

**FORMULATION AND DEMONSTRATION OF A
TECHNIQUE TO ASSESS THE INCINERABILITY
OF MUNICIPAL SOLID WASTE**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
FEBRUARY 2019**

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TECHNIQUE TO ASSESS THE INCINERABILITY
OF MUNICIPAL SOLID WASTE**

by

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Submitted

In fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2019

CERTIFICATE

This is to certify that the thesis entitled “**Formulation and Demonstration of a Technique to Assess the Incinerability of Municipal Solid Waste**”, being submitted by **Ms. Roshni Mary Sebastian**, to the Indian Institute of Technology Delhi for the award of ‘**Doctor of Philosophy**’ in Department of Civil Engineering is a record of the bonafide research work carried out by her under our supervision and guidance. She has fulfilled the requirements for the submission of this thesis, which to the best of our knowledge has reached the requisite standard.

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.



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Date: 28-02-2019

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ACKNOWLEDGEMENTS

Doctoral research holds a special place in my pursuit of academic excellence and in my journey to finding my true calling. I am forever indebted to my guides Prof Babu J Alappat and Dr Dinesh Kumar for their unstinted guidance, motivation and support through this journey. From teaching me how to tackle the research problems, challenging me to think out of the box, training me to face success and failure with the same panache and to inspiring me to be a better researcher and a better person, I owe it all to them.

I am also grateful for the valuable insights, critical comments and encouragement from my SRC, Prof B Bhattacharjee, Dr Ramesh Narayanan and Dr Arun Kumar. I appreciate their time and patience through the course of my study. I also appreciate the support from the laboratory staff, Dr Sanjay Gupta and Mr Ishwar Singh for their valuable support in the lab.

I am thankful to Prof N K Garg, HOD, Department of Civil Engineering. I appreciate all the timely assistance and support from Mr. Rajveer Agarwal, Mr Randhir Jha, Mr. Jeetram, Ms Neeru and other staff members of Civil Engineering Department.

My gratitude also goes to NRF, CRF, CRDT and Chemical Engineering Department for providing the instrumentation facility without which my work would have remained incomplete.

My friends have been an incredible part of this journey. I am beyond grateful to Dr Sumanth Chinthala, Mr. Maneesh N., Mr. Anujkumar Ghorpade and Mr. Prem Mohan for accompanying me to the sampling sites even during their busy schedules and appreciate their endurance. I am glad for all the support from Dr Shivali Chaurasia and Mr Sasi Kumar N, for their positivity and motivation. I am glad for the friendships I made for life, Ms Aswathy R, Ms Ananya Das,

Ms Preeti Nain, Ms. Tanusree Parsai, Ms Ananya Roy, and all the others during these past couple of years.

I am grateful for love and support of my family. My parents, P A Sebastian and Elizabeth Chacko for their unconditional love, for believing in me and for teaching me to dream. My siblings Tony and Tina for always having my back. My in-laws, T D Louis, Stella Louis and Fr Jilson for their selfless love and countless prayers. Above all, the unwavering love and support of my best friend and partner-in-crime, my husband Jibil Louis. Had he not been the wind under my wings, this dream of mine would have remained a dream.

Last, but not the least, I thank God Almighty, for all his blessings.

Roshni Mary Sebastian

ABSTRACT

Waste incineration has become an inevitable element of an integrated municipal solid waste (MSW) management system. Sustainability of the technology is essential for the generation of renewable energy, reducing greenhouse gas (GHG) emissions and in turn addressing climate change issues, besides effective MSW management. Incinerability of the MSW is crucial to ascertain the feasibility as well as the sustainability of waste incineration. Environmental, energy recovery and economic criteria (3-E concept) are in turn, integral to estimating the incinerability of MSW.

While the conventional assessment techniques only weigh in the energy recovery aspect, the ensuing environmental impact is seldom accounted for. With the waste to energy (WtE) industry witnessing a steady growth, especially in developing countries like China, India etc. there is a pronounced need for a technique to quantify the incinerability of MSW. To resolve this, a composite indicator for incinerability called incinerability index or *i*- Index is formulated incorporating the 3-E concept. The opinions of more than 200 experts from academia, industry and government and regulatory authorities are incorporated during the parameter selection, their relative weightage determination using analytic hierarchy process (AHP) and the development of rating curves for their normalisation. Through the eight input parameters which encompass the various aspects of this multi-criteria concept, incinerability is quantified as a unique number on a scale of 0-100 by weighted summation technique, 100 representing the most incinerable scenario.

