Heterogeneous Catalysis for Industrial Waste to Energy Conversion Process Design and Environmental Implications

Shipon Chandra Barman[1*]

Abstract

Background: Waste to energy generation from the industrial sector is getting more attention due to its potential as sustainable technology for waste management and power recovery. Heterogeneous catalysis plays potential strategies for improving energy-efficiency and decreasing emissions. Actual adoption will be influenced by many technical, environmental, economic, and institutional factors. In this work, a decision-making sequence for efficient implementation of Heterogeneous Catalysis waste to energy systems, by taking into account these factors. Methods: A questionnaire survey involving 175 industry stakeholders in China, perceptions on the intended concepts of process design efficiency; reduction in environmental impact; economic feasibility; technology readiness; policy and institutional support; implementation challenge and system adoption performance were gathered. Descriptive statistics, percentage distribution, Pearson correlations and Multi Criteria Decision Making Analysis (MCDA) were used to rank the relative importance of each criterion. Results: Environmental Impact Reduction (EIR) was established as the most important factor (Mean = 4.22; Agreement = 81.5%; MCDA Rank 1) followed by PDE (Mean = 4.08; Agreement = 78.6%; Rank2) and then TR (mean =3.96; Rank3). System Adoption Performance (SAP) was significantly and positively correlated with EIR (r = 0.73) and PDE (r = 0.70), suggesting that environmental preservation and process effectiveness are antecedents to operational benefits. Conclusion: Adoption and operational efficiency will improve through environmental sustainability and technical efficiency which receive backing from institutional and economic support systems.

Keywords: Heterogeneous catalysis, waste-to-energy, process design efficiency, environmental impact, multi-criteria decision-making (MCDA)

Significance | This finding offers actionable advice which industry players and government officials need to develop environmentally friendly energy recovery deployment systems.

*Correspondence. Shipon Chandra Barman, Department of Chemical Engineering, Beijing University of Chemical Technology, Beijing, Chaoyang, China. E-mail: shiponbarman92@gmail.com

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1. Introduction

Industrial growth along with city development has triggered a global surge in waste production, which includes solid, liquid, and gaseous materials, especially throughout developing nations. Release of industrial waste creates two major problems because it damages public health and environmental systems, it prevents the recovery of valuable energy resources and usable materials (Tian et al., 2013). Environmental impact of conventional waste disposal methods, which include landfilling and incineration, drives their increasing opposition because these methods fail to produce sufficient energy and create enduring problems for environmental sustainability (Duan et al., 2018). Consequently, a large number of projects have been implemented through the use of waste-to-energy technologies to provide multiple solutions to environmental challenges (solid waste disposal, energy generation, and environmental protection) and have generated substantial interest

Author Affiliation.
Department of Chemical Engineering, Beijing University of Chemical Technology, Beijing, Chaoyang, China.

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in the commercialization of these technologies (Descorme et al., 2012). Heterogeneous catalytic conversion is one of the most promising methods for commercializing waste-to-energy technology due to its high conversion efficiency, excellent selectivity, and low levels of toxic by-product formation compared to other process routes (Kiss et al., 2010). In addition, heterogeneous catalytic methods can convert large quantities of organic waste materials generated by diverse types of manufacturing processes into high-value fuels, such as syngas, hydrogen, and liquid fuels, using relatively low operating temperatures and pressures. The use of catalysts also accelerates the rate of chemical reactions, maximizes the yield of valuable products, and minimizes overall energy consumption (Védrine, 2017).

