 8.9%).

Table 4.4: Final ranking of criteria

Sl no	Category	Priority	Rank
1	Economic	38.8%	1st
2	Environment	26.6%	2nd
3	Regulatory	15%	3rd
4	Operational	10.6%	4th
5	Socio Cultural	8.9%	5th

Source: From the Superdecision software

For the criteria selected for this research, economic criteria rank 1st among all criteria and socio-economic criteria ranks last as per the expert's judgement. This gives the relative weightages for each main criteria and its priorities. The composite priority or final priorities of alternatives are determined by synthesizing all the pairwise matrices in the SuperDecision' software.

4.3. Priority Vector for each individual criterion

4.3.1. Priority Vector for Economy criteria for selected WTE plants

Economy	Sonipat	Tehkhand	Jabalpur	Hyderabad	Priority Vector
Sonipat	1	3	2	4	0.477
Tehkhand	0.3333	1	0.3333	2	0.156
Jabalpur	0.5	2	1	2	0.258
Hyderabad	0.25	0.5	0.5	1	0.110
	2.0833	6.5	3.8333	9	1.000

For Economic criteria under the given conditions and expert judgements, Sonipat WtE has 47.7% weightage out of 100% as compared to other WtE plants. Jabalpur WtE has 25.8%, while Tehkhand WtE and Hyderabad WtE are having 15.6% and 11% weightage. It clearly shows that Sonipat WtE scores highest weightage in terms of economic preference (i.e) the concession model based on OBI (Output based incentives) are preferred by the stakeholders while judging a WtE long term sustainability.

4.3.2. Priority Vector for Environmental criteria for selected wte plants

Environmental	Sonipat	Tehkhand	Jabalpur	Hyderabad	Priority Vectors
Sonipat	1	3	3	5	0.518
Tehkhand	0.3333	1	2	3	0.241
Jabalpur	0.3333	0.5	1	2	0.154
Hyderabad	0.2	0.3333	0.5	1	0.086
	1.8667	4.8333	6.5	11	1.000

Similarly, for Environmental criteria, Sonipat WtE scores the highest weightage (51.8%) among other plants in consideration. Tehkhand comes at the 2nd position in terms of preference, while Hyderabad WtE is having 8.6% in terms of environment criteria. This is based on experts' judgement and their preference over one plant over the other based on their understandings.

4.3.3. Priority Vector for Regulatory criteria for selected wte plants

Regulatory	Sonipat	Tehkhand	Jabalpur	Hyderabad	Priority Vectors
Sonipat	1	3	5	7	0.558
Tehkhand	0.3333	1	3	5	0.263
Jabalpur	0.2	0.3333	1	3	0.122
Hyderabad	0.1429	0.2	0.3333	1	0.057
	1.6762	4.5333	9.3333	16	1.000

In regulatory criteria also, Sonipat WtE scores well above other, signifies that it faces less resistance from the state regulator regarding the tariff pass through. As the concession agreement allows the differential as an OBI to be paid to the developer, there seems less of a chance of regulatory intervention as regards to hike in tariff for consumers owing to the price paid to the WtE developers.

4.3.4. Priority Vector for Operational criteria for selected wte plants

Operational	Sonipat	Tehkhand	Jabalpur	Hyderabad	Priority Vectors
Sonipat	1	2	5	6	0.510
Tehkhand	0.5	1	2	5	0.269
Jabalpur	0.2	0.5	1	5	0.165
Hyderabad	0.1667	0.2	0.2	1	0.057
	1.8667	3.7	8.2	17	

In operational criteria too, Sonipat scores way above other WtE plants. This might be due to the cluster's formation for Sonipat WtE. They might not be facing any issues related to waste availability for operating the power plant and operates efficiently.

4.3.5. Priority Vector for Socio Cultural criteria for selected wte plants

Socio Cultural	Sonipat	Tehkhand	Jabalpur	Hyderabad	Priority Vectors
Sonipat	1	2	3	5	0.467
Tehkhand	0.5	1	3	4	0.315
Jabalpur	0.3333	0.3333	1	2	0.139
Hyderabad	0.2	0.25	0.5	1	0.080
	2.0333	3.5833	7.5	12	

In socio cultural criteria too, Sonipat fares well among the other alternatives (46.7%). Tehkhand WTE also fares well with 31.5% weightage. It clearly indicates that local acceptance for these power plants is more comparative to other power plants.