A graphical assessment tool called incinerability plot or *i*- Plot is also developed to define various zones of incinerability, namely, non-incinerable zone, incinerable zone and autogenously incinerable zone. *i*- Plot consists of two different plots, one based on the normalised parameter values and the other based on the aggregated index value. *i*- Index of

less than nearly 45 may be assumed to be non-incinerable, while more than around 89, autogenously incinerable through this method. Besides being a visual assessment tool, this plot also defines certain permissible limits for incinerability using *i*- Index to simplify the decision-making process.

The study also demonstrates the various applications of incinerability assessment using *i*- Index, for instance, the fluctuations of incinerability temporally, seasonally, regionally or due to informal recycling or organised material recovery operations etc. and its implications on the planning of WtE facilities. An incinerability mapping for Indian sub-continent is also developed, representing the incinerability of MSW generated in more than 100 different cities, serving as a beneficial tool for policy-makers and other stakeholders, while planning WtE facilities.

The research also aims to develop a quick estimation technique for the various characteristics of the mixed MSW stream, including its incinerability. Conventionally, this computation is carried out through the physical and chemical characteristics of individual component fractions present in the MSW feed, reported by previous researchers. However, since this is from a five-decade-old study, there is a need to reassess and develop a revised database of the characteristics of individual MSW components, especially, for a developing country like India, due to the poor source segregation and heterogeneity of the MSW, climatic conditions as well as the differences in the raw materials and manufacturing processes. An extensive sampling and characterisation study is thus performed across 5 different cities in Indian sub-continent to analyse and establish the physical and chemical characteristics of individual MSW components present in Indian MSW. A demonstration of the theoretical estimation of the various characteristics of mixed MSW like proximate analysis, ultimate analysis, heat content, C/N ratio, air requirement for incineration, potential flue gas release, ash generation etc. using the

derived revised database is also performed. This eliminates the need for laborious and costly characterisation studies, for at least the preliminary feasibility studies.

This research not only proposes a novel decision-making method to estimate the incinerability of MSW but also derives a revised physical and chemical characteristics database of individual MSW components, to enable easy estimation of various properties of mixed MSW stream, without tedious laboratory analyses. The study thus simplifies the feasibility studies and facilitates the formulation of the integrated waste management strategies and regulatory policies.

Keywords: Municipal solid waste, incineration, waste to energy, incinerability, environmental indicators.

सार

वेस्ट समावेशन एक एकीकृत नगरपालिका ठोस वेस्ट (एमएसडब्ल्यू) प्रबंधन प्रणाली का एक अपरिहार्य तत्व बन गया है। ग्रीनहाउस गैस (जीएचजी) उत्सर्जन को कम करने और प्रभावी एमएसडब्ल्यू प्रबंधन के अलावा जलवायु परिवर्तन के मुद्दों को दूर करने के लिए अक्षय ऊर्जा उत्पादन के लिए प्रौद्योगिकी की स्थिरता आवश्यक है। एमएसडब्ल्यू की अस्थिरता व्यवहार्यता का पता लगाने के लिए वेस्ट भस्मीकरण की स्थिरता का पता लगाना महत्वपूर्ण है। पर्यावरण, ऊर्जा वसूली और आर्थिक मानदंड (3-ई अवधारणा) बारी-बारी से एमएसडब्ल्यू की अस्थिरता का आकलन करने के लिए अभिन्न अंग हैं।

जबकि पारंपरिक मूल्यांकन तकनीक केवल ऊर्जा वसूली पहलू में मदद करते हैं, आगामी पर्यावरण का मूल्यांकन शायद ही कभी किया जाता है। जहाँ एमएसडब्ल्यू से ऊर्जा उत्पादन (WtE) वाले उद्योगों में लगातार वृद्धि देखी जा रही है, वही विशेष रूप से विकासशील देशों जैसे चीन, भारत आदि में एमएसडब्ल्यू की अस्थिरता को निर्धारित करने के लिए एक तकनीक की स्पष्ट आवश्यकता है। इसे हल करने के लिए, इन्सिनराबिलिटी सूचकांक या i- सूचकांक तैयार किया गया है जो कि, 3-E अवधारणा को ध्यान में रखता है। 200 से अधिक अकादमिक, उद्योगपतिओं और सरकारी और नियामक अधिकारियों की राय पैरामीटर चयन के दौरान शामिल की गई है, जिनका सापेक्ष महत्त्व का मूल्यांकन एनालिटिक हायरार्की प्रोसेस (एएचपी) द्वारा किया गया है और साथ ही साथ उनके रेटिंग के लिए रेटिंग कर्व्स का मानकीकरण किया गया है।