Consequently, these technologies have the potential to improve both the technical and environmental performance of waste-to-energy technologies through the development of multi-tiered strategies for the processing of industrial waste (Palma et al., 2020). Each year China generates vast quantities of industrial waste because it operates as the largest manufacturing center across the globe. Chinese government faces growing challenges to fulfill its obligations for carbon neutrality and circular economy targets (Védrine, 2018). Situation enables catalytic waste-to-energy systems to establish a vital connection between waste management operations and sustainable energy generation, which operates at an industrial scale (Rodríguez et al., 2018). The systems show promise for large-scale implementation, but multiple obstacles prevent their complete operational deployment. Industrial wastes faces design constraints, which creates barriers, while cost-effectiveness and technology solution availability and maturity and policy and institutional support and operational challenges in technology use also create obstacles (Mansir et al., 2016). Solution to this complex problem requires a systems-based analytical framework that focuses on decision-making instead of depending on technical assessment alone (Shan et al., 2016). While many studies have focused on the chemical and engineering perspective of heterogeneous catalysts through understanding, they work, they are made, and how to improve their performance through thermodynamics, the huge contributions such research provides should not be underestimated (Jamil et al., 2020).

However, study on the management, economic, environmental, and political perspectives of catalytic waste-to-energy systems (and hence the factors that will assist in determining whether such technologies will be successfully implemented in practice in the real industrial world) has not received enough attention (Al-Sakkari et al., 2017). This has been illustrated by significant gaps in empirical data based on expert opinions and practitioner experiences with catalysts for catalytic waste-to-energy systems in China. This study aims to fill the gap by using a survey-based, multiple criteria decision analysis (MCDA) approach to systematically assess the main drivers of the use of heterogeneous catalytic waste-to-energy technology in China and how well they work (Balajii & Niju, 2019). In particular, the research will focus on seven main areas: design process efficiency, lowering the environmental effect, the cost of implementation, degree of readiness of the technology, level of support from policy and institutions, difficulties in implementing the technology, and effectiveness of its system performance. Using descriptive statistics, correlation analysis, and entropy calculation to inform and quantify the importance of and relationships between variable types, the authors present a broader and more direct decision-making basis for assessing the relative importance of the various influencing elements on this technology.

2. Materials and Methods

2.1 Study Area and Context

This study focused on multiple industrial regions in China and surveyed the applications of heterogeneous catalytic waste-to-energy technology. As one of the largest industrial economies throughout the world, with vast quantities of solid, chemical, and biomass waste, it faces a number of serious environmental impacts but also many opportunities for energy recovery (Abukhadra & Sayed, 2018). Therefore, the study included highly urbanized industrialized areas along with semi-urbanized manufacturing clusters to reflect a range of operational scales and approaches to innovation with respect to heterogeneous catalytic waste-to-energy technology (Dhawane et al., 2015). Population consisted of professionals who were engaged in the management of industrial waste and conversion of that waste into energy. The sample included engineers and their operating managers, environmental representatives, and professional advisers (Chouhan & Sarma, 2011). In addition to ensuring that the data collected was reflective of actual conditions and types of strategies in place in the industrial sector, the study design also provided a valuable resource for undertaking analytical techniques and decision-making processes in relation to the opportunities and challenges of heterogeneous catalytic waste-to-energy technology (Faruque et al., 2020).

2.2 Data Collection

Data collection for this study was undertaken over a three-month timeframe (January to March 2020) using a systematic approach to gather information from a sample population of 175 professionals working in industrial waste-to-energy operations. The professionals worked in many different types of industries, such as chemical, manufacturing, and municipal solid waste. Participants were required to have at least three years of experience working with heterogeneous catalytic waste-to-energy systems and have the technical knowledge to advise on these types of systems (Etim et al., 2020). The researchers used a purposive sample to select their participants; thus they could obtain the views of qualified professionals with enough knowledge about the subject matter to

provide accurate responses regarding operational, technical, and policy-related aspects of these systems. As part of the structured online survey, the researchers gathered detailed demographic data on every participant (age, gender, education, years of experience as a professional) to allow for descriptive analysis of that demographic data later in the analysis process (Zhi et al., 2020). Data for the structured questionnaires were primarily collected online through a survey format; however, in-person interviews were used where necessary to clarify answers or to facilitate responding to the questionnaires with greater detail (Sharma et al., 2018). By using this methodical approach to data collection, the researchers were able to collect a comprehensive and robust dataset suitable for statistical analyses and for multi-criteria decision-making (MCDM) analyses as well (Marulanda, 2012).