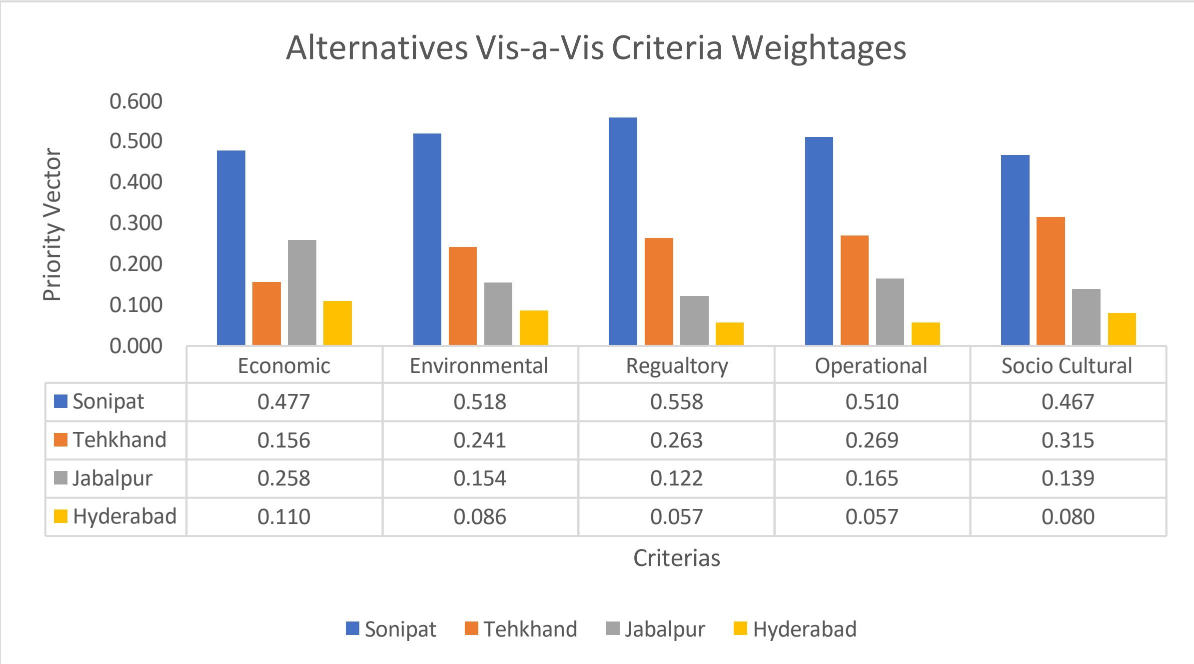
After all the matrix are formed according to the experts' feedback, they are checked for consistency and is found to be well under the permissible level of 0.1. After all the matrix are formed according to priority vector of each criterion for the alternatives, the final priorities obtained from the 'SuperDecision' software after synthesizing the main hierarchy to get the final rankings.

The chart below establishes the consistency of each criterion matrix used in analysis. It can be inferred that all the matrix developed for each criterion for the alternatives are consistent and within the allowable consistency ratio.

Consistency Check Parameters	Economic Criteria	Environmental Criteria	Regulatory Criteria	Operational Criteria	Socio-Cultural Criteria
CR	0.017	0.048	0.065	0.067	0.021

If all the priority vectors from each criterion are plotted against the alternatives, the corresponding standings of all alternatives with respect to each criterion can be obtained as given below:

Figure 4.2: Alternatives Vis-a-Vis Criteria Weightages



Source: Author's analysis

The analysis clearly indicates that while Sonipat WTE has got maximum weightages for each criteria studied, Tehkhand comes in the 2nd position in each criterion except economic criteria. Jabalpur WTE has more weightage than the Tehkhand WTE in case of economic criteria.