आठ इनपुट मापदंडों के माध्यम से जो इस बहु-मापदंड अवधारणा के विभिन्न पहलुओं को समाहित करते हैं, भारोत्तोलन तकनीक द्वारा 0-100 के पैमाने पर एक अद्वितीय संख्या के रूप में इन्सिनराबिलिटी की मात्रा निर्धारित की गयी है, 100 सबसे अधिक भयावह परिदृश्य का प्रतिनिधित्व करते हैं।

एक ग्राफिकल एसेसमेंट टूल जिसे इनकनेरेबिलिटी प्लॉट या i- प्लॉट कहा जाता है, को भी इन्सिनराबिलिटी के विभिन्न ज़ोन, अर्थात् नॉन- इन्सीनेरेबले ज़ोन, इन्सीनेरेबले ज़ोन और ऑटोजेनिक इन्सीनेरेबले ज़ोन को परिभाषित करने के लिए विकसित किया गया है। i- प्लॉट में दो अलग-अलग प्लॉट होते हैं, एक सामान्यीकृत पैरामीटर वैल्यू के आधार पर और दूसरा एग्रीगेटेड इंडेक्स वैल्यू पर आधारित होता है। i- लगभग 45 से कम के सूचकांक को नॉन- इन्सीनेरेबले माना जा सकता है, जबकि लगभग 89 से अधिक को इस विधि के माध्यम से

ऑटोजेनिक इन्सीनरेबले माना जा सकता है। विज़ुअल असेसमेंट टूल होने के अलावा, यह प्लॉट निर्णय लेने की प्रक्रिया को आसान बनाने के लिए i- इंडेक्स का उपयोग करके असंयम के लिए कुछ अनुमेय सीमा को भी परिभाषित करता है।

i- इंडेक्स का उपयोग करते हुए इन्सिनराबिलिटी आकलन के विभिन्न अनुप्रयोगों का भी अध्ययन करता है, उदाहरण के लिए, अस्थायी रूप से, क्षेत्रीय रूप से या अनौपचारिक रीसाइक्लिंग या संगठित सामग्री वसूली संचालन आदि के कारण अस्थिरता के उतार-चढ़ाव और WtE सुविधाओं की योजना पर इसके प्रभाव। डब्ल्यूटीई सुविधाओं की योजना बनाते समय नीति निर्माताओं और अन्य हितधारकों के लिए एक लाभकारी उपकरण के रूप में सेवारत, 100 से अधिक विभिन्न शहरों में उत्पन्न एमएसडब्ल्यू की असंयमता का प्रतिनिधित्व करते हुए, भारतीय उप-महाद्वीप के लिए एक तकनीक का विकास भी किया गया है।

इस शोध का उद्देश्य मिश्रित एमएसडब्ल्यू स्ट्रीम की विभिन्न विशेषताओं के लिए एक त्वरित आकलन तकनीक विकसित करना है, जिसमें इसकी इन्सिनराबिलिटी भी शामिल है। परंपरागत रूप से, यह गणना एमएसडब्ल्यू फ़ीड में मौजूद अलग-अलग अवयव की भौतिक और रासायनिक विशेषताओं के माध्यम से की जाती है, जो पिछले शोधकर्ताओं द्वारा रिपोर्ट की गई थी। हालांकि, चूंकि यह पांच दशक पुराने अध्ययन से है, इसलिए विशेष रूप से भारत जैसे विकासशील देश के लिए जहाँ अनुचित स्रोत अलगाव और विभिन्न जलवायु परिस्थितियों के साथ-साथ विभिन्न विनिर्माण प्रक्रियाओं में अंतर है, वहां अलग-अलग एमएसडब्ल्यू घटकों की विशेषताओं के एक संशोधित डेटाबेस को फिर से विकसित करने की आवश्यकता है। इस प्रकार एक व्यापक नमूनाकरण और लक्षण वर्णन अध्ययन भारतीय उप-महाद्वीप के 5 अलग-अलग शहरों में भारतीय एमएसडब्ल्यू में मौजूद व्यक्तिगत एमएसडब्ल्यू घटकों की भौतिक और रासायनिक विशेषताओं का विश्लेषण करने और स्थापित करने के लिए किया गया है। व्युत्पन्न संशोधित डेटाबेस का उपयोग करके मिश्रित एमएसडब्ल्यू की विभिन्न विशेषताओं जैसे अनुमानित विश्लेषण, अंतिम विश्लेषण, हीट कंटेंट, सी / एन अनुपात, भस्मीकरण के लिए हवा की आवश्यकता, संभावित फ्लू गैस रिलीज, राख पीढ़ी आदि के सैद्धांतिक अनुमान का प्रदर्शन भी किया गया है। यह कम से कम प्रारंभिक व्यवहार्यता अध्ययन के लिए, श्रमसाध्य और महंगे लक्षण वर्णन अध्ययन की आवश्यकता को समाप्त करता है।