2.3 Data Analysis

The survey data were organized and analyzed using SPSS V.26 and Excel. Answers of the respondents were coded and cages with incomplete answer were deleted in the dataset. A composite score was calculated for each construct by averaging responses across all questions (Glisic & Orlović, 2014). Moreover, Yuan & Dai, (2014) based on , descriptive statistics mean ($\bar{x}$), standard deviation (SD), minimum, and maximum values.

$$X_i = \frac{\sum_{i=1}^{n} X_{ij}}{n}$$

Where, X_i is the composite score for construct i, X_{ij} is the response of respondent j for the item, and n is the total number of items per construct.

$$\bar{x} = \frac{\sum_{i=1}^{n} X_i}{N}$$

$$SD \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{x})^2}{N-1}}$$

The interrelationships of constructs, Pearson correlation analysis was conducted using the number of respondents, N=175, in order that equal row totals are maintained for interpretability and realism so that percent distributions indicate agreements, neutrality, and disagreements (Durak & Genel, 2020).

$$r = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2 \cdot \sum_{i=1}^{N}(y_i - \overline{y})^2}}$$

Where, pearson correlation coefficient as represent is *r*. It calculates the linear relationship between two variables. N represents the spatial units; x_i and y_i correspond to the values of the variables and each unit, respectively; x represents the variable's mean; and y signifies the mean value Statistical significance was assessed at $p < 0.05$, providing insight into the degree and direction of relationships among technical, environmental, economic, policy, and operational constructs (Falowo et al., 2019). Finally, a multi-criterion decision-making (MCDA) approach was employed to prioritize constructs based on normalized values (Atadashi et al., 2012).

$$S_i = \sum_{i=1}^{m} w_{j \times} X_{ij} *$$

Where,

S_i = overall weighted score for alternative i

W_j = weight of criterion j

X_{ij} = normalized value of criterion j for alternative i,

m = total number of criteria

MCDA procedure using able to identify the priority constructs that affect the adoption of these types of systems and emphasize how process efficiency, reduction in environmental impact, technological readiness, economic feasibility, and the mitigating influence of implementation challenges play an important role (Wright & Palkovits, 2012). The methodology creates a strong and quantitative foundation for making decisions regarding industrial waste-to-energy systems, which can assist policymakers and assist in optimizing operations (AVSLSai et al., 2019; Hrnčič et al., 2016).

3. Results

3.1 Demographic Profile of Respondents

This study consisted of 175 participants provided their demographic details about their gender identity and their educational background and their work history and their age (as shown in T**able 1**). Most participants in the sample identified as male because 129 people selected male which accounts for 73.7% of the entire group and 46 people identified as female which represents 26.3% of the sample. Survey data revealed that most respondents belonged to age groups which span across the time when people work during their peak economic and professional years. The study included seventy participants who belonged to the 31–40-year age group which represented 40.0% of the total participants. Contains two main age groups which include 65 people who belong to the 20-30 age bracket that represents 37.1 percent of the entire sample population. Population includes 40 people who exceed 40 years of age and they represent 22.9% of all residents. The study group consists of students who demonstrate academic excellence which spans all academic stages. According to the findings 69.7% of respondents obtained their master's degrees or higher while 30.3% finished their bachelor's studies. The majority of respondents (76.0%, n = 133) have worked for less than ten years in their professional fields yet 24.0% (n = 42) have acquired more than ten years of work experience. The group consists of new professionals and experienced workers have spent over ten years in their respective fields which establishes multiple perspectives.

