Bio-recovery of municipal plastic waste management based on an integrated decision-making framework

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Bio-recovery of municipal plastic waste management based on an integrated decision-making framework

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Abstract

Recent years have seen rapid development in industrialization and urbanization with huge growth in the population throughout the world. In this regard, an efficient and robust framework for the concept of a green city and sustainable development goals to manage municipal plastic wastes is still needed. This study models a bio-recovery of municipal different plastic wastes management based on a new integrated Multi-Criterion Decision-Making (MCDM) approach through a case study in Mashahd, Iran. The proposed integrated MCDM framework includes the Shannon Entropy (SE), Ordered Weighted Aggregation (OWA), Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and, *ELimination Et Choice Translating REality* (ELECTRE) systems in an intelligent way. Through decision-making computations, all criteria are approved after extraction from the literature review by experts with more than 60% agreement percentage. Different scenarios of economic, energy, and environmental crises are created. One finding of this paper is to create a new entrance in economic competition with plastic biodegradation to present a novel, environmental-friendly product with high-quality and low-cost advantages. Another finding determines that with an application of plastic wastes bio-recovery, citizens' satisfaction from urban management system will be increased from 49% to 64%. Whereas, based on the outcomes of this investigation, the rate of municipal waste industries development, smart city goals' meeting, and rate of hazardous material emission from municipal

solid wastes are increased to 58%, 25%, and 70%, respectively. The declared numerical outcomes illustrate the effectiveness of plastic waste bio-recovery on the smart city approach.

Keywords: Municipal plastic waste management; Fungus biodegradation; Green city; Sustainable development goals.

1 Introduction

Recent years have seen a quick growth in the population, urbanization, and industrialization, which creates several environmental problems. This makes Municipal Waste Management (MWM) one of the most serious environmental challenges in megacities [1-3]. Because of availability, flexibility in specifications, financial issues, weights, and mechanical characterization of all plastic types, they are utilized in any applications which are included 10-12 % of MWM field [4-5]. Moreover, these wastes with a low level of degradation rate cause a future emerging disaster in the environment [6]. According to surveyed data, around 300 million tons of plastic are produced annually in the world [4]. Conventional waste management systems like landfilling [7], incineration [8], pyrolysis [9], bio-digestion for gas production [10], and composting [11] were used for managing plastic-based wastes [12]. It goes without noting that the plastic biodegradation technique using microorganisms has known as the effective, environmental-friendly, low-cost, and easy-to-operate and control method for wastes [13]. In a mesophilic temperature situation, all types of plastics are decomposed by a fungus which is more efficient than another biotic activity [14]. Based on these facts and needs, this study proposes an efficient framework for the bio-recovery of municipal plastic waste management based on a novel integrated decision-making approach.

The literature review on the field of MWM is very active, and many types of research have been done to consider the plastic biodegradation for developing a framework for Green Cities (GC), Sustainable Development Goals (SDGs) and Smart Cities (SC) [15]. As one of the primary studies in this field, El-shafei et al., [16] in 1998, investigated the biodegradation of disposable Polyethylene (PE) by the *Streptomyces fungi*. Their model evaluated some parameters like temperature, pH, degradation time, and speed of mixing [16]. Later in 2003, Kathiresan et al., [17] studied the biodegradation of PE bags and plastic cups by eight fungal species of *Aspergillus*.

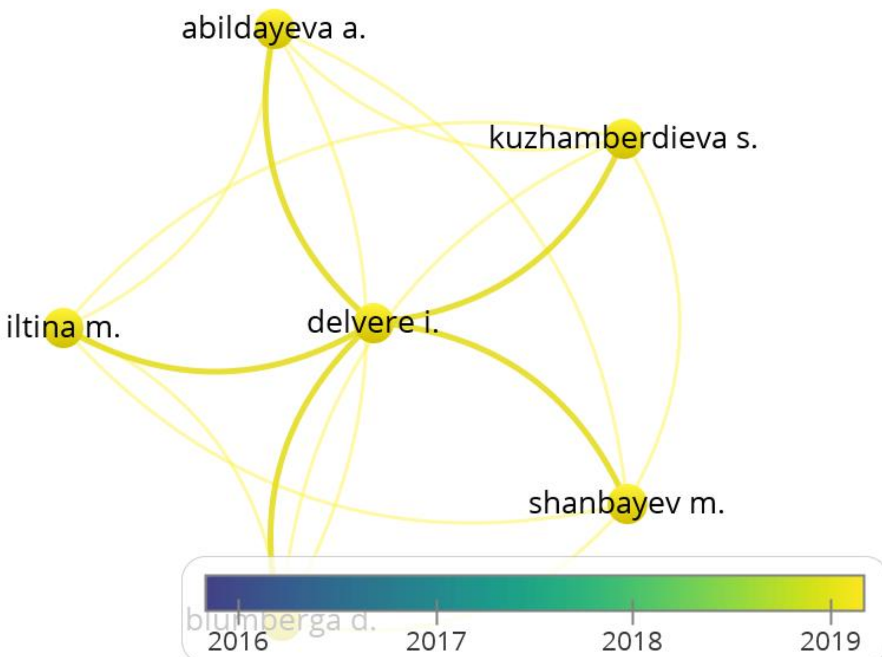
Likewise, the efficiency of PE biodegradation was appraised according to temperature and the time of bio-reaction. In 2007, Fariha et al., [18] analyzed the synergistic effect of chemical (nitric acid) and photochemical (UV radiation) pretreatment on the biodegradation rate of Low-Density PE (LDPE) by *Fusarium sp* AF4 in the synthesized cultivation environment. Moreover, Fourier Transform Infrared Spectrophotometry (FTIS) method was utilized for determining the percentage of biodegradation and variation of temperature, pH, degradation time, and speed of mixing were scrutinized on the LDPE weight reduction [18].

In 2011, Usha et al., [19] studied the efficacy of PE biodegradation (PE weight elimination) based on the liquid culture method with considering temperature, time and pH factors [19]. The biodegradation of High-Density PE (HDPE) by *Aspergillus* from the marine ecosystem of the Gulf of Mannar in India, was reported by Devi et al., [20] in 2015. Meanwhile, in the same method, temperature, reaction time and intensity of mixing (rpm) were assumed as effective parameters and weight elimination was considered as an objective function of research [20]. In the same year, Ameen et al., [21] isolated several *funges* from the Red Sea coast and have investigated their ability for biodegradation of LDPE. In 2017, Awasthi et al., [22] used the potato dextrose broth culture of *Rhizopus Oryae* NS5 fungi to evaluate its efficacy for biodegradation of LDPE. In 2018, Muhonja et al., [23], isolated some species of Aspergillus, which depicted the potential to degrade PE in a synthetic medium. In the same year, Kumar et al., [24] compared the effects of three types of fungi including Aspergillus Oryzae, Aspergillus fumigatus, and Aspergillus nidulans on biodegradation of LDPE in mineral salt media. Later in 2020, Zhang et al., [25] argued performance of Aspergillus flavus from the guts of wax moth Galleria mellonella for PE decomposition as a plastic waste management. In the same year, Sánchez et al., [26] overviewed the potential of macro- and micro-plastics biodegradation in the petroleum-based polymers case study. They focused on the application of fungal enzymes in the destruction of synthetic polymers structures [26]. More recently, in 2021, Mojtahedi et al., [57] developed a coordinated municipal solid waste management framework based on the SDGs with routing optimization. They found that the fair allocation of wastes for each recovery centers, is an important factor in achieving the SDGs. Hosseinalizadeh et al., [58] proposed a multi-objective decision-making approach based on energy, economic and environmental factors for a comprehensive municipal solid waste management in Tehran, Iran. Their finding is the high impact of energy consumption in comparison with the environmental pollution criterion.

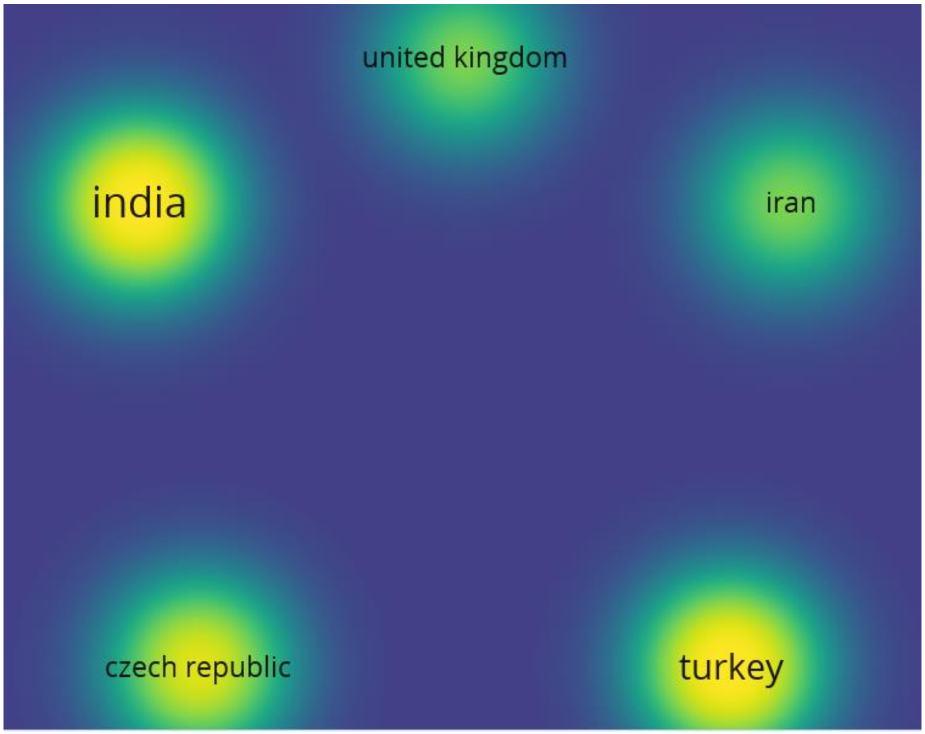
With regards to the aforementioned studies, the determination of applicable methods for PE, HDPE and LDPE wastes based on fungal biodegradation according to the SDGs and the implementation conditions for the GC, is assumed as a research gap and this study aims to fill this gap. In this regard, the present research aims to: (i) prioritize the best model for fungal biodegradation of PE, HDPE and LDPE wastes using an integrated decision-making method combining the Shannon Entropy (SE), Ordered Weighted Aggregation (OWA), Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and, ELimination Et Choice Translating REality (ELECTRE) methods, (ii) analyze the sensitivity of each mathematical model based on the scenario building system and (iii) to present a business model based on Circular Economy (CE) and Porters' Five Forces (PFF) system.

In conclusion, this paper presents an integration of SE with OWA/AHP/TOPSIS/ELECTRE for a complete MCDM process. The criteria are weighted by SE computation and the selected alternatives in each category are ranked by OWA/AHP/TOPSIS/ELECTRE methods considering criteria weights. After calculating all MCDM models and determining final weights, an extensive sensitive analysis is done by modifications of criteria weights in different scenarios such as economic, energy, and environmental crises. Therefore, the ranking process is completed in different situations with a focus on futurization goals. Next, with an application of PFF model, the marking research of the present study is done. Because in developing countries, the economic issue is critical in the environmental project, and the mentioned business-based model helps managers make decisions about plastic waste biodegradation management in megacities. Finally, with an assessment on the CE model, benefits of plastic waste bio-recovery are determined to propose managerial insights.