4.4. Final Ranking of the selected WtE plants:

The final ranking of the alternatives is obtained after superimposing the weightages of the main criteria on the scores obtained from the alternatives in respect to the individual criteria matrix.

The relative score for each criterion is calculated by multiplying the weights with the scores obtained for each column and then adding all the scores in the row for the respective alternatives. The final Score thus obtained for each alternative are compared for the ranking purpose. This is being illustrated below:

Table 4.5: Final AHP matrix of select WTE plants

Summary	Economy		Environmental		Regulatory		Operational		Socio Cultural		**Final Score**
	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	
Sonipat	0.388	0.477	0.266	0.518	0.150	0.558	0.106	0.510	0.089	0.467	0.503
Tehkhand	0.388	0.156	0.266	0.241	0.150	0.263	0.106	0.269	0.089	0.315	0.221
Jabalpur	0.388	0.258	0.266	0.154	0.150	0.122	0.106	0.165	0.089	0.139	0.189
Hyderabad	0.388	0.110	0.266	0.086	0.150	0.057	0.106	0.057	0.089	0.080	0.087

Source: From the Superdecision Software

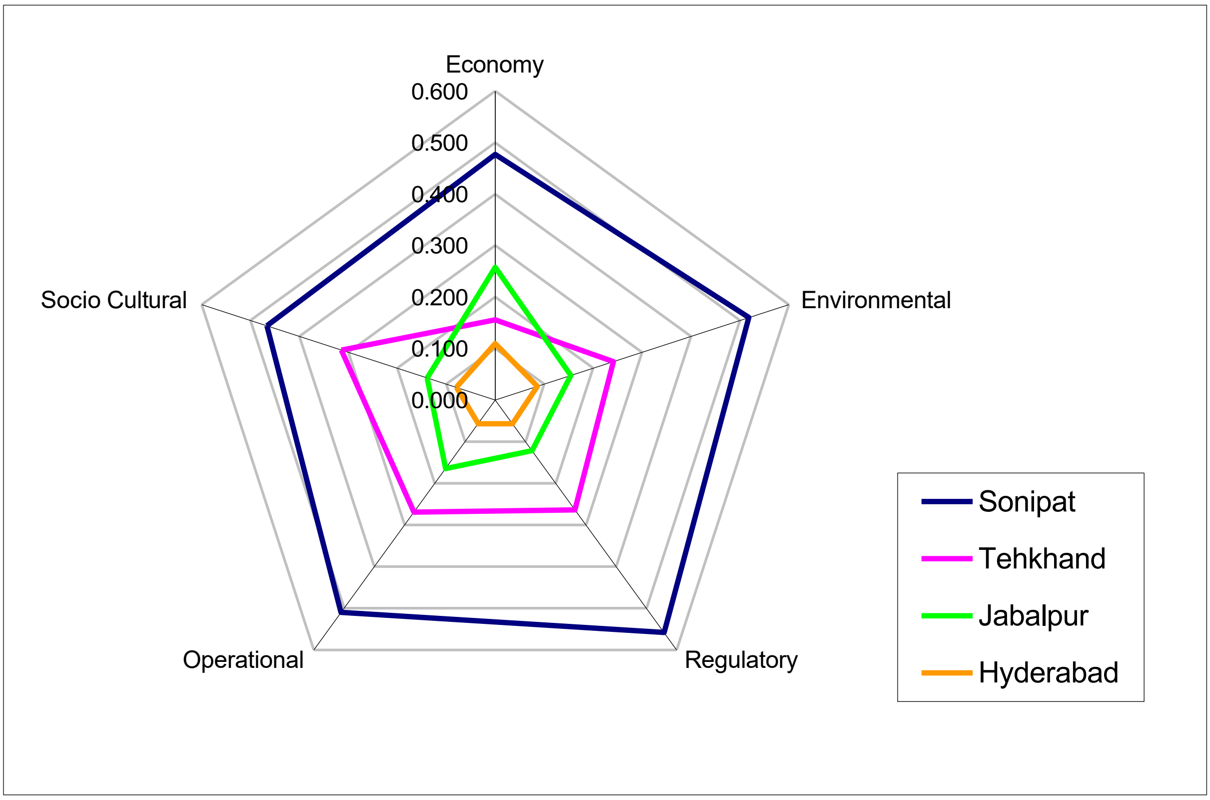
Table 4.6: Final ranking of select plants