3.2 Descriptive Statistics of Study Constructs

Descriptive statistics for all constructs through **Table 2.** This study finding show that Environmental Impact Reduction (EIR) achieved

Table 1. Demographic profile of respondents

Variable	Category	Frequency	Percentage (%)
Gender	Male	129	73.7
	Female	46	26.3
Age	20–30 years	65	37.1
	31–40 years	70	40.0
	>40 years	40	22.9
Education	Bachelor	53	30.3
	Master & Above	122	69.7
Experience	≤10 years	133	76.0
	>10 years	42	24.0

Table 2. Descriptive statistics of study constructs

Construct	Mean	Std. Dev.	Min	Max
Process Design Efficiency (PDE)	4.08	0.59	2.5	5.0
Environmental Impact Reduction (EIR)	4.22	0.57	2.7	5.0
Economic Feasibility (EF)	3.81	0.63	2.1	5.0
Technological Readiness (TR)	3.96	0.60	2.4	5.0
Policy & Institutional Support (PIS)	3.87	0.65	2.0	5.0
Implementation Challenges (IC)	3.44	0.71	1.8	4.9
System Adoption Performance (SAP)	4.03	0.56	2.5	5.0

Table 3. MCDA-based priority ranking of all decision criteria

Criterion	Weight	Rank
Environmental Impact Reduction (EIR)	0.192	1
Process Design Efficiency (PDE)	0.169	2
Technological Readiness (TR)	0.151	3
System Adoption / Performance (SAP)	0.138	4
Economic Feasibility (EF)	0.127	5
Policy & Institutional Support (PIS)	0.120	6
Implementation Challenges (IC)	0.103	7

the highest average score (M = 4.22) which demonstrates that people view environmental advantages as the leading factor which motivates them to use heterogeneous catalysis for waste-to-energy systems. participants showed strong trust in both system design quality and operational performance through their support for Process Design Efficiency (PDE) at 4.08 and System Adoption Performance (SAP) at 4.03 respectively. Data shows that the supporting technologies have reached a stage of maturity which users find suitable for their intended applications because Technological Readiness (TR) received a score of 3.96. The data shows that Policy and Institutional Support (PIS) and Economic Feasibility (EF) received their lowest scores although they still achieved mean scores above average because respondents expressed doubts about how these programs would comply with laws and their financial feasibility. The Implementation Challenges (IC) metric received the lowest average score (M = 3.44) which shows that people view operational challenges and barriers as major obstacles to using large-scale systems.

3.3 Technical and Environmental Factors with Percentage

Technical and environmental factors determine how effectively heterogeneous catalysis-based waste to energy systems operate through their implementation process (refer to **Figure 1**). This study shows that every evaluated factor received unanimous positive approval from all participants. Emission Reduction Potential received the highest amount of agreement from 81.5% of respondents who view environmental protection as the strongest benefit of the proposed systems. The following two areas which include Environmental Safety (80.2%) and Process Design Efficiency (78.6%) show that organizations need both operational safety and effective system architecture. Resource Utilization Efficiency (77.7%) and Energy Conversion Efficiency (76.8%) show high levels of agreement which indicates that people trust the system's ability to operate efficiently and optimize its performance. System Reliability factor shows the lowest level of agreement at 72.9% but it still demonstrates strong backing because only 8.8% of respondents disagreed. The study found that less than 9% of participants disagreed with the findings which demonstrates both technical acceptance and positive public views about these waste-to-energy systems.