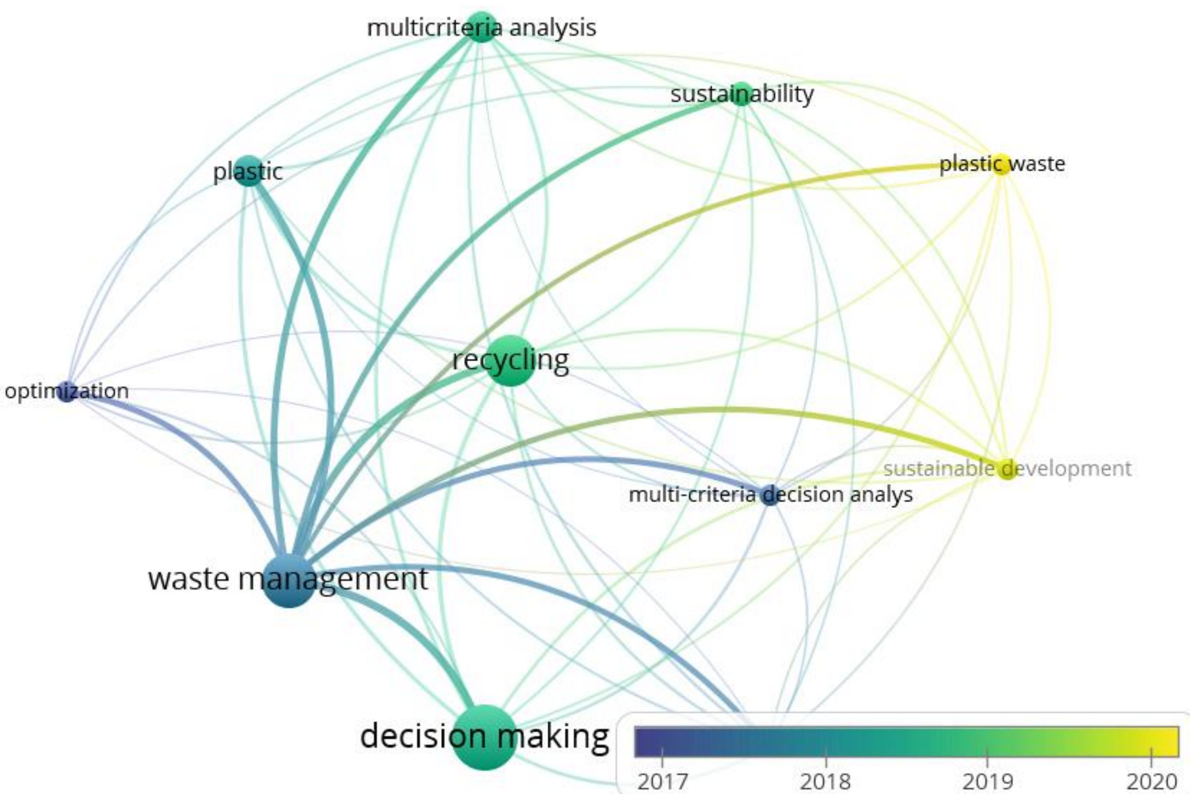
For exact determination of methodology and tools selection reasons, library assessment by VOS viewer is done for application of MCDM in plastic waste issues through Fig. 1. The published documents are filtered by authors' categorization, country distribution, and keywords occurrences (MCDM, waste management, and plastic waste) for the declared appraisal, with more than 1, 2, and 5 documents, respectively. The outcomes of Fig. 1-a demonstrates that the application of MCDM about plastic waste management are developed after 2019, and now it is a hot issue among scientific communities. Likewise, as per Fig. 1-b, it is clear that some researches are contributed in Iran about the application of MCDM due to plastic waste management, and it approves the necessity of these types of investigation in the declared region. Finally, based on Fig. 1-c, it is worth noting that the integrated MCDM and waste management is not coupled by plastic waste subject in a considerable level. Therefore, it can be proven that integrated MCDM-CE-PFF can fill the economic aspects of the plastic waste management research area strongly. The synergy of MCDM-CE-PFF for the plastic waste organization with a concentration on biological treatment approach is considered as a novelty of the present investigation.



(a)


united kingdom
india
iran
czech republic
turkey

(b)


multicriteria analysis
sustainability
plastic waste
plastic
recycling
optimization
sustainable development
multi-criteria decision analys
waste management
decision making
2017
2018
2019
2020

(c)

Fig. 1. Outcomes of bibliography and historical analysis of MCDM applications in plastic waste issues through (a) author outputs, (b) country distribution, and (c) keywords occurrence.

Following this introduction, Section 2 addresses materials and methods to provide the research methodology, the case study, types of plastic wastes, the decision-making methods and the scenario building system. Section 3 does the tests and provides the results and discussions. Also, technology, social and economic aspects of the present study are appraised through Section 4. Finally, Section 5 concludes a summary of this research with findings and recommendations.

2 Materials and Methods

2.1 Research methodology

The research methodology in a holistic view is depicted in Fig. 2. In this regard, the statistical information about the municipal plastic waste management of Mashhad city in Iran is extracted by field data gathering from the waste management center of Khorasan Razavi province. Then, regarding the appraisal of plastic waste biodegradation, alternatives of PE, HDPE and LDPE are harvested from the literature review. In the third stage, assessment criteria for a Multi-Criterion Decision-Making (MCDM) system are selected and ranked by SE system. In the following, OWA, AHP, ELECTRE and TOPSIS methods are employed to develop an integrated approach. The outcomes of plastic waste biodegradation ranking are analyzed with the SB method according to future variations. Finally, the plastic waste bio-management is constructed by a novel eco-environmental framework based on the PFF and CE concepts.

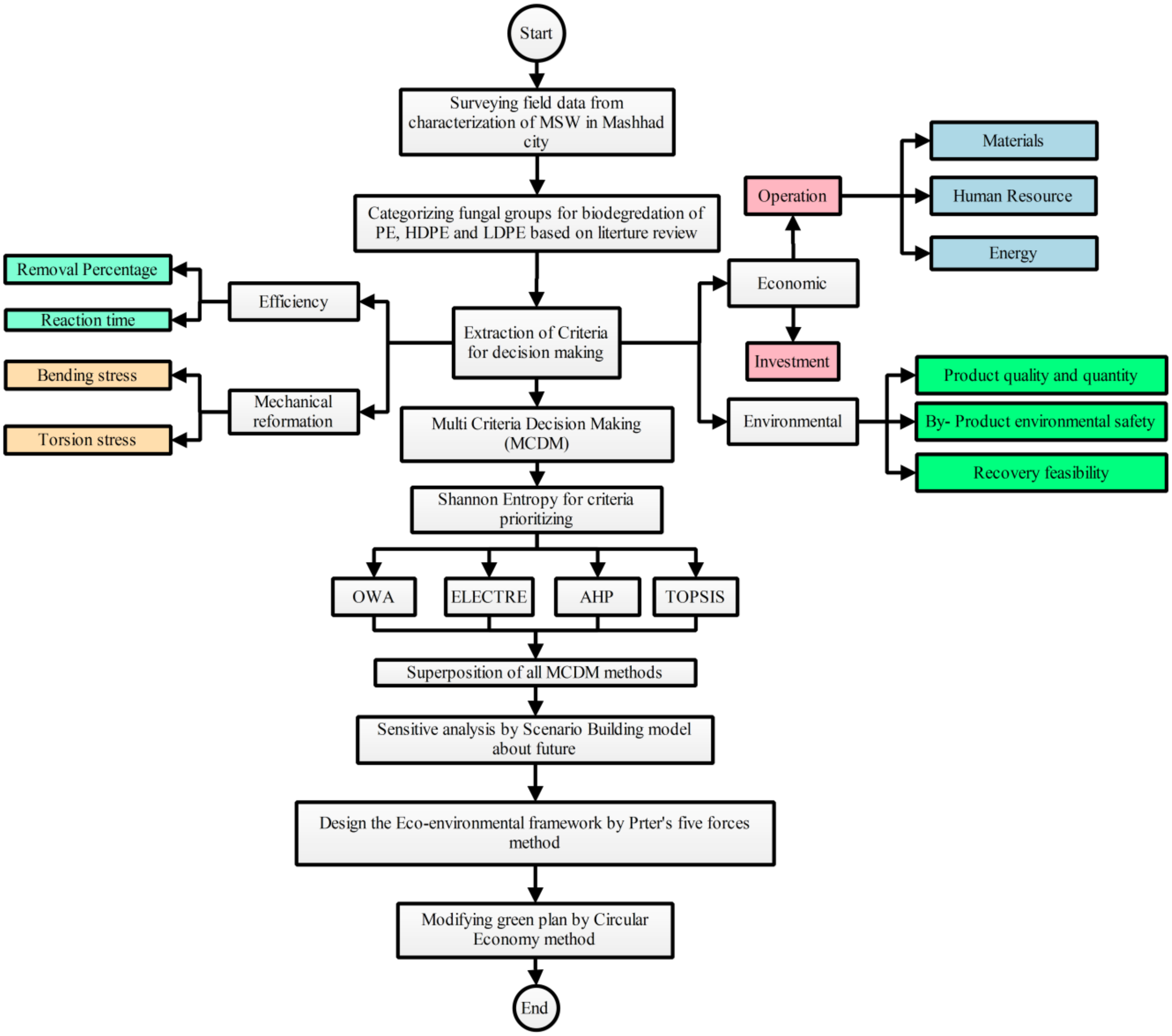


Fig. 2. Research methodology in this study.

2.2 Case study

Mashhad city is the second-largest and the most populated city in Iran and it is located in northeast of country in the center of Khorasan Razavi province with touristic land use [27]. The geographical map of this city is given in Fig. 3. The population of Mashhad city is around three million, with waste generation rate equal to 850 gr/ca/day. According to the field surveying in the waste management facility of Mashhad, 230.5 tons per day (838,900 tons per year) for plastic wastes are generated. As depicted in Fig. 4, the plastic wastes are the biggest group of wastes in Mashhad

[28]. The data of this Fig. is collated from 2018 by Mashhad city's waste management center. This chart shows that 98.8 % of the generated waste is related to biological waste, and remain value is assigned to another substance. Therefore, amounts of plastic waste generation are computed around 4,300 tons/year.

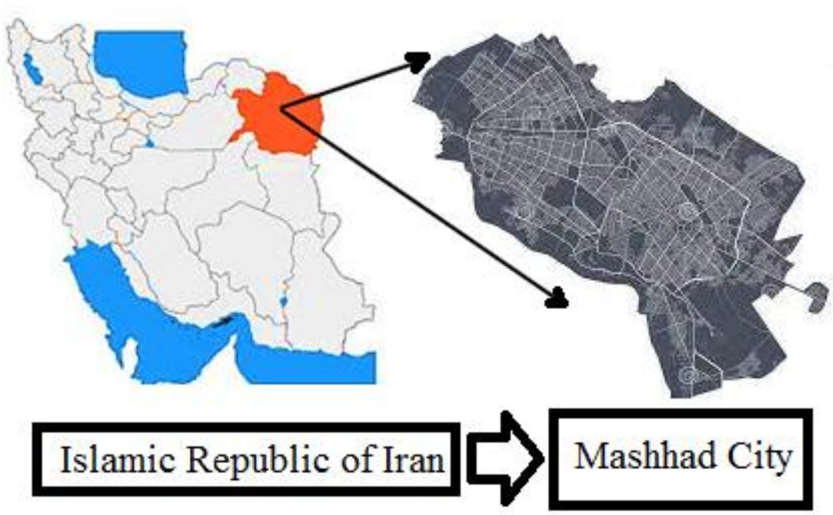


Fig. 3. Map of Mashhad city in Iran.

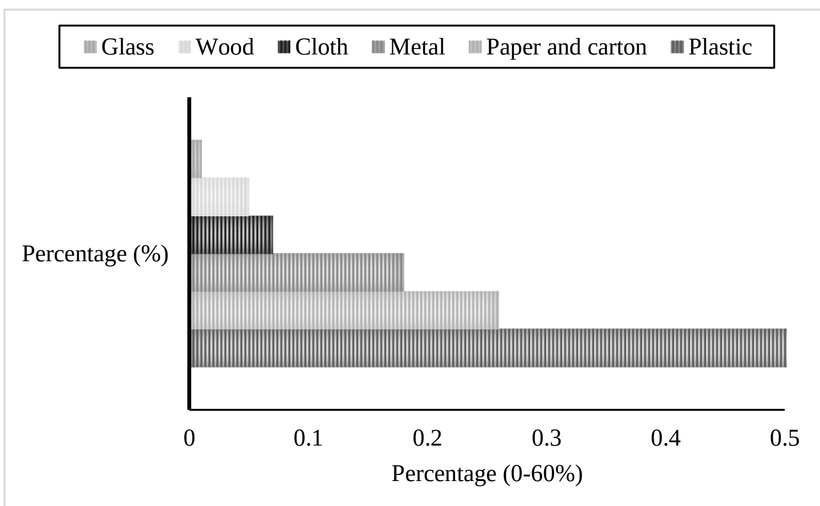


Fig. 4. Percentage of municipal solid waste compounds in Mashhad city, 2018.