यह शोध न केवल एमएसडब्ल्यू की अस्थिरता का अनुमान लगाने के लिए एक नई निर्णय लेने की विधि का प्रस्ताव करता है, बल्कि विभिन्न एमएसडब्ल्यू घटकों के संशोधित भौतिक और

रासायनिक विशेषताओं डेटाबेस को भी प्राप्त करता है, ताकि बिना थके हुए प्रयोगशाला विश्लेषणों के मिश्रित एमएसडब्ल्यू स्ट्रीम के विभिन्न गुणों के आसान अनुमान को सक्षम किया जा सके। यह अध्ययन इस प्रकार व्यवहार्यता अध्ययन को सरल बनाता है और एकीकृत वेस्ट प्रबंधन रणनीतियों और नियामक नीतियों के निर्माण की सुविधा प्रदान करता है।

कीवर्ड: नगरपालिका ठोस वेस्ट, भस्मीकरण, ऊर्जा के लिए वेस्ट, अस्थिरता, पर्यावरण संकेतक।

TABLE OF CONTENTS

Certificate.....	i
Acknowledgements.....	ii
Abstract.....	iv
List of figures.....	x
List of tables.....	xii
Nomenclature.....	xiv
1. INTRODUCTION	1
1.1. COMBUSTIBLE QUALITY OF MSW	3
2. WASTE TO ENERGY: OPTIONS, OPPORTUNITIES AND CHALLENGES	6
2.1. THERMAL TREATMENT OF MSW: TECHNO-ECONOMIC CONSIDERATIONS	7
2.1.1. <i>Technical considerations for waste incineration</i>	7
2.1.2. <i>Economic considerations for waste incineration</i>	8
2.2. STATE OF THE ART MSW MANAGEMENT: ROLE OF MSW CHARACTERISTICS	11
2.2.1. <i>Characterisation of MSW: Options and constraints</i>	12
2.3. THERMAL TREATMENT OF MSW: ASIAN SCENARIO	15
2.4. ASSESSMENT OF COMBUSTIBLE QUALITY OF MSW: CONVENTIONAL APPROACH	20
2.5. MCDM FOR MSW MANAGEMENT PROBLEMS.....	22
3. OBJECTIVES AND SCOPE OF THE STUDY	25
3.1. OBJECTIVES OF THE STUDY	25
3.2. SCOPE OF THE STUDY	25
4. FORMULATION AND DEMONSTRATION OF INCINERABILITY INDEX.....	27
4.1. INTRODUCTION.....	27
4.2. METHODOLOGY	28
4.2.1. <i>Stage 1: Selection of parameters</i>	28
4.2.2. <i>Stage 2: Determination of weightages</i>	33
4.2.3. <i>Stage 3: Development of normalisation curves</i>	40
4.2.4. <i>Aggregation of composite indicators</i>	45
4.2.5. <i>Selection of aggregation function for incinerability index: what to use?</i>	48
4.2.6. <i>Sensitivity analysis</i>	55
4.3. DEMONSTRATION OF INCINERABILITY ESTIMATION USING <i>I</i> - INDEX	60
4.3.1. <i>Introduction</i>	60
4.3.2. <i>Computation of i- Index: A Step- by- Step Approach</i>	61
4.3.3. <i>Estimation of Parameters for Quantifying Incinerability</i>	62
4.3.4. <i>Aggregation of Parameters</i>	71
4.4. UNCERTAINTY ANALYSIS	73