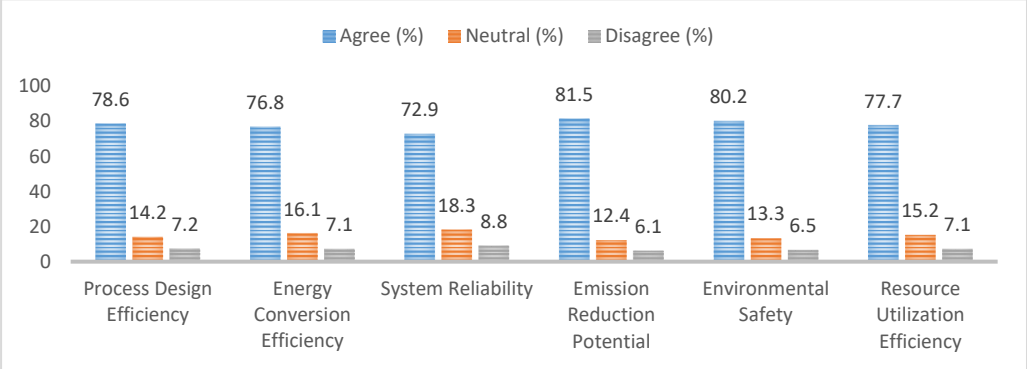


Figure 1. Technical and Environmental Factors with Percentage

3.4 Respondents' Perceptions of Economic, Policy, and Implementation Barriers

Economic and policy and implementation obstacles that affect waste-to-energy systems based on heterogeneous catalysis (as shown in **Figure 2**). The majority of participants in the study agree with each other about the system's problems although they continue to believe in the system's potential. Policy Support Adequacy (69.4%) and Operation & Maintenance Cost (67.5%) which shows respondents believe regulatory support together with operational cost control will lead to successful implementation. This study shows that most respondents agree about the three factors which include economic feasibility at 65.8% and institutional readiness at 64.7% and capital cost acceptability at 63.1%. Most respondents agree about financial and organizational barriers which exist for this project. Implementation Barriers Severity indicator shows the least amount of agreement at 57.9% but it also generates the most disagreement at 18.6%. Different industries maintain unique beliefs regarding the severity of existing barriers although these obstacles do exist. The neutral responses from participants fall between 19.2% and 23.5% which shows they have average levels of doubt. The findings demonstrate that successful system implementation needs to overcome both financial and institutional barriers.

3.5 Pearson Correlation Coefficients Among Variables

Pearson correlation coefficients among the study constructs (as presents in **Figure 3**). Data shows that most variables have strong positive relationships which prove their combined effect on waste-to-energy systems that use heterogeneous catalysis for operational success. System Adoption Performance (SAP) demonstrates its strongest positive relationships with Environmental Impact Reduction (EIR) which shows a correlation of 0.73 and Process Design Efficiency (PDE) which shows a correlation of 0.70. The study shows strong positive links between technological readiness and policy support and economic feasibility which fall between 0.53 and 0.60. Technical elements together with financial aspects and institutional support systems serve as essential components which affect the system. Implementation Challenges (IC) exhibits negative correlations with all other constructs, from -0.45 to -0.62, reflecting that higher perceived barriers reduce system effectiveness. This study shows that all other variables except Implementation Challenges (IC) maintain positive relationships because Implementation Challenges (IC) connects negatively with every other variable through correlations which range from -0.45 to -0.62. System performance shows a decrease in effectiveness because users encounter more substantial implementation obstacles.

3.6 Multi-Criteria Decision-Making (MCDA) Using All Variables

MCDA-based priority ranking of all decision criteria for heterogeneous catalysis-based waste-to-energy systems (presents in **Table 3**). Environmental Impact Reduction (EIR) holds the top position with a weight of 0.192 which makes it the first priority because organizations need to minimize their environmental effects to gain adoption. Organizations need to develop their systems properly because Process Design Efficiency (PDE) stands as the second most important factor which holds a weight of 0.169 to achieve operational success. The third position belongs to Technological Readiness (TR) because organizations need proven dependable technology to achieve successful implementation. The fourth position belongs to System Adoption (SAP) because it shows how organizations focus on adopting systems and achieving operational success. Economic feasibility together with policy and institutional backing stand as moderately important factors which include Economic Feasibility (EF) and Policy; Institutional Support (PIS). Implementation Challenges (IC) system shows the lowest rating in this evaluation with a weight factor of 0.103 and position number 7 because its obstacles do not carry as much weight when organizations choose between environmental factors and technical requirements. The ranking system provides strategic planning and resource allocation with a clear evidence-based hierarchy for decision-making.