2.3 Fungal based plastic waste treatment

Different types of fungus were utilized for biodegradation of plastic, various groups like PE, LDPE and HDPE that the evaluated microorganisms on this study, are collected in Table 1 [29-35]. Likewise, in Mashhad city, from all amounts of plastic wastes 35 (1,500 tons/year), 18 (770 tons/year) and 17 (730 tons/year) percentages are related to PE, LDPE and HDPE, correspondingly [28]. For determination of all criteria values, some different methods are utilized as per Table 2. The criteria are extracted from the literature review and discussed in the investigations [5-38]. Each paper has assessed some viewpoints of biodegradation of plastic waste by fungus and the present study has extracted and collected the declared criteria from the references. In addition, some economic criteria such as investment cost ($), consumed materials ($), human resource ($), and energy consumption ($) are considered because of the importance of economic factors in government-based managements and opinion of principals who are the supervisor of this project.

Also, the outcomes of employed methods are standardized by Relation Deviation Index (RDI) [2,95, 96,99,100,] as given in Eq. (1):

$$RDI = \frac{|Best \text{ Value - Current Value}|}{(Max \text{ Value - Min Value})} \quad (1)$$

where the best value is one of max or min values according to the goal of each criterion.

Table 1. Types of fungus for PE, LDPE and HDPE biodegradation.

PE	**LDPE**	**HDPE**
Aspergillus nidulans	Rhizopus oryzae NS 5	Aspergillus tubingensis
Aspergillus oryzae	Aspergillus versicolor	Aspergillus flavus
Aspergillus fumigatus	Aspergillus flavus	Aspergillus Terreus MF12
Penicillium simplicissimu	Fusarium solani	
Aspergillus flavus	Alternaria alternate	
Aspergillus glaucus	Aspergillus caespitosus	
Aspergillus. niger	Aspergillus terreus	
Mucor rouxii NRRL 1835	Eupenicillium	
	Hirayamae	
	Consortium	
	Phialophora alba	

	Paecilomyces variotii	
	L. theobromae	
	Mucor circinelloides	

Table 2. Criteria value determination in present research.

Criteria	Value determination method	References
Removal Percentage (%)	Literature Review	[5-35]
Reaction Time (day)	Literature Review	[5-35]
Bending Stress (N. mm^{-2})	Literature Review	[5-35]
Torsion Stress (N. mm^{-2})	Literature Review	[5-35]
Investment Cost ($)	Field Inquiry	All facilities and equipment which are priced in 2021.
Consumed Materials ($)	Field Inquiry	All chemical and biological compounds which are priced in 2021.
Human Resource ($)	Field Inquiry	Iranian human resource price in 2021 and advising by three waste management principles for determination of human resource quantity in each scenario.
Energy ($)	Field Inquiry	Iranian industrial energy price and computing total energy usages as per reaction time and mixture energy demand in 2021.
Product's Quality and Quantity (kg, remain Chemical Oxygen Demand)	Literature Review	[36-38]
By Product and Environmental Safety (Tu)	Literature Review	[36-38]
Recovery Feasibility (Microbial Yield)	Literature Review	[36-38]

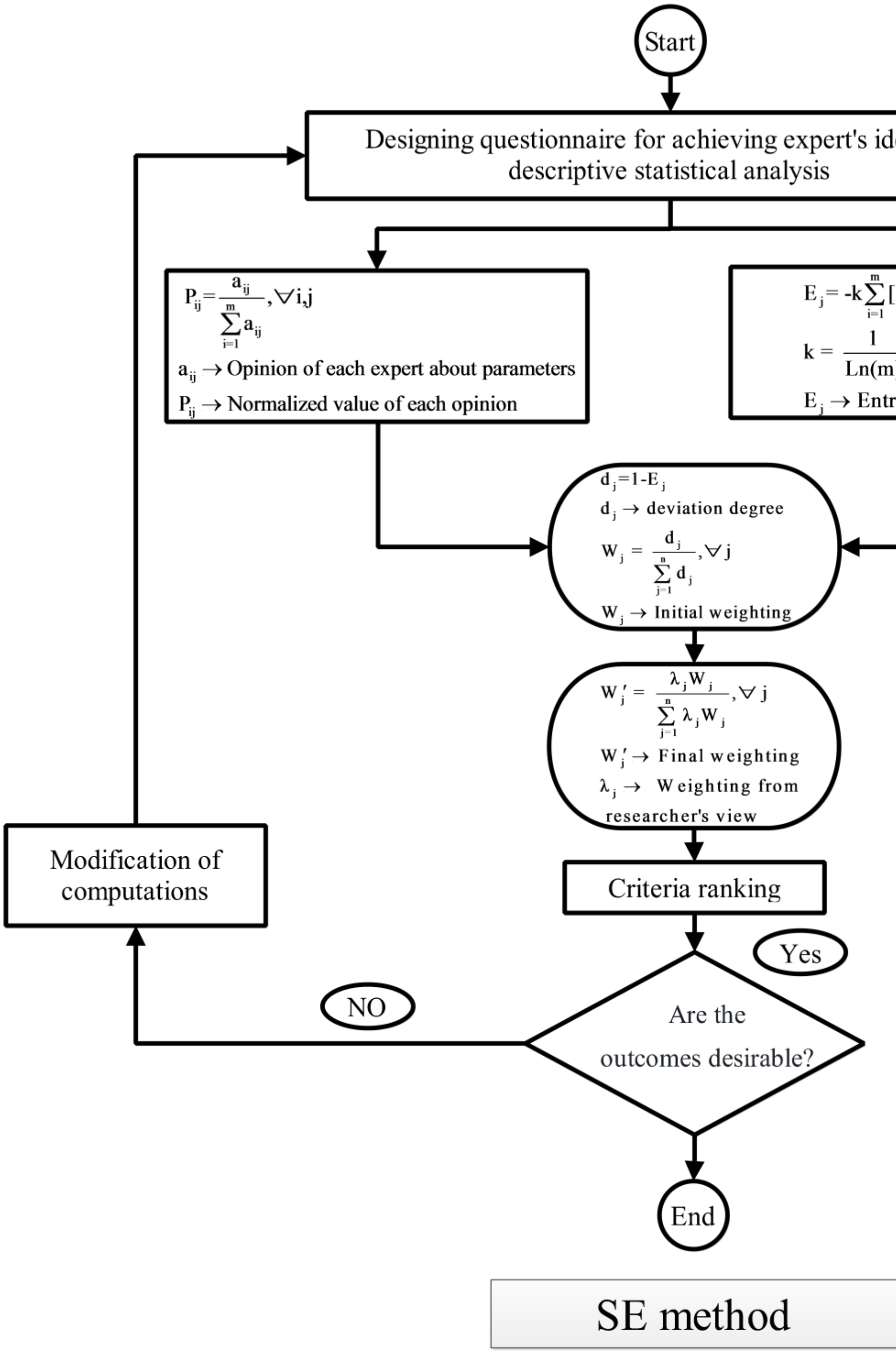
2.4 Proposed MCDM model

The algorithm of SE [39], OWA [40], AHP [41], TOPSIS [42] and ELECTRE [43] computations are demonstrated according to Fig. 5 where the SE model is given in Fig. 5-a. As such, the flowchart for the TOPSIS in Fig. 5-b, AHP in Fig. 5-c, OWA in Fig. 5-d and ELECTRE in Fig. 5-e, is drawn. It should be noted that the computations were run in MATLAB 2013b (for the SE and OWA methods), Excel 2016 (for the TOPSIS and ELECTRE methods) and Expert choice 11 (for the AHP method) software. For the determination of different criteria regarding the MCDM computations, all questionnaires are given to 23 experts in the plastic waste management fields from Mashhad city, Iran. The 23 experts in this part of the study are available knowledge management banks which is found in Mashhad city with appropriate background according to Human Resource (HR) of the municipality in the case study. Consequently, specifications of experts including selection criteria, main experience, and position levels, are presented in Table 3. It goes without saying that the nationality of all experts in Iran. This research meets the goals of sustainable development for the plastic waste management and green management of plastic wastes through biological processes.

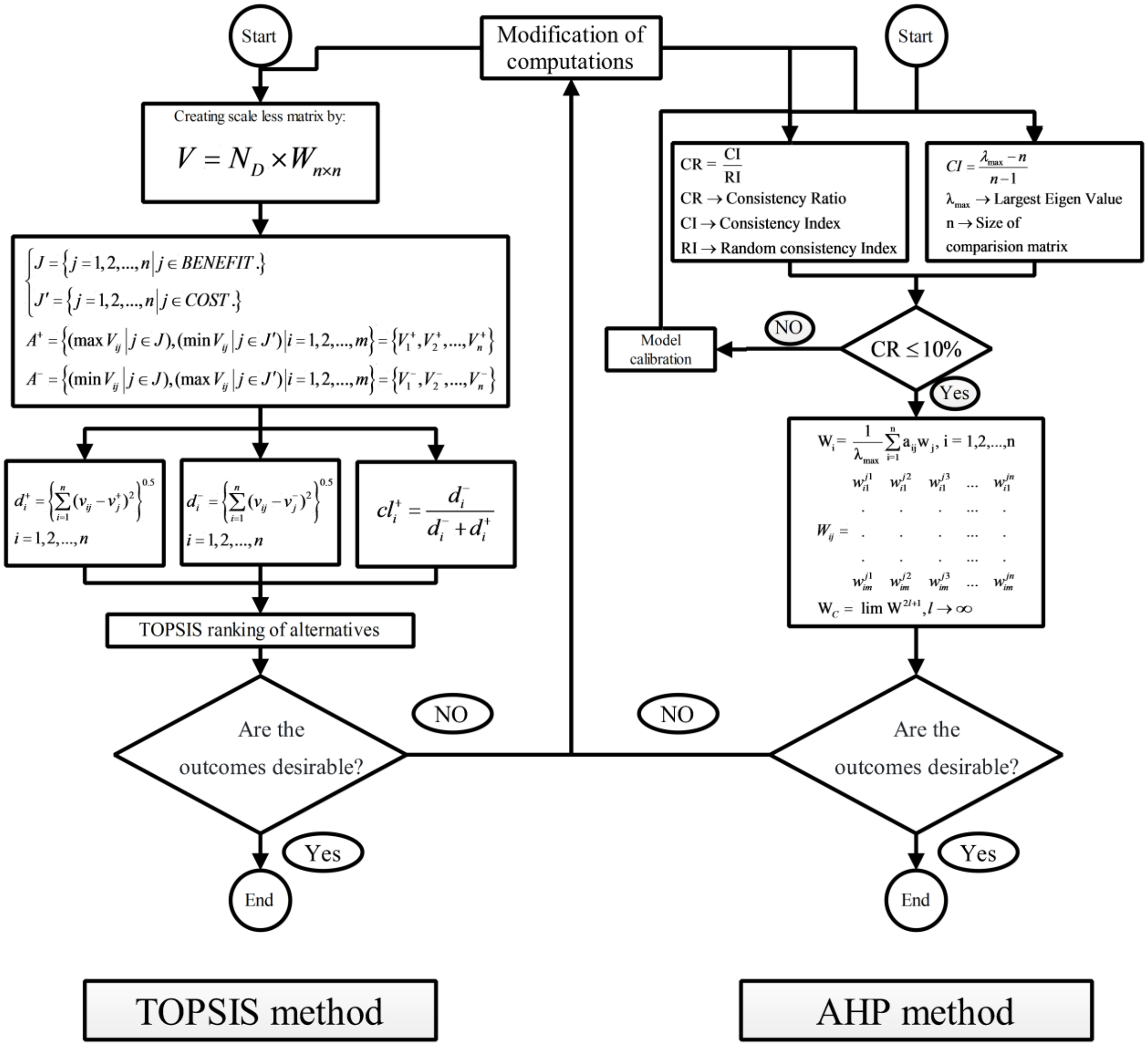
Table 3. Specification of experts for MCDM computations in the present research.