Sl no	Category	Priority	Rank
1	Sonipat	50.3%	1^{st}
2	Tehkhand	22.1%	2^{nd}
3	Jabalpur	18.9%	3^{rd}
4	Hyderabad	8.7%	4^{th}

Summarising all the weightages along with scores for all individual criteria, the final score for selection of the best alternative is arrived at. It clearly shows that Sonipat WtE plant and the model it adopted scores well over the other WtE plants. The experts judgement with AHP modelling clearly favours the Sonipat WtE model as the best alternative among the four selected WtE plants for research. Sonipat WTE ranks 1st in the model scoring a final weightage of 50.3%. Tehkhand comes in 2nd position with 22.1%. Jabalpur is in close contest with Tehkhand with 18.9% and comes in 3rd position and the Hyderabad WTE comes last in the ranking.

This might be from the fact that the plant is well designed and the concession agreement almost covers all the aspects to make the waste to energy power plant sustainable for long term. As the revenue risk is eliminated from the beginning through the bid variable based on Output based incentive that allows the developer to recover the gap amount arising out of the tariff differential from the state commission's order from the ULB. This makes the project insulated from any revenue risk and also incentivise the developer to run the power plants at its maximum capacity to produce maximum energy generation from the plant. As the plant is out put based, it rewards the project developers to perform its best under any situation.

Figure 4.3: The spider chart depicting the best alternative among the plants



Source: Authors' own research

The spider chart above clearly indicates that the Sonipat model scores well above from the alternatives based on the parameters selected for this study.

4.5. Sensitivity Analysis

The sensitivity analysis was conducted to assess the robustness of the AHP model's results by examining how changes in the weights of criteria affect the ranking of selected WtE plants. This analysis helps validate the model by showing the impact of varying the importance of different criteria on the final decision. The analysis was conducted using the 'What-if' scenario feature in SuperDecisions software. The 'What-if' sensitivity analysis explores how changes in input parameters impact the outcome. The principle behind this type of analysis is to identify how sensitive the model's conclusions are to changes in assumptions, thus providing insight into the reliability and robustness of the decision-making process. In the first sensitivity analysis, we evaluated the influence of the main criterion on selecting WtE plants and found that it is consistent.

The effect of changing the priority vector of one of the criteria would definitely change the ranking of WtE plants. In the sensitivity analysis, the weights of the main criteria are changed to observe the change in rankings of the WtE plants. However, the priority and rank remain unchanged that signifies that the model is robust and can be adopted for any combinations of change. It can be customised accordingly to local conditions and varying criteria. This approach ensures that the model's recommendations are robust and adaptable to varying priorities and preferences, thereby providing a comprehensive validation of the results.

CHAPTER 5

DISCUSSION AND IMPLICATIONS

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5.1. Discussion

The paper's discussion highlights how the selection of waste-to-energy (WtE) plant depends on a careful balance of various factors:

It explains that while economic factors are the most important (with a weight of 50.4%), other factors such as environment, regulatory, operational and socio-cultural criteria also play significant roles in the decision-making process .The study emphasizes that a structured approach like the Analytic Hierarchy Process (AHP) helps decision-makers clearly see these trade-offs, enabling a more transparent and robust evaluation process. From a broader perspective, the discussion shows that each selected WtE plants has its strengths and limitations.

The Sonipat model stands out because it scores way above in weightages in every criteria set in this research. In operational criteria, it scores way above as it smartly combines waste from not only Sonipat but also surrounding cities located within a 50 km radius. This clustering approach overcomes the low waste generation challenge seen in smaller individual urban local bodies (ULBs) by aggregating sufficient waste (at least 500 tonnes per day), which is crucial for the financial and operational viability of waste-to-energy (WtE) projects.