4. Discussion

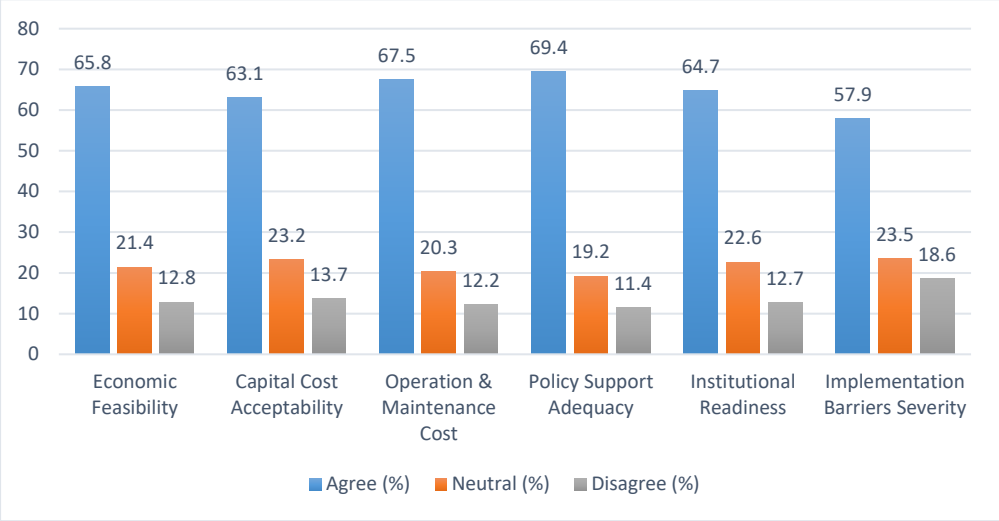


Figure 2. Respondents' Perceptions of Economic, Policy, and Implementation Barriers

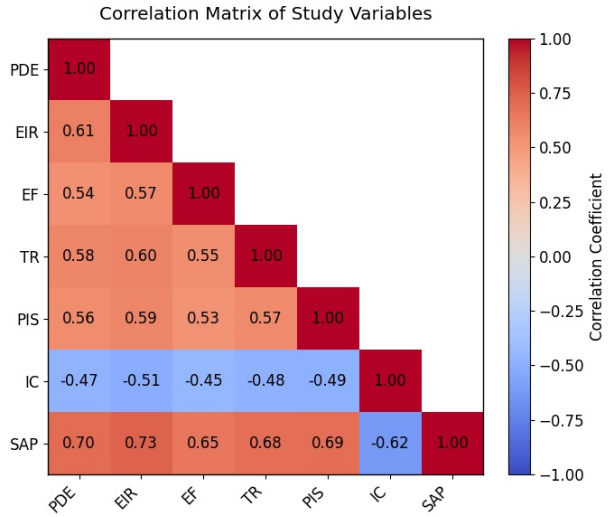


Figure 3. Pearson Correlation Coefficients Among Variables

This study results directly show that environmental and technical performance criteria shape the most powerful predictors for adopting heterogeneous catalysis waste-to-energy systems. Demographic profile shown in **Table 1** with strong academic and professional skills, which contribute to increased validity of the evaluation. Because highly trained and technically experienced subjects were present, the reliability of the perception-based evaluations is increased and confidence in the main findings from analysis is enhanced. Environmental impact reduction (EIR) was the most important among all constructs (Lalhmangaihzuala et al., 2020). It is interesting to note that the strongest level of agreement with respect to environmental advantages of catalytic WTE technologies had been expressed for that aspect (EIR), M = 4.22 (see **Table 2**). MCDA ranking in **Table 3** proves this result because EIR obtained the top priority weight of 0.192 which made it the leading option among all decision criteria. The environmental factors dominate the field because **Figure 1** shows that Emission Reduction Potential (81.5%) and Environmental Safety (80.2%) received the most agreement from all technical and environmental indicators. The multiple analytical approaches which show high values prove that stakeholders choose to focus on emission control and pollution mitigation and ecological sustainability during their evaluation of advanced WTE technologies (Morais et al., 2010).