4.4.1.	<i>Introduction</i>	73
4.4.2.	<i>Methodology</i>	74
4.4.3.	<i>Monte-Carlo Approach</i>	76
4.4.4.	<i>Results and discussion</i>	77
5.	GRAPHICAL DETERMINATION OF INCINERABILITY OF MUNICIPAL SOLID WASTE	86
5.1.	OVERVIEW	86
5.2.	GRAPHICAL REPRESENTATION OF INCINERABILITY.....	86
5.3.	DEFINING INCINERABILITY ZONE.....	90
5.3.1.	<i>Bulk Density</i>	90
5.3.2.	<i>CO₂ release per kilogram of MSW</i>	91
5.3.3.	<i>Heat content</i>	91
5.3.4.	<i>Moisture content</i>	92
5.3.5.	<i>Quantity of auxiliary fuel required to maintain 1000⁰ C</i>	93
5.3.6.	<i>Specific heat</i>	93
5.3.7.	<i>SO₂ release per kilogram of MSW</i>	94
5.3.8.	<i>Volatile content</i>	95
5.4.	GRAPHICAL DEPICTION OF I- INDEX.....	95
5.5.	INCINERABILITY ASSESSMENT USING GRAPHICAL METHOD.....	99
5.6.	SUMMARY.....	101
6.	APPLICATIONS OF INCINERABILITY INDEX	102
6.1.	REGIONAL VARIATION OF INCINERATION: MAPPING OF INCINERABILITY IN INDIAN SUB-CONTINENT.....	102
6.1.1.	<i>Incinerability mapping: An analysis</i>	104
6.1.2.	<i>Regional variations in incinerability</i>	107
6.1.3.	<i>State-wise power generation potential from MSW</i>	109
6.1.4.	<i>Incinerability of MSW generated in South East Asia</i>	110
6.2.	TEMPORAL VARIATIONS IN INCINERABILITY OF MSW.....	111
6.2.1.	<i>Temporal variations in different economies: An analysis</i>	112
6.3.	INFLUENCE OF RECYCLING ON INCINERABILITY.....	118
6.3.1.	<i>Variation in incinerability of MSW with recycling of component fractions: A theoretical approach</i>	120
6.3.2.	<i>Approach A: Recycling of Individual components</i>	120
6.3.3.	<i>Approach B: Simultaneous segregation of different components</i>	125
6.3.4.	<i>Variation in incinerability of MSW with recycling in a developed economy</i> ..	126
6.4.	SUMMARY.....	126
7.	AN EASY ESTIMATION OF MIXED MUNICIPAL SOLID WASTE CHARACTERISTICS FROM COMPONENT ANALYSIS	128
7.1.	INTRODUCTION.....	128
7.2.	MATERIALS AND METHODOLOGY.....	130
7.2.1.	<i>Sampling</i>	130

7.2.2.	<i>Component fractions</i>	131
7.2.3.	<i>Basic characterisation</i>	132
7.3.	EXPERIMENTAL RESULTS.....	133
7.3.1.	<i>Physical characteristics</i>	134
7.3.2.	<i>Chemical composition</i>	138
7.4.	ESTIMATION OF MSW PROPERTIES.....	139
7.4.1.	<i>Proximate analysis</i>	139
7.4.2.	<i>Ultimate analysis</i>	140
7.4.3.	<i>Gross calorific value of MSW</i>	141
7.4.4.	<i>Stoichiometric air requirement</i>	142
7.4.5.	<i>Total flue gas release from MSW</i>	142
7.4.6.	<i>Total ash generation</i>	143
7.4.7.	<i>Auxiliary fuel requirement</i>	143
7.5.	APPLICATIONS OF REVISED PHYSICO-CHEMICAL COMPOSITION DATA.....	144
7.6.	HEAT CONTENT.....	148
7.7.	AIR REQUIREMENT AND FLUE GAS RELEASE.....	148
7.8.	AUXILIARY FUEL REQUIREMENT.....	150
7.9.	ASH GENERATION.....	150
7.10.	SUMMARY.....	151
8.	CONCLUSIONS	152
9.	SIGNIFICANCE AND FUTURE SCOPE OF THE WORK	155
9.1.	SIGNIFICANCE OF THE WORK.....	155
9.2.	FUTURE SCOPE OF THE WORK.....	156
	REFERENCES	156
	Appendix I-A	174
	Appendix I-B	178
	Appendix I-C	187
	Appendix II	198
	Appendix III	199
	Appendix -IV	204
	Appendix V	209
	Appendix VI	210
	Curriculum Vitae	211