By ensuring there is a steady and adequate supply of waste, the model meets one of the key prerequisites for setting up a successful WtE plant and reduces risks linked to underfeeding the facility. Evaluating the other parameters too, the concession agreement is so designed that it integrated all value chain in its facilities that is embedded in the Project Structure with Built-in Risk Mitigation. In economic parameters too, the model uses Output-Based Incentive (OBI) as the bid variable, meaning that payments to the developer are directly linked to the actual electricity generated. These things are reflected in the research through the experts judgement and the AHP analysis.

Similarly, the Tehkhand WTE in Delhi shows the role of VGF to reduce the upfront capital cost by the developer. The VGF for this project that is around 23% of the total project cost was supported by the Govt. It signals a strong government commitment to the project, reducing the potential risk usually associated with high-capital projects like WtE facilities. In the case of Jabalpur project also, here the bid was structured using processing fees along with an additional revenue stream from power sales, showcasing an effective method to manage financial risk and ensure a steady income throughout the plant's operation. The Hyderabad WTE , though slightly more complex and capital intensive, offers a pathway towards sustainable urban waste management by diversifying revenue streams and ensuring comprehensive treatment of various waste components.

The paper also discusses the sensitivity analysis, which is crucial for understanding how changes in the priority of criteria can affect the overall ranking of the power plants.

Such analysis confirms that the model is reliable and reveals that even with variable weights, the results are relatively stable, further supporting the robustness of the AHP approach /

5.2. Implications of this study

Policymakers can utilize the model as a replicable framework, adapting it to different regional contexts by incorporating local waste composition, policy environments, and economic conditions. This adaptability makes it a valuable tool across various geographical locations for decision making.

It has greater implications for the Urban Local Bodies that are planning to come up with innovative approaches for waste management problems. With Govt's support in budgeting, financial incentives such as VGF, it can come up with innovative PPP framework and design the concession agreements in such a way that it will be win-win situation for all stakeholders. This research can be widely used as a plug and play tool for the urban local bodies wherein they can customise the approach by taking various parameters that are best suited to their local context and decide accordingly that which model is suitable for them under what context and risk factors.

5.3. Contribution to Existing Literature

This study provides a novel, structured evaluation of Indian WTE plants using AHP, a methodology often underutilized in the Indian waste sector. It bridges the gap between qualitative policy critiques and quantitative technical comparisons, creating an integrated viability framework.

- Expands on the limited empirical data available on Indian incineration plants
- Provides replicable AHP methodology for evaluating future plants
- Highlights underexplored dimensions like social acceptability and institutional readiness

The viability of incineration-based WTE in India is not a binary outcome but a spectrum shaped by policy coherence, stakeholder coordination, financial innovation, and public trust. While technical feasibility exists, systemic realignment is required for sustainable impact. If India is to meet its Swachh Bharat and climate mitigation goals, WTE must transition from an isolated intervention to a core pillar of integrated urban waste management.

CHAPTER 6
POLICY RECOMMENDATIONS

Chapter 6:
POLICY RECOMMENDATIONS

This chapter provides evidence-based policy recommendations and outlines a strategic roadmap for enhancing the viability of incineration-based Waste-to-Energy (WTE) projects in India. Drawing upon the comparative analysis and rating using the AHP conducted in the previous chapters, this section translates analytical insights into actionable proposals for stakeholders including policymakers, investors, urban local bodies (ULBs), and WTE operators.

6.1. Strengthening the Policy Ecosystem

6.1.1. Streamlining Regulatory Approvals

One of the key impediments identified during case studies was the fragmented regulatory approval or environment clearance process. An integrated single-window clearance system for WTE projects under state nodal agencies could significantly reduce gestation time. This will effectively address the time delay issues arising out of the extensive environmental clearance procedure.

This would streamline project implementation and enhance investor confidence in the sector. Implementing such a system would align with best practices in corporate governance, which emphasize transparency and efficiency in regulatory processes (Eka et al., 2024). This approach not only fosters a more conducive environment for investment but also reflects the growing demand for transparency in corporate governance practices ("Corporate Governance," 2021).