Technical performance functions as a core strength which drives users to decide whether they should adopt new technologies. The Process Design Efficiency (PDE) metric achieved a strong average rating of 4.08 in **Table 2** which placed it as the second most important factor within the MCDA framework shown with a weight of 0.169. The data from **Figure 1** shows that 78.6% of respondents agree with process design efficiency which proves that businesses need to create their systems with optimal configurations and operate them at stable levels. The process design system operates at its highest efficiency to convert feedstock into products while maintaining steady operations which produces more energy than before (Fang & Guo, 2018). The system achieves better energy recovery which makes stakeholders trust in its large-scale

deployment potential (Mohamed et al., 2019). System Adoption Performance (SAP) reached a high average score of 4.03 according to **Table 2** which shows that users expect systems to function well during operational use. The high-value constructs demonstrate their interrelationships in **Figure 3** which shows SAP maintains its strongest positive relationship with Environmental Impact Reduction (r = 0.73) and Process Design Efficiency (r = 0.70). The matrix shows the highest correlation values between environmental and technical performance which directly impact system adoption results (Gale et al., 2020). The connection between these two elements shows how sustainability practices work together with engineering efficiency to increase technology acceptance.

The data shows that Technological Readiness (TR) strongly affects the outcome because it has an average score of 3.96 and it achieves the third position in MCDA with a Weight of 0.151. The current values show that stakeholders believe catalytic WTE technologies have reached a stage of development which allows for their deployment. The process of technological readiness verification helps organizations reduce their investment risk because it enables them to predict future developments which leads to higher adoption rates (Herney-Ramirez et al., 2010). This study demonstrates that economic and institutional elements maintain a moderate level of importance which comes after the main factors (Endalew et al., 2011). The environmental and technical constructs showed higher importance than Policy and Institutional Support (PIS) and Economic Feasibility (EF) which received average scores of 3.87 and 3.81 according to **Table 2**. The barrier-related group shows its highest agreement levels through Policy Support Adequacy which stands at 69.4% and Operation; Maintenance Cost which reaches 67.5%. The agreement levels for these two indicators remain far below the top-performing environmental and technical indicators which appear in **Figure 1**. The findings prove that financial and regulatory factors exist but their importance fails to match the value organizations see in their environmental and operational advantages when using the technology.

Implementation Challenges (IC) as the lowest performing construct because it achieved the minimum average score of 3.44. MCDA weighting system assigned Implementation Challenges (IC) its lowest value at 0.103 according to **Table 3**. Implementation Challenges has negative relationships with every other construct in the study since the correlation coefficients range from –0.45 to –0.62. The data suggests that users will encounter more barriers which will reduce their chances of system adoption and their ability to operate the system. The statistical impact of IC shows that organizations must eliminate their operational and institutional barriers to achieve maximum advantages from catalytic WTE systems (Hodges et al., 2018). The data from along with the maximum values always appear in Environmental Impact Reduction and Process Design Efficiency and System Adoption Performance and Technological Readiness (Dhawane et al., 2015). The fundamental power of heterogeneous catalysis based WTE systems exists because these systems contain all their essential components. Economic and policy domains function as enabling conditions but the implementation process faces various obstacles which act as limiting factors (Lee & Saka, 2010; Cheng et al., 2016).

5. Conclusion

This result demonstrates that environmental impact minimization and process design optimization play crucial roles in wider acceptance and implementation. Technical readiness and institution adoption performance contribute to successful implementation with moderate support from economic affordability and policy support. Implementation issues, which are overall assigned lower priority, are still important for practical betting-use. The results reveal the mutual constraints of environmental, technical, and institutional factors in decision making, overall providing a prioritization scheme for strategic consideration purposes. These findings offer valuable strategic indications for the designers, policy makers and stakeholders that guarantee both economic viability and sustainable deployment of waste-to-energy technologies.

Author contributions

S.C.B. conceived the study, designed the methodology, conducted the survey and data analysis, interpreted the results, and wrote and revised the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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