Selection criteria	Main experience	Position levels	Number of experts
Job position and managerial vision	Metropolitan management	The mayor and executive deputies in the field of environment	3
High experience in urban planning and developer systems in the city	Supervising the implementation of environmental programs in Mashhad	Middle manager of municipality in Mashhad city	2
High experience in economic analysis of metropolitan projects	Economic analysis of plastic waste processing project in Mashhad city	Deputy mayor of Mashhad city	1
Contracting perspective in the management and processing of plastic waste in Mashhad city	Implementation of collection, transferring,	Private contractors	4

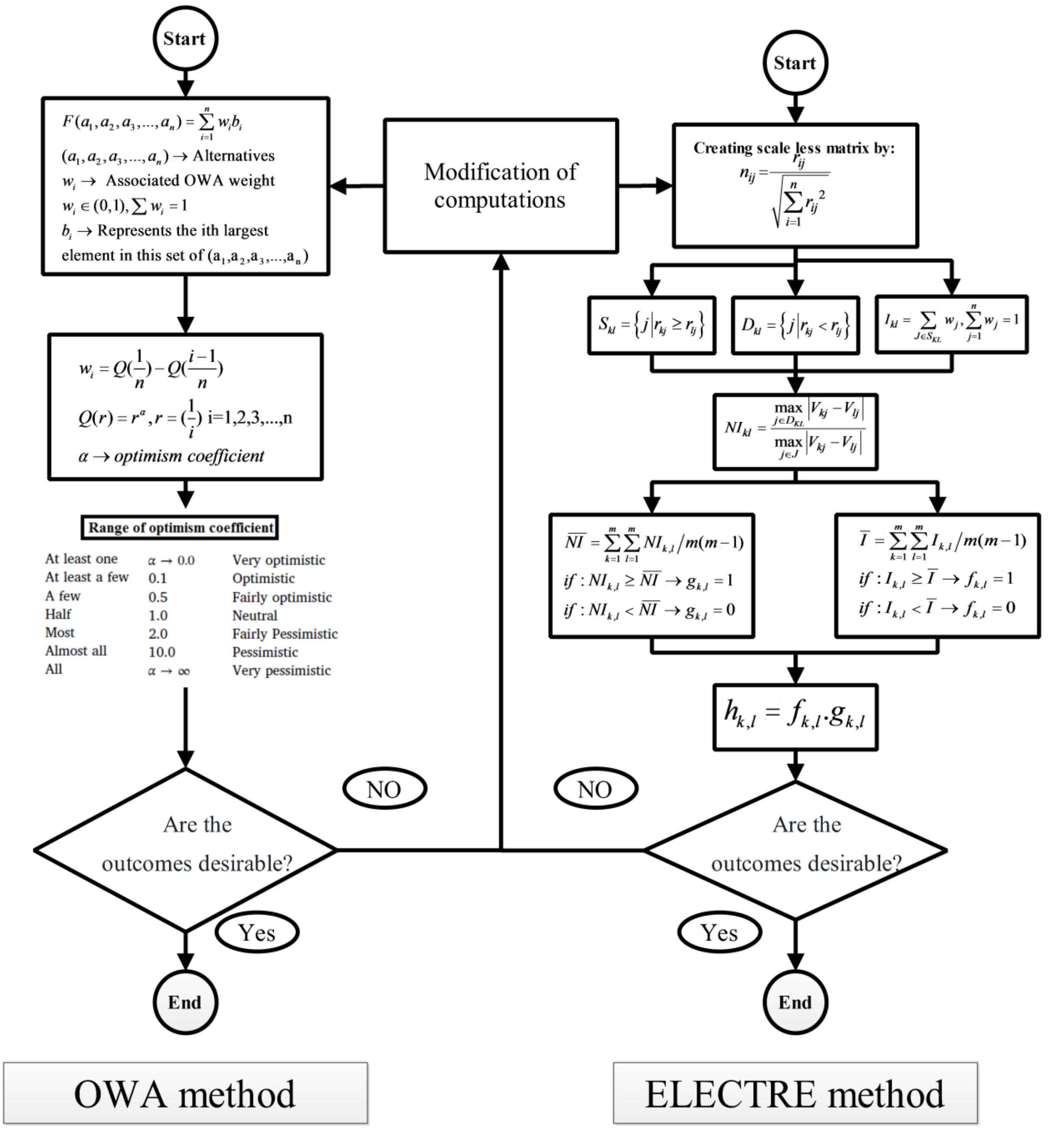
	and operation of plastic wastes in Mashhad city		
Expert and specialized perspective in the field of environment and urban services	Supervision and specialized studies in the field of municipal solid waste management	Middle experts of the organization	8
Executive viewpoints in solid waste management issues	Operation of Mashhad's landfill more than 15 years	Landfill experts in Mashhad city	5


Start
Designing questionnaire for achieving expert's idea and descriptive statistical analysis
$P_{ij}=\frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}, \forall i,j$
$a_{ij} \rightarrow$ Opinion of each expert about parameters
$P_{ij} \rightarrow$ Normalized value of each opinion
$E_j = -k\sum_{i=1}^{m}[P_{ij}Ln(P_{ij})], \forall j$
$k = \frac{1}{Ln(m)}$
$E_j \rightarrow$ Entropy of each parameter
$d_j=1-E_j$
$d_j \rightarrow$ deviation degree
$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \forall j$
$W_j \rightarrow$ Initial weighting
$W'_j = \frac{\lambda_j W_j}{\sum_{j=1}^{n} \lambda_j W_j}, \forall j$
$W'_j \rightarrow$ Final weighting
$\lambda_j \rightarrow$ Weighting from researcher's view
Criteria ranking
Yes
NO
Are the outcomes desirable?
Modification of computations
End
SE method

(a)


Start
Modification of computations
Start
Creating scale less matrix by:
V = N_D × W_n×n
CR = CI / RI
CR → Consistency Ratio
CI → Consistency Index
RI → Random consistency Index
CI = (λmax − n) / (n − 1)
λmax → Largest Eigen Value
n → Size of comparision matrix
NO
Model calibration
CR ≤ 10%
Yes
TOPSIS ranking of alternatives
NO
NO
Are the outcomes desirable?
Are the outcomes desirable?
Yes
Yes
End
End
TOPSIS method
AHP method

(b) (c)



(d) (e)

Fig. 5. Algorithms of MCDM computations (a) SE (b) TOPSIS (c) AHP (d) OWA (e) ELECTRE.

Finally, for clarification of experts' roles through the decision-making processes, the schematic plan of experts' demographics and background are presented in Fig. 6. Based on the mentioned Fig., which is obtained from Table 3, the relativity of the declared experts is determined as a knowledge network. Based on this plan, all experts are categorized into three sections contain technical, managerial, and economic specialists. Likewise, the links of the network demonstrate the job relations of experts, which are distributed in different groups of decision making. The declared scheme illustrates that all collected decisions are provided based on different aspects and experiences.

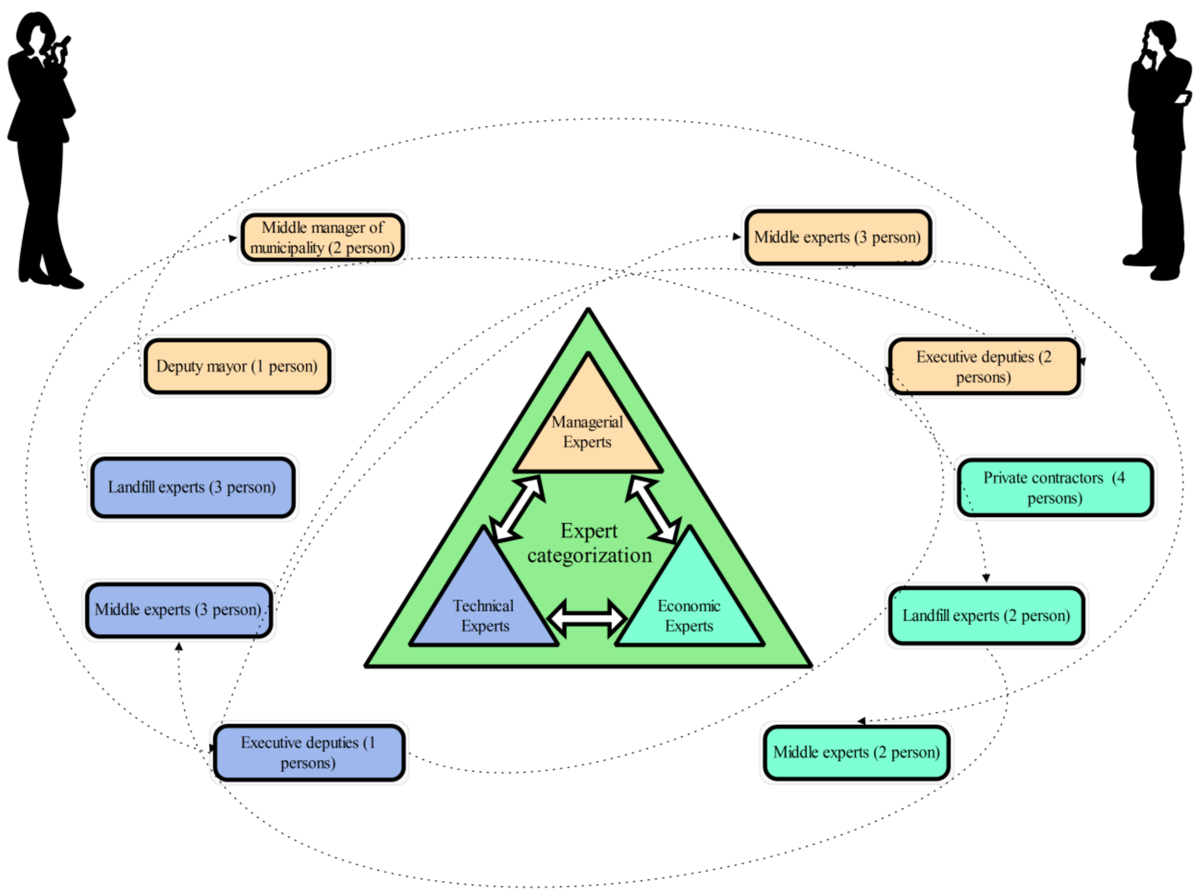


Fig. 6. The schematic network and categorization of experts through the present study.

2.5 Scenario Building (SB), Porter's Five Forces (PFF) and Circular Economy (CE)

In the current investigation, SB system [44] is used for sensitive analysis based on Fig 7. While, in the sensitivity analysis, mean TOPSIS, ELECTRE, and AHP methods as a superposition of all weights are considered based on possible drawn situations. Plus, the criteria weights of scenario buildings are determined based on SE with the corporation of the mentioned experts. Also, PFF

[45] is utilized for designing an economic business plan (as given in Fig. 8). Finally, the CE model designed the green plastic waste management system [46] in Mashhad city based on Fig. 9. The PFF is planned in three time periods, including short time (5 years), middle time (15 years), and long time (25 years). For extracting all aspects of CE and PFF, two different types of the questionnaire are designed. At that time, 50 (25 principals, 15 staff, and 10 contractors) and 35 (15 principals, ten staffs and ten contractors) persons of the municipality of Mashhad city have completed them in Google form online system for CE and PFF, respectively. The municipality of Mashhad city employed all interviewed experts in this section, and they submitted their ideas through the request of organization's senior managers within the framework of the obligatory letter section. Also, the mentioned experts are selected from different parts of the organization with appropriate environmental science, engineering, and management viewpoints as per HR opinion.