6.1.2. Technology-Neutral Incentives

Current incentives such as Viability Gap Funding (VGF) and feed-in tariffs often favor certain technologies. A shift towards **output-based incentives** (e.g., per unit of energy generated or GHG saved) would reward actual performance over theoretical capacity as outlined by the

Sonipat model in our research. This choice should be left to the ULB managing the waste on which technology they need to adopt.

Technology-neutral incentives in the waste-to-energy sector can foster innovation while addressing environmental concerns, balancing efficiency and sustainability in waste management practices. Such incentives can encourage the adoption of diverse technologies, ultimately leading to improved waste management outcomes and greater resource efficiency in line with circular economy principles. These approaches align with the broader goals of enhancing resource efficiency and promoting sustainable practices across various sectors, particularly in waste management (Bekchanov et al., 2022). These strategies not only support the transition towards a circular economy but also emphasize the importance of stakeholder engagement in achieving sustainable waste management outcomes (Mia, 2025).

6.1.3. Institutional Strengthening and Capacity Building

Empowering Urban Local Bodies (ULBs)

Many ULBs lack the capacity to plan, procure, and monitor large-scale infrastructure like WTE plants. Dedicated State WTE Cells under ULBs can act as knowledge hubs to evaluate feasibility, monitor PPP contracts, and ensure compliance. This is the need of the hour as the projects , specifically WTE projects are bid out in PPP mode and there is dearth of knowledge in the ULBs set up. It lacks the experience and expertise required to design PPP projects and effectively managing the concession agreements with proper monitoring. A dedicated cell where existing resources can be trained accordingly with assistance from external experts in PPP would provide the right leverage to ULBs. Thus, empowering ULBs with right set up and human skills are imperative for successful execution of the project.

Public-Private Partnership (PPP) Enhancements

A revised **Model Concession** Agreement (MCA) tailored to WTE specifics (e.g., guaranteed tipping fees, performance-linked payments) should be adopted across states. It can be experienced that although many of the WtE projects are bid out on the basis of PPP, not all are performing well. This is due to the internal fallacy in the concession agreement of PPP. Not one size suits all. PPP projects should be well studied based on local conditions and flexibility should be incorporated inherently into the concession agreement that should be tailor specific to the regions and waste composition and private players willing to take up the job. Also, cross sector collaboration between the urban local bodies, government departments and external experts are very much required for institutional reforms for the WTE eco system.

Table 6.1: Institutional Reforms to Strengthen WTE Ecosystem

Recommendation	**Target Stakeholder**	**Expected Impact**
State WTE Cells	State Govts/ULBs	Localized technical oversight
Revised PPP Framework	NITI Aayog/MoEFCC	Improved investor confidence
Urban Sanitation Task Forces	MoHUA/ULBs	Cross-sector collaboration

Source: Authors own research

Technical Optimization of Incineration-Based WTE

Mandating Pre-processing and Segregation

Performance of incineration plants improves drastically with source segregation and RDF quality control. Central mandates for mechanical-biological treatment (MBT) prior to incineration should be institutionalized.

Emission Monitoring and Transparency

Only a few plants (like Hyderabad) proactively disclose emission levels. Real-time online emission monitoring (OCEMS) should be mandated and linked to CPCB servers for public disclosure. This is a much-required initiative as there is apprehension in local community regarding the emission levels of the WTE plants and because of this distrust without any proper information, they tend to oppose the waste to energy plants. By mandating such disclosures, information could be shared effectively and continuously with the local groups so that any unnecessary apprehensions could be avoided. This will also help the regulators to monitor the parameters and keep the developer in check.

6.2. Economic and Financial Instruments

6.2.1. Dynamic Tariff Design

A dynamic tariff mechanism indexed to calorific value and electricity output can incentivize plants to maximize efficiency. This also ensures fair returns for investors. However, the downside remains with the power procurement being heavily regulated in favour of consumers. As the WTE tariff already comes under preferential tariff mechanism and enjoys a premium tariff over others, it might be a challenge. However, WTE projects should be more seen as an environment friendly health initiative rather than a power generating tool. If the cost of environment and health could be integrated to WTE projects, then the dynamic tariff can get many more takers.