LIST OF FIGURES

Figure 2.1: The flowchart of a WtE plant	8
Figure 2.2: Composition of MSW generated in countries belonging to different income groups	12
Figure 2.3: Statistics of MSW characterization studies over the years [a] Globally [b] India	14
Figure 2.4: Composition of MSW of Delhi city from 1971 projected till 2024	16
Figure 2.5: [a] Position of study areas in Tanner diagram [b] Thumb rule using heat content	21
Figure 4.1: Process flow chart for the formulation of i-Index	29
Figure 4.2: Hierarchical structuring of the research problem	35
Figure 4.3: Responses received during AHP questionnaire surveys	38
Figure 4.4: Normalisation curves for [a] Bulk density [b] CO ₂ released [c] Calorific value [d] Auxiliary fuel requirement.....	43
Figure 4.5: Normalisation curves for [e] Moisture content [f] Specific heat [g] SO ₂ released [h] Volatile content	44
Figure 4.6: Variations in MSW composition with income level	49
Figure 4.7: Comparison of i- Index values by weighted and unweighted root sum power function	52
Figure 4.8: Comparison of i- Index values by weighted and unweighted multiplicative aggregation.....	54
Figure 4.9: Variation in i- Index values with variations in individual parameters	57
Figure 4.10: Percentage variation in i- Index values with variations in individual parameters	58
Figure 4.11: Composition of MSW generated in South Delhi in 2017	61
Figure 4.12: Heat balance across the furnace of an incineration plant	67
Figure 4.13: Comparative assessment of <i>i</i> - Indices of various raw MSW feeds	72
Figure 4.14: Monte Carlo simulation for uncertainty analysis	76
Figure 4.15: Variation in i- Index when input parameter is missing	78
Figure 4.16: Uncertainty analysis of relative weightages.....	79
Figure 4.17: Difference in incinerability scores due to equal weighting.....	80

Figure 4.18: Difference between actual and simulated incinerability scores using different weightage schemes.....	80
Figure 4.19: Uncertainty analysis of <i>i</i> - Index; original <i>i</i> - Index and the <i>i</i> - Index computed using simulated data (indicated along with 5 th and 95 th percentile values)	81
Figure 4.20: Uncertainty analysis of <i>i</i> - Index; original <i>i</i> - Index and the <i>i</i> - Index computed using simulated data (indicated along with 5 th and 95 th percentile values)	82
Figure 4.21: Correlation between incinerability quantified by weighted summation and weighted multiplicative aggregation.....	83
Figure 4.22 [a]: Tornado plot.....	84
Figure 4.22 [b]: Spider plot.....	84
Figure 4.23: Net uncertainty in various stages of construction of <i>i</i> - Index	84
Figure 5.1 [a]: Graphical representation of <i>i</i> - Index on the basis of sub-index values.....	88
Figure 5.1 [b]: Graphical representation of <i>i</i> - Index on the basis of aggregated values.....	88
Figure 5.2: Radar plot showing the incinerability zone using sub-indices	97
Figure 5.3: Radar plot showing incinerability zone using <i>i</i> - Index.....	98
Figure 5.4: Graphical incinerability assessment using <i>i</i> - Plot	100
Figure 6.1: Graphical mapping of incinerability of MSW in Indian sub-continent	105
Figure 6.2: <i>i</i> - Plot [a] Based on normalised parameter values [b] Based on aggregated indicator	108
Figure 6.3: State-wise MSW generation, power generation potential from MSW and <i>i</i> - Index of generated MSW	110
Figure 6.4: Incinerability of MSW generated in South East Asian countries on a scale of 0-100	111
Figure 6.5: <i>i</i> -Index values for MSW generated in Delhi, UK, USA and Beijing during the study period	114
Figure 6.6: Variation in the incinerability of MSW over the years in the US	117
Figure 6.7: Variation in incinerability of MSW with recycling of different fractions of MSW	121
Figure 6.8: Variation in <i>i</i> - Index values for MSW in different cases under consideration...	123
Figure 7.1: Tanner diagram representing proximate analysis.....	145
Figure 7.2: GCV of MSW generated in study areas estimated on as-received basis and the corresponding reported data.....	149
Figure 7.3: Theoretical and actual air requirement and flue gas release at stoichiometry, while incinerating different MSW feeds on as-received basis	149