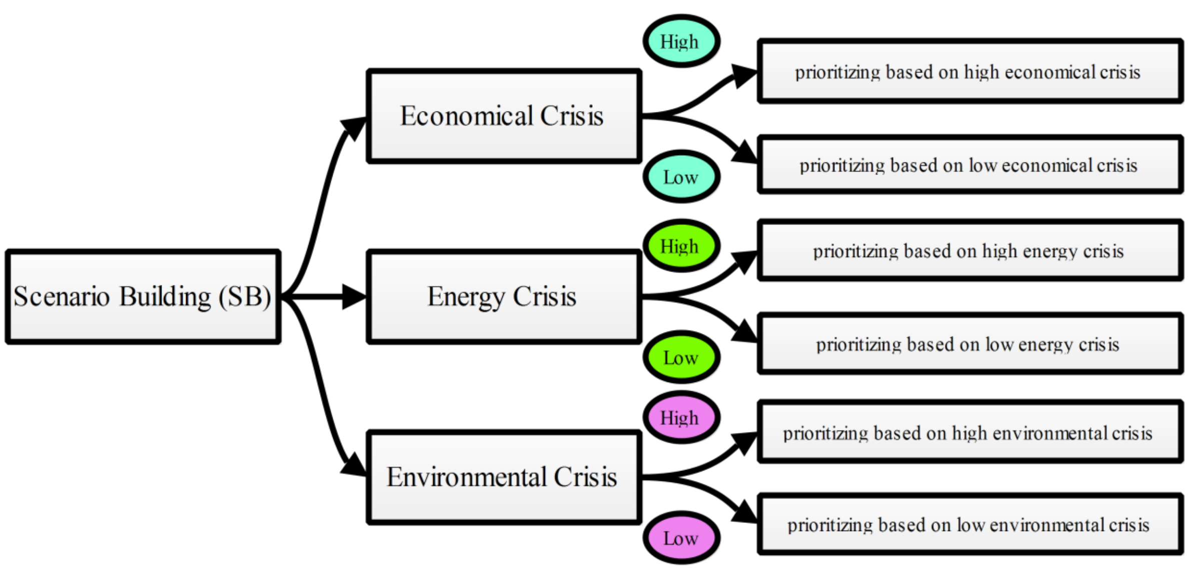


Fig. 7. Algorithm of sensitive analysis based on SB system.

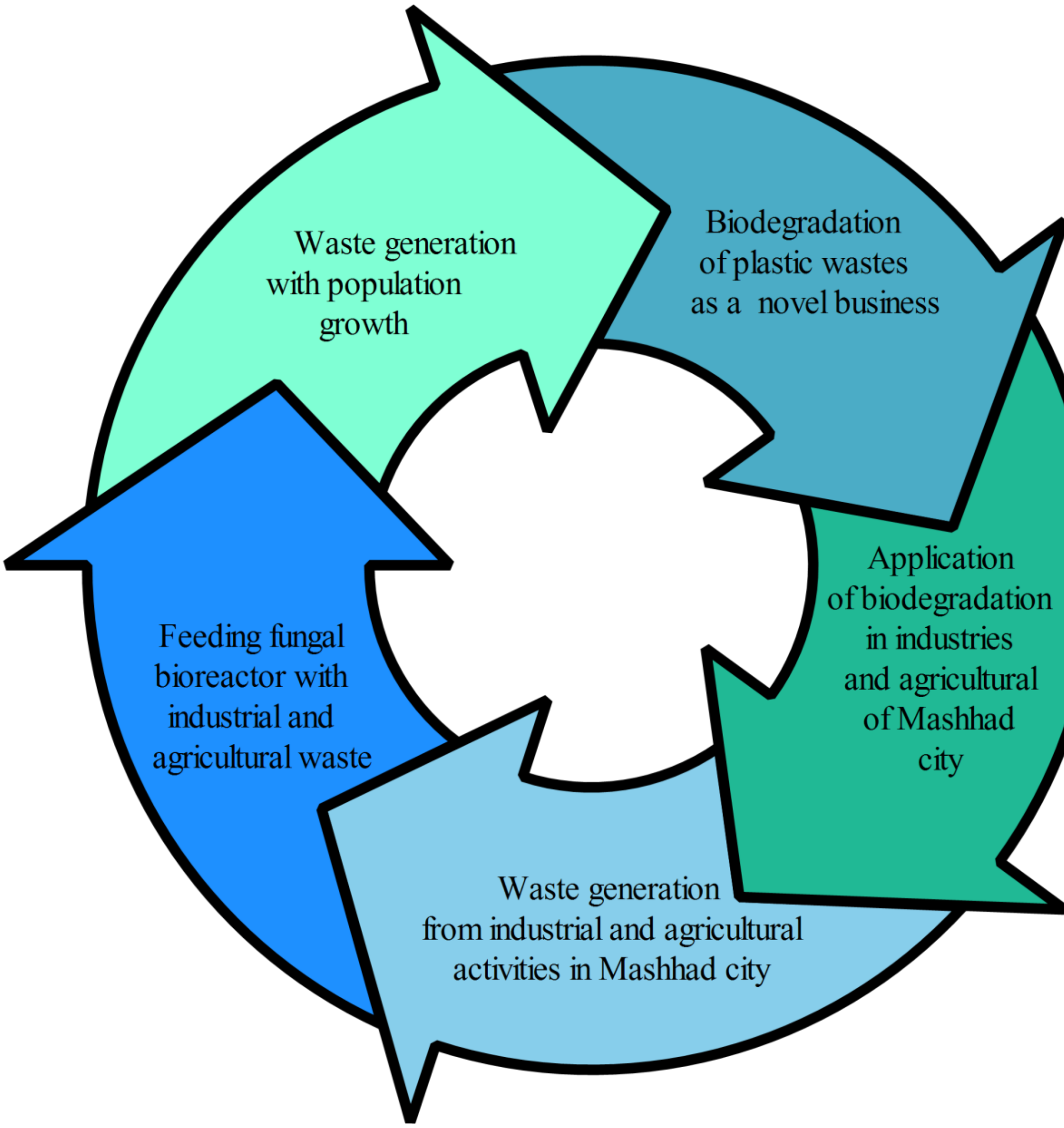


Fig. 8. Economic cycle flow of CE in the present research.

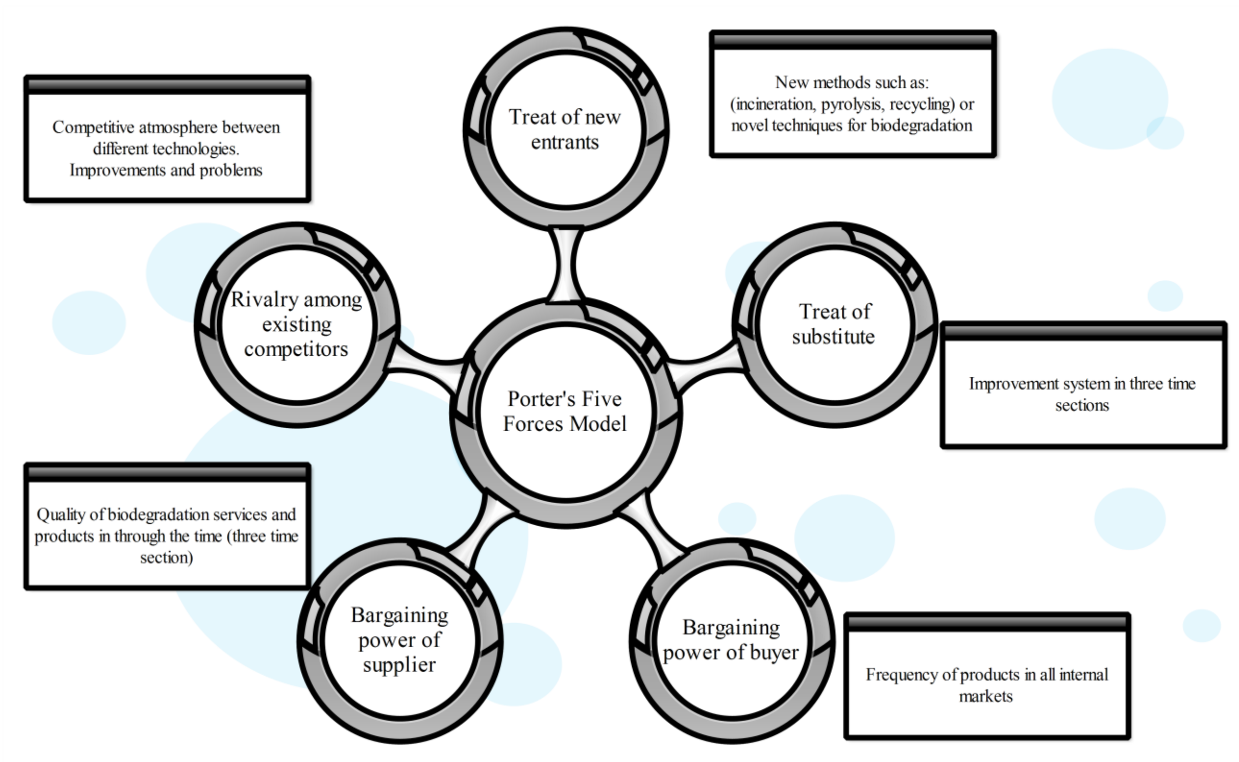


Fig. 9. Pattern of PFF model in the present research.

3 Results and Discussions

Before the expression of numerical parameters through this study, it is worth noting that all collected criteria from the literature review are approved by 23 experts of the present study. Also, the agreement percentage of experts about the suggested criteria is illustrated as per Fig. 10. With consideration to the declared Fig., it is clear that all criteria are permitted with more than 60% agreement percentage through this investigation. Therefore, the library assessment of criteria is appropriate for this study, and it is a strong reason for the application of Table 2 through the MCDM computations.

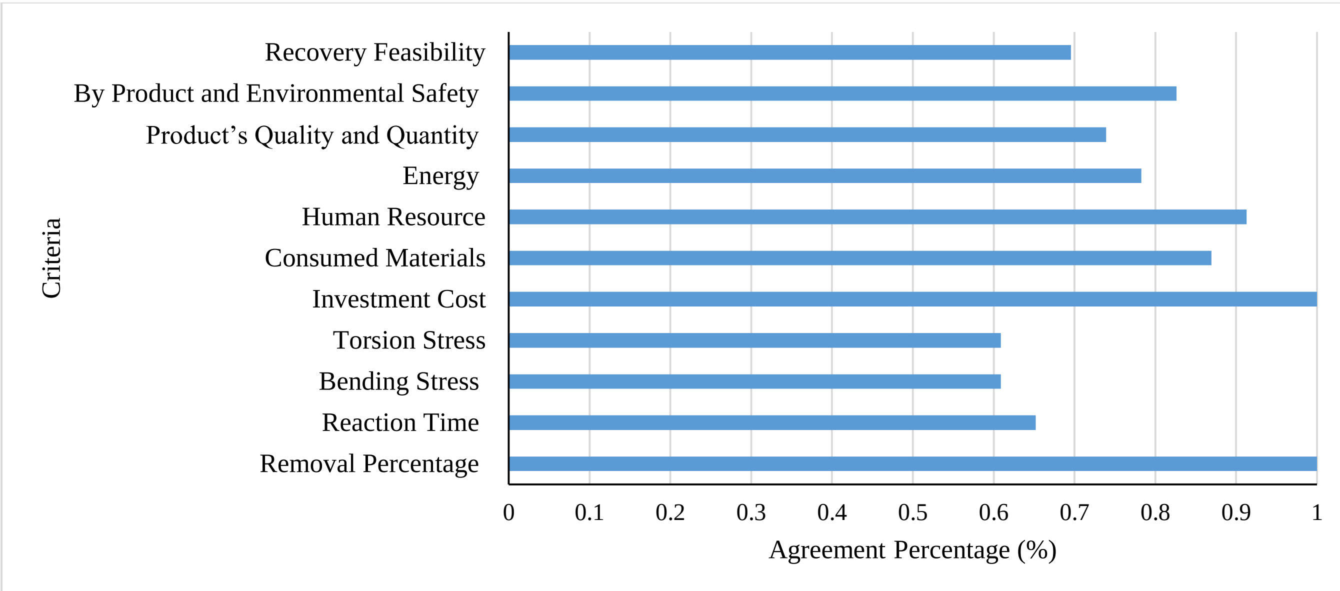


Fig. 10. The outcomes of agreement percentage of criteria by 23 experts through the present research.

The outcomes of SE model for weighting to criteria including Removal Percentage (RP), Reaction Time (RT), Bending Stress (BS), Torsion Stress (TS), Investment Cost (IC), Consumed Materials (CM), Human Resource (HR), Energy (E), Product’s Quality and Quantity (PQQ), By Product and Environmental Safety (BPE) and Recovery Feasibility (RF) are summarized in Fig. 11. According to Fig. 11, RP, RT, CM, PQQ and RF have the most weight in managers, operators and planners (23 experts). Also, the maximum and minimum weight value are related to RF and HR with 0.195 and 0.1, correspondingly.