6.2.2. Performance-Linked Green Bonds

Municipalities could issue WTE-linked Green Bonds under the SEBI Green Bond Framework to attract ESG-conscious investors. Bond interest rates can be linked to plant performance indicators like uptime or emissions. Green bonds are the favour of the market due to rapidly involving ESG market and can be tapped for WTE projects by the municipalities.

Table 6.2: Financial Mechanisms for WTE

Instrument	Description	Benefit
Dynamic Tariff Indexing	Adjusted to energy output and RDF quality	Promotes efficiency
Green Bonds	Performance tied interest rates, align with SDG	Encourages sustainable finance
Carbon Credit Integration	Via Perform, Achieve and Trade (PAT) or Renewable Energy Certificates (REC) mechanisms	Monetizes GHG reductions

Source: Secondary research and Authors' analysis

6.3. Community Engagement and Social License to Operate

6.3.1. NIMBY Mitigation Programs

Public opposition remains a major hurdle. Structured community engagement programs with local stakeholder mapping, grievance redressal cells, and regular plant open days can build trust.

6.3.2. Co-benefits Communication

Highlighting co-benefits like local job creation, improved waste handling, and land rehabilitation through ash utilization can shift public perception. These social initiatives combined with livelihood can create a better uptake from the local community for the WTE projects.

6.4. Alignment with Global Best Practices

6.4.1. Japan's High-Efficiency Plants

Japan is one of the leader in decentralized incineration WTE plants that combines high-calorific RDF, public communication campaigns, and district heating integration. These plants are small in size but operationally very efficient. They regularly communicate with the public and invite their active participation through town halls and employs much improved ash vitrification technologies with very less percentage of ash for landfills

6.4.2. Germany's Circular Economy Legislation

The German Waste Management Act mandates upstream waste minimization and promotes thermal treatment only after material recovery. It is essential for promoting sustainable practices and ensuring that resources are used efficiently while minimizing environmental impact.

This legislation encourages the transition from traditional linear models to more sustainable circular practices, fostering eco-efficiency and resource conservation. This shift not only helps in reducing waste but also contributes to economic growth and social well-being, aligning with the principles of sustainable development. This approach emphasizes the importance of integrating environmental legislation within industrial practices to support the shift towards a circular economy. (Kyriakopoulos, 2021)

CHAPTER 7

CONCLUSION, LIMITATIONS AND DISCUSSION

Chapter 7:
CONCLUSION, LIMITATIONS AND DIRECTION

7.1. Conclusion

The study has critically evaluated the viability of incineration-based Waste-to-Energy (WTE) projects in India through a comparative analysis of four operational plants using the Analytical Hierarchy Process (AHP). The multidimensional assessment covered economic, environmental, Regulatory, operational and socio-cultural factors.

Though these criteria are selected after carefully examining the major parameters that generally affects the viability of any incineration based WTE in India, there remains major critical gaps that need to be addressed while adopting incineration based WTE power plants India.

The selection of waste incineration plants is critically impacted by inconsistent waste quality, inadequate segregation, technical complexities, issues with assuring a continuous supply of quality waste, and high capital costs—all of which need to be carefully managed for long-term success. Though this research only reflects some of the parameters that are currently impacting the operational waste to energy plants in terms of its long-term sustainability, there are other critical parameters and other technical and operational challenges that cannot be ignored while making decisions regarding a suitable model for adoption in Indian context.