LIST OF TABLES

Table 2.1: Status of WtE industry in prominent South Asian countries	18
Table 2.2: MCDM methods used in environmental decision-making scenarios	23
Table 4.1: Responses received from the preliminary questionnaire	30
Table 4.2: Comparison matrix for the criteria, with respect to the feasibility of incineration	36
Table 4.3: Comparison matrix for the parameters with respect to the 3-E criteria.....	37
Table 4.4: Relative weightages of the criteria with respect to the incinerability of MSW	39
Table 4.5: Relative weightages of parameters with respect to the incinerability of MSW.....	39
Table 4.6: Parameter scores and normalised values for different MSW feeds	56
Table 4.7: Aggregated i- Index values by different aggregation functions	56
Table 4.8: Loss of information in the index during aggregation	59
Table 4.9: Experimental methodology for characterisation studies.....	62
Table 4.10: Physical and chemical characteristics of components of MSW	63
Table 4.11: Proximate and ultimate analyses of MSW _{South Delhi}	65
Table 4.12: Elemental composition of No. 2 Fuel oil.....	68
Table 4.13: Normalised parameter values for MSW generated in South Delhi, 2017	72
Table 4.14: Sources of uncertainty in Incinerability index	75
Table 5.1: Composition of different MSW feeds.....	87
Table 5.2: Sub-index values of the parameters for various feeds	87
Table 5.3: Estimated auxiliary fuel requirement for MSW generated in different economies	94
Table 5.4: Parameter values for defining zone of incinerability.....	96
Table 6.1: Average MSW composition in different regions of India	107
Table 6.2 [a]: Values of the input parameters and the corresponding normalised values for different MSW feeds.....	113
Table 6.2 [b]: Values of the input parameters and the corresponding normalised values for different MSW feeds.....	113
Table 6.3 [a]: Parameter and normalised values for different MSW feeds (Approach A) ...	122
Table 6.3 [b]: Parameter and normalised values for different MSW feeds (Approach B) ...	122
Table 7.1: Different MSW fractions characterised for the study	132
Table 7.2: Moisture content determination of individual component fractions over different seasons in the study areas	135

Table 7.3: Summary of the physical and chemical characteristics of different MSW components in India.....	136
Table 7.4: Percentage deviation from the characteristics reported by Kaiser (1966a) and Tchobanoglous et al. (1993)	137
Table 7.5: Percentage composition of MSW generated in the study areas.....	139
Table 7.6: Proximate analysis of mixed MSW	145
Table 7.7: Elemental composition of mixed MSW generated in different study areas	147

NOMENCLATURE

MSW	Municipal solid waste
% E	Percentage elemental composition
AHP	Analytic hierarchy process
A_i	Inert content in individual component fractions
ANP	Analytic Network Process
AQI	Air quality index
C & D	Construction and demolition
C_c	Average composition of component
Cc_i	Component fraction (%) in the corresponding city
C, H, N, S, O	% carbon, % hydrogen, % nitrogen, % sulphur, % oxygen in the MSW feed respectively.
CBA	Cost-benefit analysis
CI	Consistency index
C_{Indi}	Composite indicator
$C_{pw}, C_{pa}, C_{pin}, C_{pf}$	Specific heat of MSW feed, air, individual waste components and fuel respectively.
CR	Consistency ratio
CV_{ij}, CV_{dj}	Gross calorific value of individual waste components on as-received basis and dry basis, respectively
$CV_{MSW}, CV_{Fuel}, CV_{Ash}, CV_i$	Gross calorific value of MSW, fuel, ash and individual waste components respectively.
D	Difference in <i>i</i> - Index
DPR	Detailed project report
E_f	Energy input to the system as auxiliary fuels
E_i	Annual energy imported
ELECTRE	Elimination Et Choix Traduisant la Realite
E_p	Annual energy production in the form of heat or electricity
EU	European Union
E_w	Energy contained in the MSW feed
GAIA	Geometric Analysis for Interactive Aid
GCV	Gross calorific value
GCV_{MSW}, GCV_f, GCV_r	GCV of MSW, fuel fed to the furnace and raw mixed MSW.
GHG	Greenhouse gas
GoI	Government of India