The RDI value of different fungus specifications for degradation of PE, LDPE and HDPE are presented in Fig. 12-14, respectively. The RDI value computes the distance of parameter from the best solution, so the closer values of RDI to zero are assumed as ideal solutions. Based on RDI amounts and SE outcomes as inputs for MCDM models, the results of AHP, ELECTRE, and TOPSIS algorithms for PE, LDPE, and HDPE decomposing fungus prioritizing are demonstrated in Fig. 15-17, correspondingly.

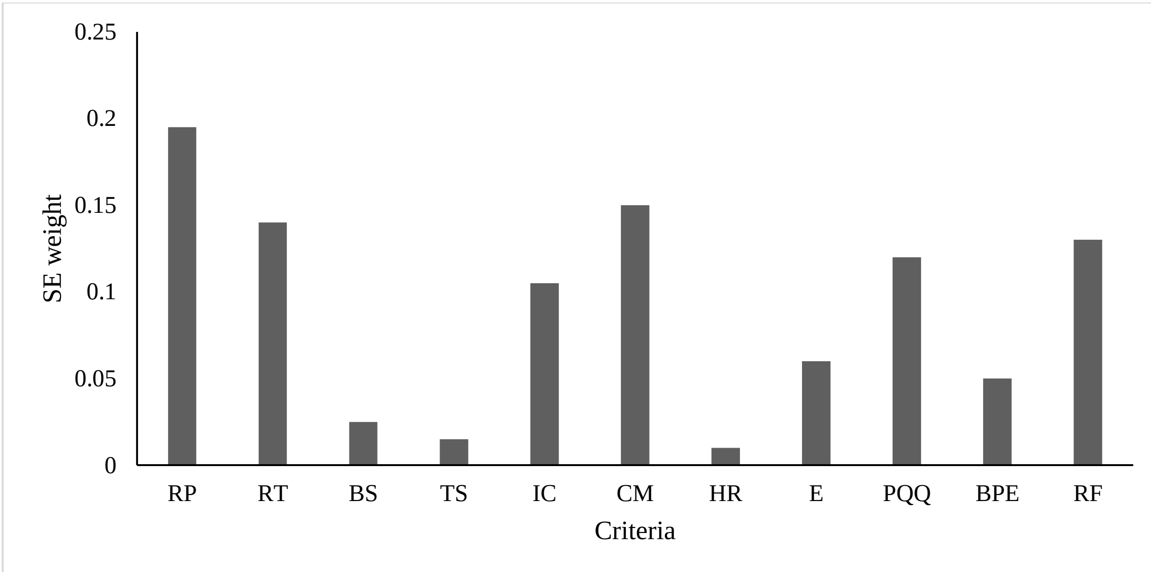


Fig. 11. The outcomes of SE prioritization for weighting criteria.

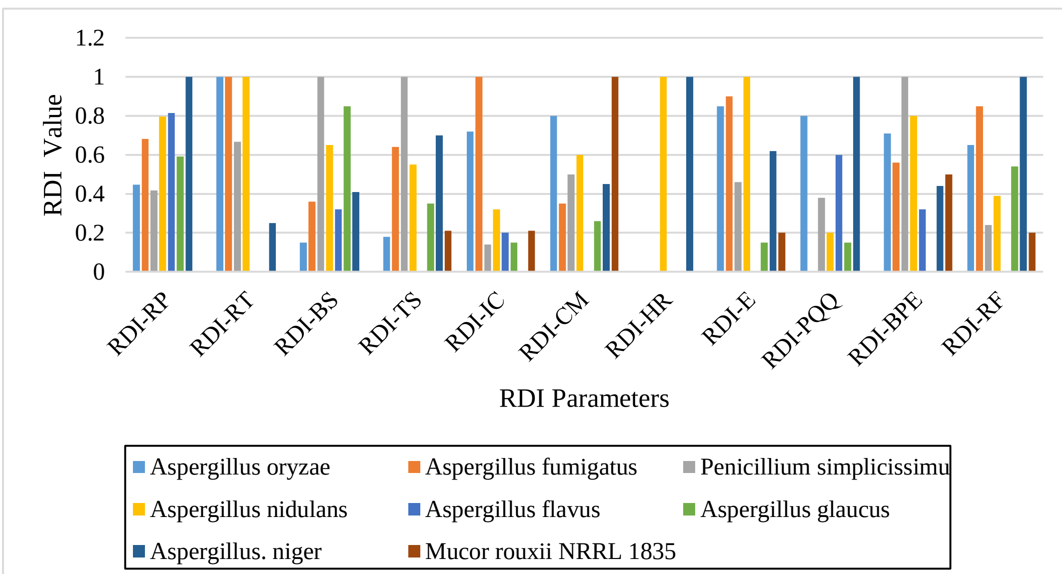


Fig. 12. The RDI value of fungus specifications in PE biodegradation.

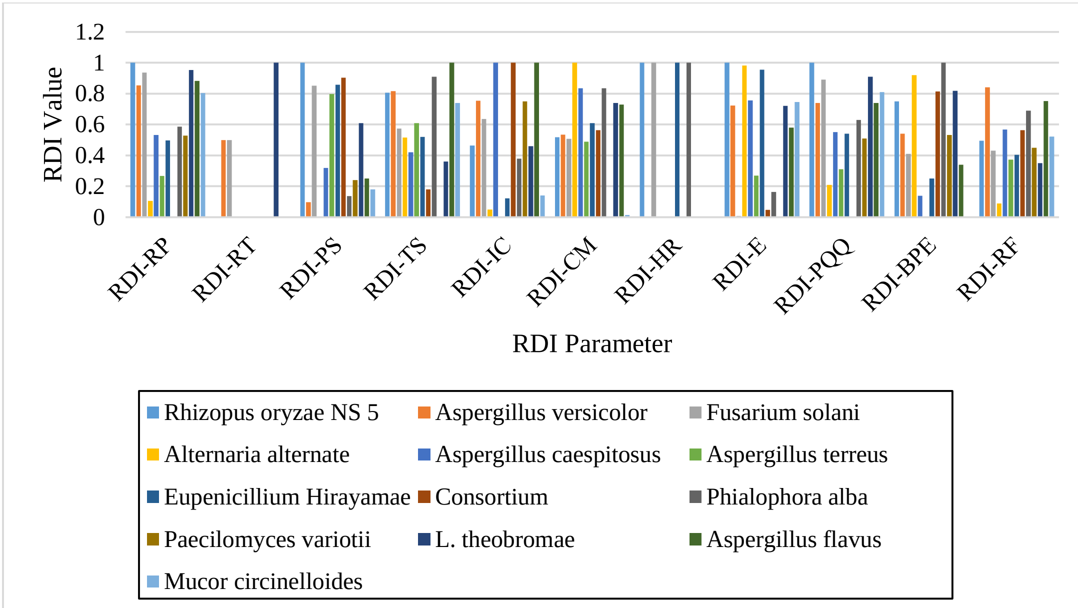


Fig. 13. The RDI value of fungus specifications in LDPE biodegradation.

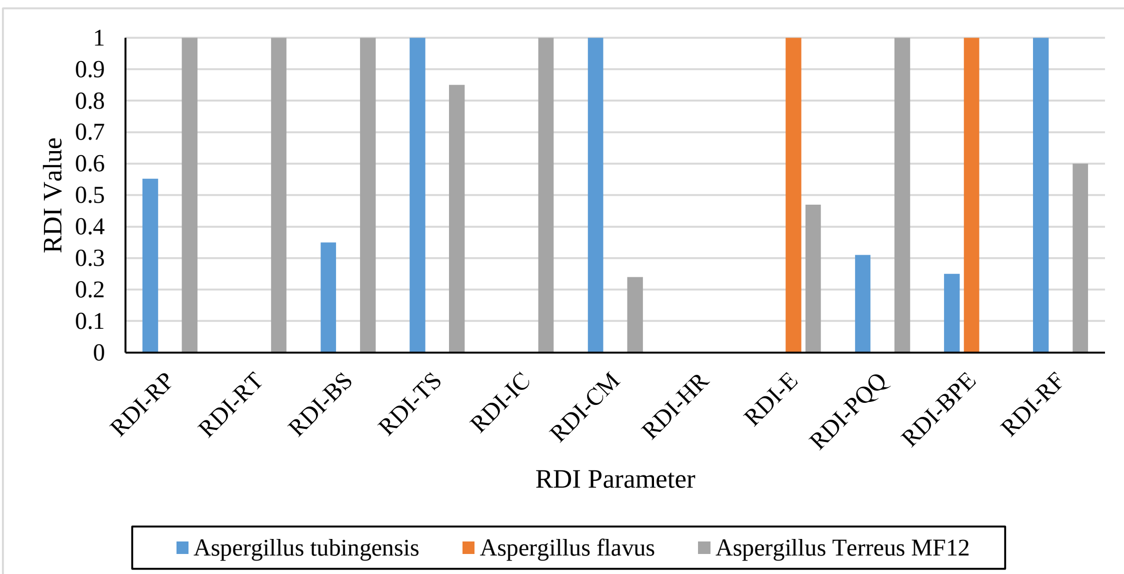


Fig. 14. The RDI value of fungus specifications in HDPE biodegradation.

As can be indicated in Fig. 15, it is clear that *Mucor rouxii* NRRL 1835 and Aspergillus flavus have the most satisfaction for biodegradation of PE based on TOPSIS, AHP and ELECTRE computation systems. Likewise, the application of *Aspergillus oryzae* is not recommended according to the mentioned Game Theory (GT) based methods (TOPSIS, AHP and ELECTRE).

In the following, based on Fig. 16, for decomposition of LDPE wastes, Consortium fungi have been suggested by all TOPSIS, AHP and ELECTRE computation systems. According to Fig. 17, Aspergillus flavus have designated for biodegradation of HDPE by experts' idea. Reversely, the degradation of LDPE, Aspergillus versicolor, Fusarium solani and Aspergillus flavus cannot meet the experts' ideas and they didn't select as bio-engine for LDPE recovery process.

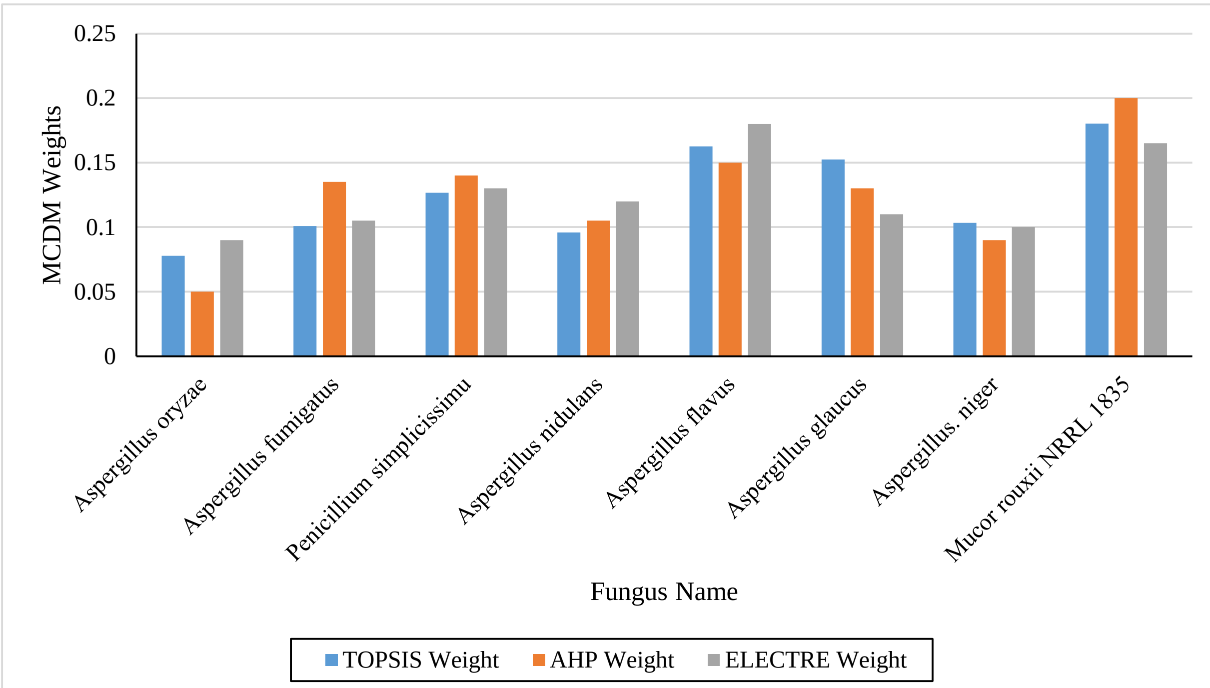


Fig. 15. The TOPSIS, AHP and ELECTRE weights for ranking fungus in PE biodegradation.