Further enhance public acceptance and trust, addressing concerns related to health and environmental impacts and fostering a collaborative approach between stakeholders and local communities is crucial for the successful implementation of waste-to-energy projects (Caferra etal,2022). Ultimately, fostering a transparent dialogue and providing clear information about the benefits and safety of waste-to-energy technologies will be vital for overcoming public skepticism and achieving successful project outcomes. Moreover, integrating scientific assessments and independent evaluations can help build confidence in waste-to-energy projects, addressing public concerns about emissions and environmental safety (Caferra et al., 2023)

High capital costs, fluctuating RDF prices, and low tipping fees are some of the factors that contribute to the overall financial challenges faced by waste-to-energy (WtE) projects, necessitating innovative funding solutions and effective management strategies. To address these challenges, stakeholders must explore alternative revenue streams and enhance operational efficiencies to ensure the sustainability of WtE initiatives. In addition, collaboration among government, private sector, and local communities can foster a more supportive environment for WtE projects, ultimately leading to improved waste management outcomes. By leveraging public-private partnerships and exploring diverse funding mechanisms, WtE projects can enhance their financial viability and operational success. This collaborative approach will not only address existing challenges but also promote sustainable waste management practices across various regions. This comprehensive strategy is essential for overcoming the inherent complexities of implementing waste-to-energy solutions in diverse urban contexts.

The findings also underscore that underperformance of WtE projects in India arises less from the absence of supportive policies and more from inconsistencies in implementation, enforcement and accountability, which must be addressed alongside technology choice if long-term sustainability is to be realized. While extensive primary fieldwork was not possible within the scope of this thesis, its quality has been strengthened by explicitly acknowledging this limitation and by placing greater emphasis on socio-political drivers of WtE performance. The thesis therefore complements the AHP-based quantitative comparison with a more critical appraisal of the method itself and of the existing policy and regulatory frameworks, highlighting how institutional, political and governance factors shape project outcomes beyond what can be captured through numerical criteria alone.

7.2. Limitations of the Research

The study primarily concentrates on municipal solid waste (MSW)/ mixed waste, meaning other types of waste such as agricultural or medical waste are not included. The restricted waste stream focus might limit the applicability of the findings when considerations are evolved for processing other waste streams that have different characteristics and treatment challenges. The study was completely focused on the Indian Scenario, thus restricts itself only to Indian scenarios. Though the criteria are more of similar in nature in other countries, however, it may differ in other criteria like regulatory challenges, socio cultural challenges in other countries. So, the data sources are geographically limited. As a consequence, the results might not be as applicable to regions outside India, where waste characteristics, policies, and economic conditions can vary significantly.

The data availability is less in this type of studies and the data constraints and limited expert interviews might hamper the overall decision. The data constraints are likely affecting the outcome of the research, which means the outcomes are dependent on the availability and quality of the data from these expert interviews and their apprehensions to a particular parameter. This dependency might lead to potential biases or limitations inherent in the source data that were not originally designed to answer the specific research questions of this study. There is narrow comparison criteria as the study only focusses on five main criteria. An in-depth study can extend the main criteria going beyond 7 or 8 with its sub criteria thus making the decision-making process robust.

The analytical process is based on the Analytical Hierarchy Process (AHP), which involves pairwise comparisons and priority vector calculations. While AHP is a well-established method, its reliance on subjective judgments can introduce bias. The consistency checks help manage this; however, the subjectivity present in the method remains a limitation in terms of replicability and universal acceptance.

Each of these points highlights that while the study provides a comprehensive and detailed analysis of viability of WtE plants in Indian context using the AHP model, its limitations remind us that further research and localized data integration are essential before generalizing the findings universally.

7.3. Future Research Directions

While this study offers valuable insights into selecting the suitable WtE plant and its model from existing options, there are several areas for future research. A significant challenge for future research is integrating evolving policies, particularly those related to climate change, into the decision-making model.

Addressing these challenges will require adaptive and flexible models capable of incorporating new data and responding to shifting external conditions. To tackle these challenges, future research should focus on several key areas such as expanding the model to incorporate more granular sub-criteria that could offer a more comprehensive analysis and enhance the decision-making framework. Furthermore, testing the AHP model in various regional contexts with various risk scenarios, infrastructure capacities, and policy frameworks would help in generalizing the findings and tailoring the model to address specific local needs.

Areas of future research could be application of multi-criteria decision-making (MCDM) techniques beyond AHP (e.g., TOPSIS, VIKOR) and longitudinal studies on post-commissioning performance of WTE plants and Life Cycle Assessment (LCA) of various operating projects taking health and environmental cost for overall sustainability.

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