HIC, UMIC, LMIC, LIC	High-income, upper middle-income, lower middle-income, low-income countries
H_{ash}	Sensible heat of ash
H_S	Steam enthalpy
IC	Inert content of MSW
I_{AFEF}	<i>i</i> - Index by ambiguity and eclipsing free function
I_{MAX}	<i>i</i> - Index by maximum operator
I_{MIN}	<i>i</i> - Index by minimum operator
I_{RMS}	<i>i</i> - Index by root mean square
I_{RS2}	<i>i</i> - Index by root sum power (2)
I_{RS4}	<i>i</i> - Index by root sum power (4)
I_{RS10}	<i>i</i> - Index by root sum power (10)
I_{UM}	<i>i</i> - Index by unweighted multiplicative aggregation
I_{US}	<i>i</i> - Index by unweighted summation
I_{WM}	<i>i</i> - Index by weighted multiplicative aggregation
I_{WRMP}	<i>i</i> - Index by weighted root mean power
I_{WRMS}	<i>i</i> - Index by weighted root mean square
I_{WRS2}	<i>i</i> - Index by weighted root sum power (2)
I_{WRS4}	<i>i</i> - Index by weighted root sum power (4)
I_{WRS10}	<i>i</i> - Index by weighted root sum power (10)
I_{WS}	<i>i</i> - Index by weighted summation
$i_{initial}$	Initial incinerability score of the MSW feed
i_{final}	Incinerability score due to change in weighting, normalization or aggregation scheme
I_i	Parameter values
ISWA	International Solid Waste Association
ISWM	Integrated solid waste management
LCA	Life cycle assessment
m	Number of entities
$m_{ash}, m_a,$	Mass of ash and air supplied to the furnace
MAUT	Multi-attribute Utility Theory
MC, MC_{MSW}	Moisture content, moisture content present in the MSW
MC_diff, CV_diff, Inert_diff, C_diff, H_diff, N_diff, S_diff, O_diff	Percentage deviation of experimentally determined moisture content, calorific value (GCV), inert content, carbon, hydrogen, nitrogen, sulphur and oxygen from characteristics reported by Kaiser (1966a) and Tchobanoglous et al. (1993).

MCD	Municipal corporation of Delhi
MCDM	Multi-criteria decision-making
m_{dgw}, m_{dgf}	Mass of dry gas released from MSW feed and fuel, respectively.
m_f	Mass of fuel supplied to maintain 1000 ⁰ C inside the furnace
Min _i and Max _i	Minimum and maximum values of the parameter
m_{MSW}	Mass of MSW feed
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment, Forest and Climate Change
MOLP	Multi-objective Linear Programming
Mons	Monsoon
MT/y	Million tonnes per year
m_{sw}, m_{sf}	Mass of steam released from MSW feed and fuel, respectively.
n	Number of parameters
N	Number of components in MSW
$N_{combair}$	Nitrogen present in combustion air
NGO	Non-governmental organisation
NMP	National Master Plan
NSDP	Net state domestic product
NSWAI	National Solid Waste Association of India
NV	Normalised value
OECD	Organization for Economic Cooperation and Development
PDF	Probability distribution function
P_i	Normalised value of i th parameter
PV	Parameter value
$Q_{MSW}, Q_{Air}, Q_{Fuel}$	Heat released from MSW feed, air supply and auxiliary fuel respectively.
r	Power
RDF	Refuse-derived fuel
RI	Random index
SMART	Simple Multi-Attribute Rating Technique
Sum	Summer
TAI	Technology achievement index
TOPSIS	Technique for Order Preference with Similarity to Ideal Solution
TPD	Tonnes per day
TPY	Tonnes per year
UK	United Kingdom

ULB	Urban local body
UP	Uttar Pradesh
USA	United States of America
VC	Volatile content of MSW
W_A	Mass of inert/ash content
WC_{combair}	Water content in the combustion
WCE	Weighted cross-entropy
WC_{gen}	Steam generated during combustion
WC_{MSW}	Water content present in the MSW feed
W_D	Mass of dry waste
W_{dj}, W_{rj}	Weights of dry and raw MSW components
W_{DT}	Weighted distance
W_{ej}	Weight of the element in individual components
w_i	Relative weight of i^{th} parameter
W_{ij}	Weights of the inert fraction in individual components
W_{int}	Winter
w_j	Normalized weight assigned to sub-indicator j.
WQI	Water quality index
W_R	Mass of raw waste
WtE	Waste to Energy
W_{wi}	Wet weight of individual waste components
x_i	Per capita generation in the city
y	Input factor in uncertainty determination
ρ_i, ρ	Bulk density of individual waste components and MSW feed respectively
λ_{max}	Maximum eigenvalue
ω	Eigenvector
ΔT	Temperature of waste/fuel/air, with 0° C as the reference temperature