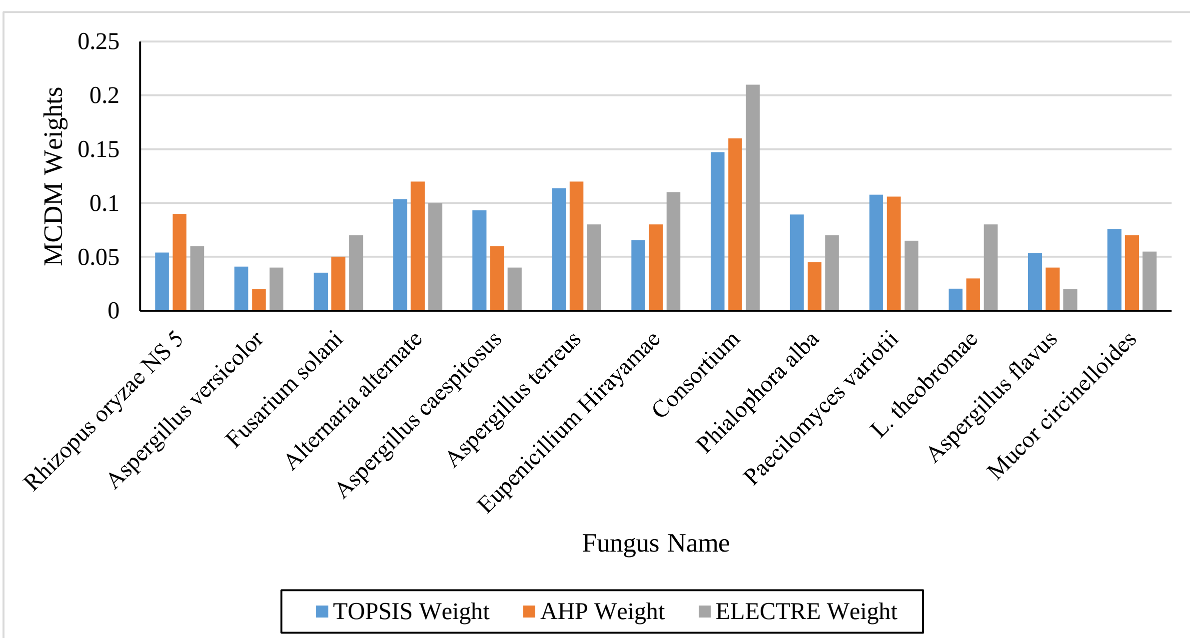


Fig. 16. The TOPSIS, AHP and ELECTRE weights for ranking fungus in LDPE biodegradation.

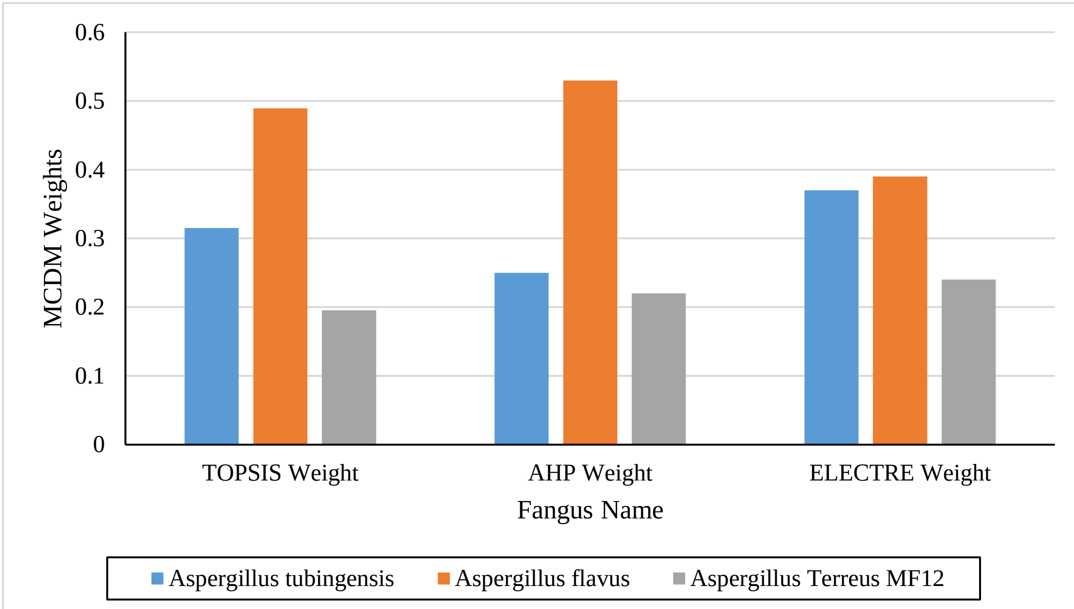


Fig. 17. The TOPSIS, AHP and ELECTRE weights for ranking fungus in HDPE biodegradation.

Based on Fig. 18, OWA analysis has illustrated that Mucor rouxii NRRL 1835 fungus has been dominated for biodegradation of PE between all alternatives from very optimistic to very pessimistic situations. Also, according to Fig. 19 and 20, Consortium and Aspergillus flavus have been selected as the best opportunities compared to other ones for biodegradation of LDPE and HDPE based on OWA logic in all situations from very optimistic to very pessimistic, respectively. Therefore, as a result, it can be expressed that all GT models approve the distinction of *Mucor rouxii* NRRL 1835, Consortium, and Aspergillus flavus for different sections of bio-engine.

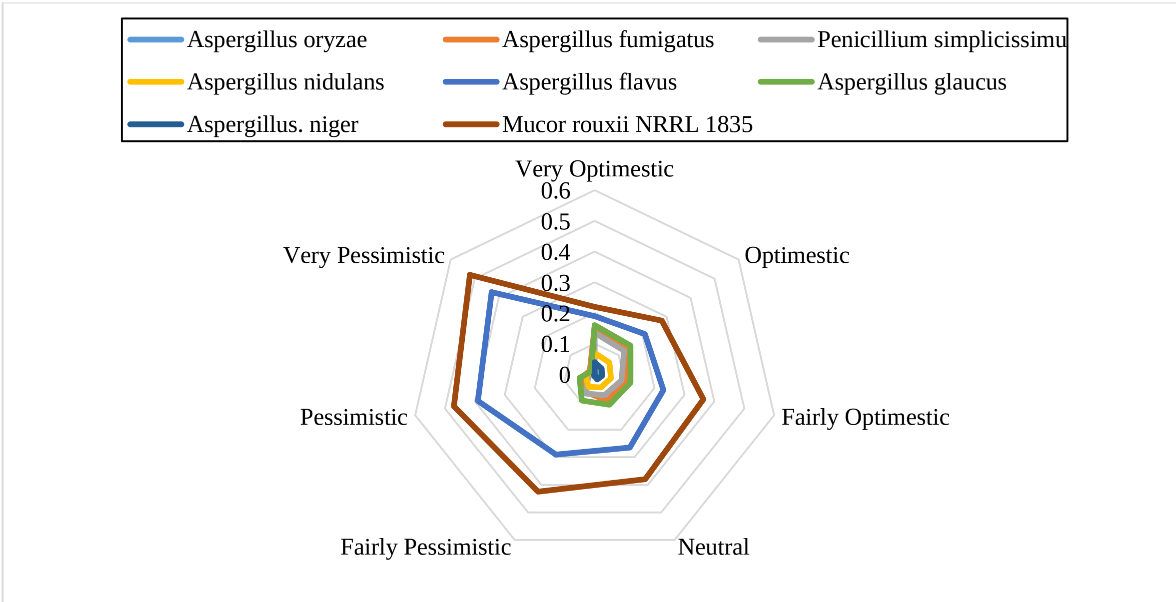


Fig. 18. The OWA weights for ranking fungus in PE biodegradation.

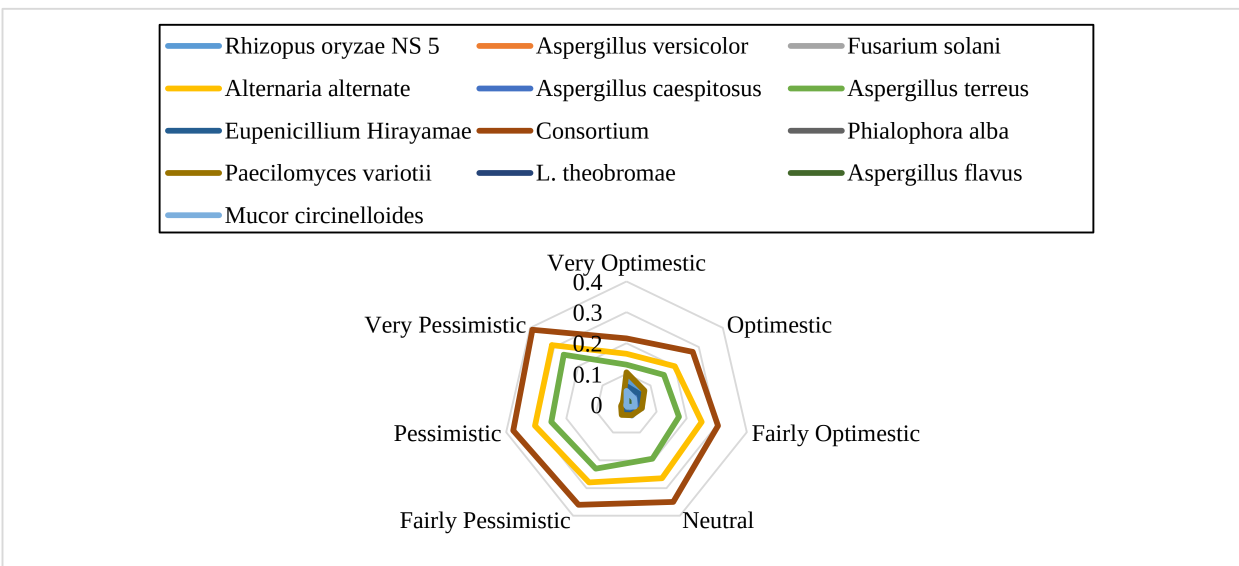


Fig. 19. The OWA weights for ranking fungus in LDPE biodegradation.

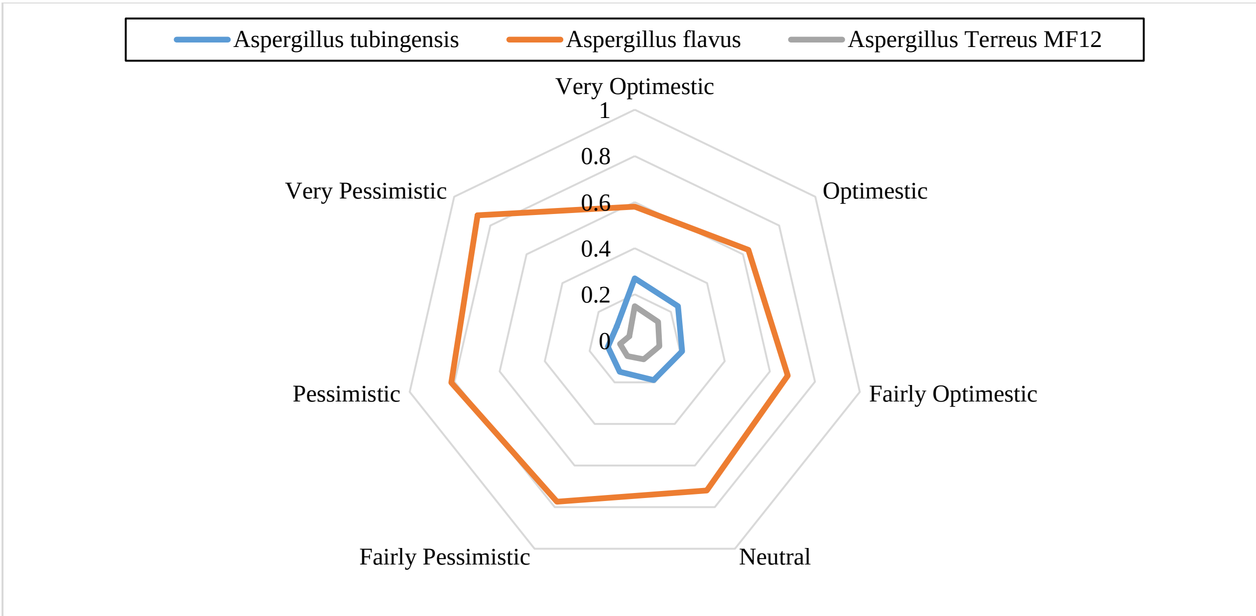


Fig. 20. The OWA weights for ranking fungus in HDPE biodegradation.

The sensitive analysis of MCDM about the selection of best fungal is done by AHP, TOPSIS and ELECTRE computations and SE scenario (Fig. 21) in three conditions: economic, energy, and environmental crises. While each crisis is divided to low and high intensity and all SE's experts gave their ideas in six categories as per Fig. 21.

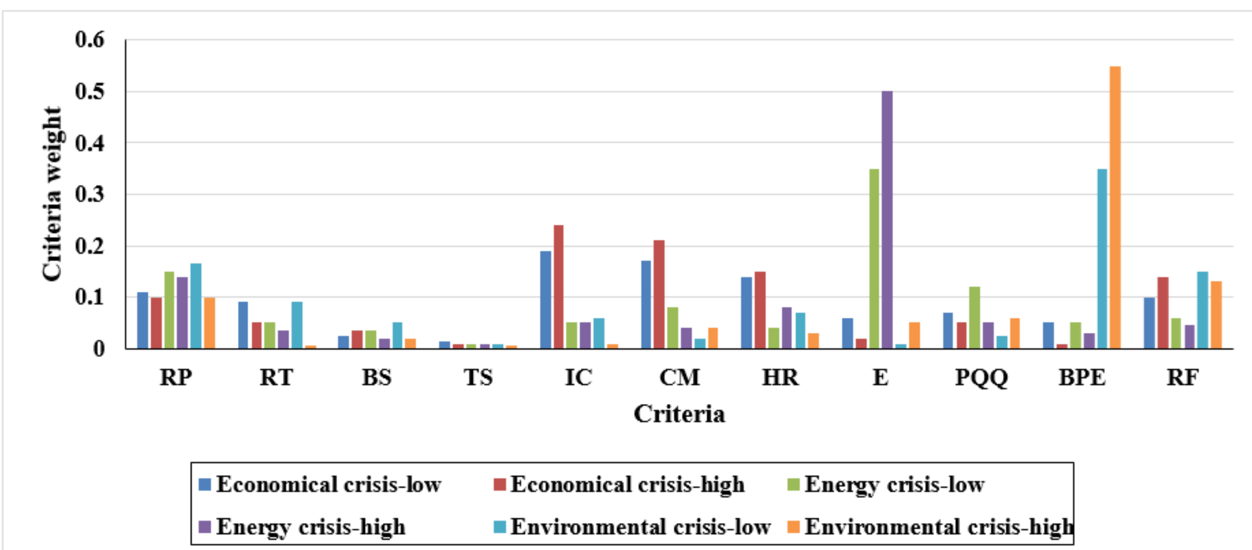


Fig. 21. The criteria weights as per different scenarios in sensitive analysis based on SE.

The sensitive analysis of PE biodegradation has illustrated that Aspergillus flavus is the best selection in high and low economic/energy crisis. Likewise, Aspergillus glaucus was the best choice in low and high environmental crises. Totally, based on Fig. 22, the *Aspergillus glaucus* and Aspergillus flavus can be operated in a crisis situation in comparison of other alternatives.

According to Fig. 23 for sensitive analysis of LDPE biodegradation by fungus, in a high and low level of economic/environmental crises, *Aspergillus terreus* can be achieved the best situation between all alternatives. While, in aspects of energy crisis, *Paecilomyces variotii* has been selected as a bio-engine's core. Overall, in different crises, *Aspergillus terreus* has the most resilience in comparison other options. Plus, in normal situation, Consortium has been suggested as per the super position of all MCDM computations.

Based on Fig. 24, the sensitive analysis of HDPE biodegradation has demonstrated that in both (high and low) levels of economic, energy and environmental crises, *Aspergillus flavus*, *Aspergillus tubingensis* and *Aspergillus Terreus* MF12 have been nominated, respectively. It goes without saying that the Aspergillus flavus has been dominated as a bio-engine in normal conditions (without any crisis).

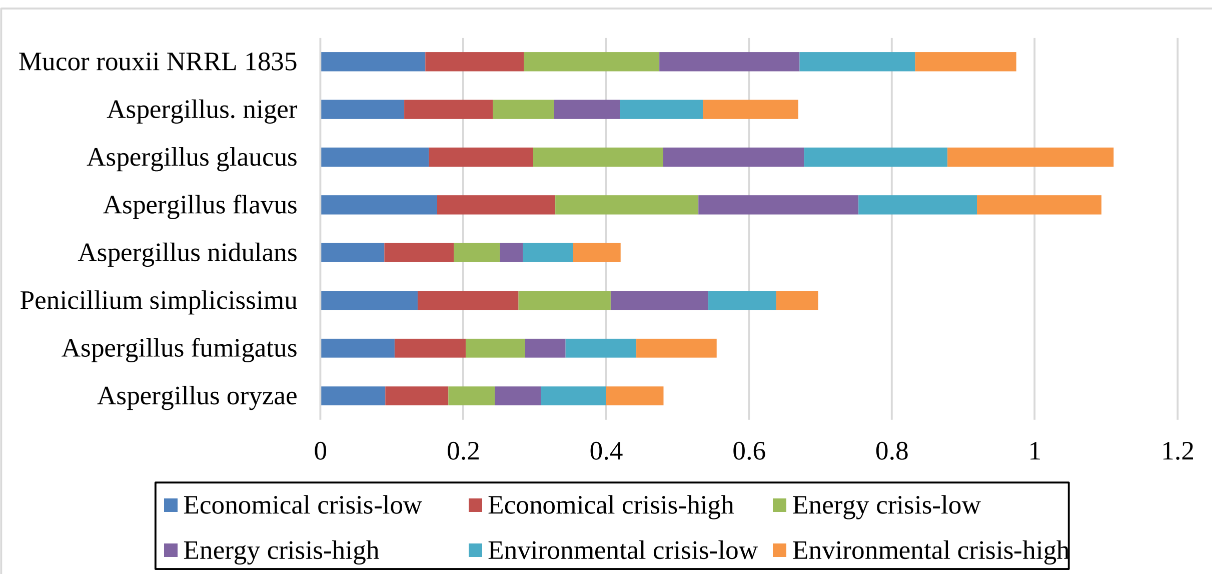


Fig. 22. The sensitive analysis of fungus ranking for PE biodegradation.

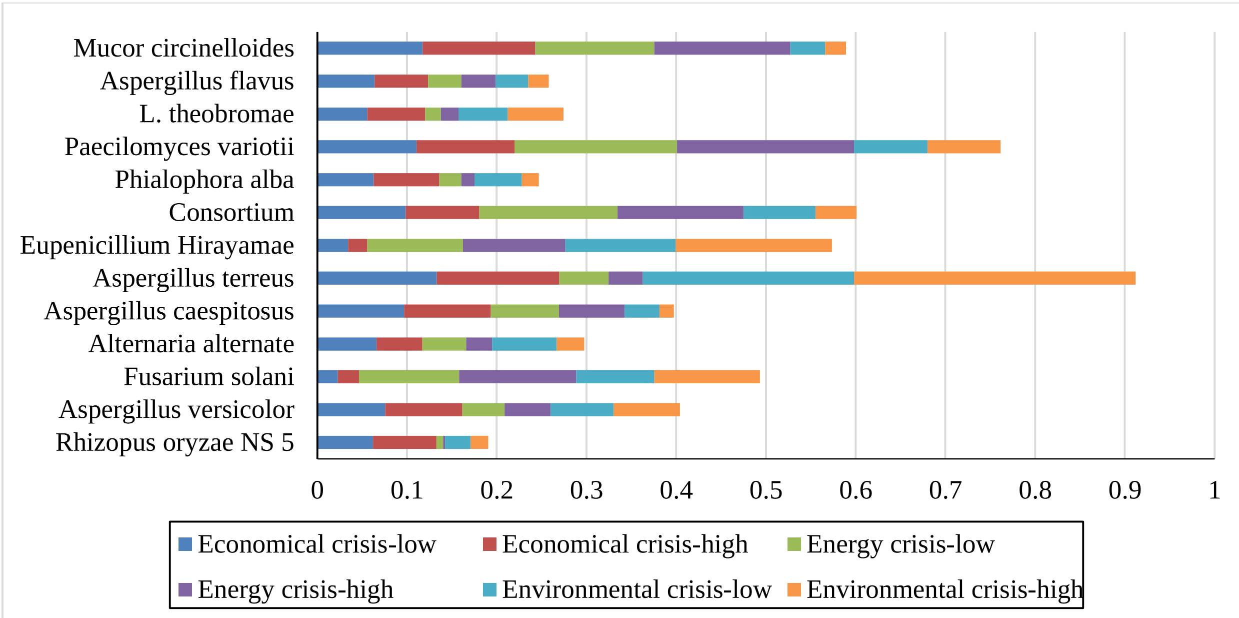


Fig. 23. The sensitive analysis of fungus ranking for LDPE biodegradation.

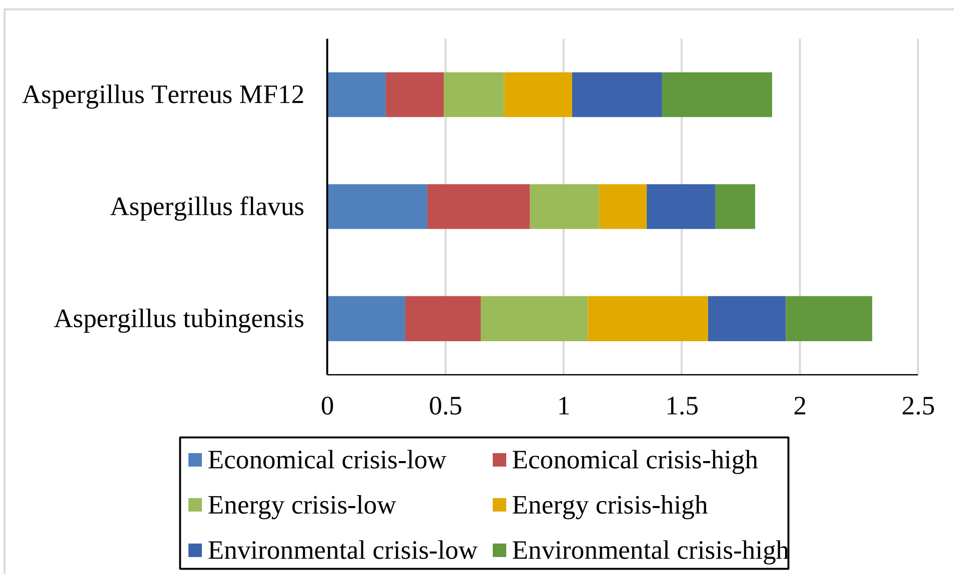


Fig. 24. The sensitive analysis of fungus ranking for HDPE biodegradation.

For designing the bio-engine due to biodegradation of PE, LDPE and HDPE in the same time and based on fungus activities, a CE platform is presented as per Fig. 25. Based on the mentioned system, PE, LDPE and HDPE are injected to bioreactor 1 until 3, respectively for plastic waste recovery of Mashhad City in normal condition. With the implementation of this bioreactor as centralized or decentralized plastic waste recovery packages in a city, SDGs [47], SC [48] and GC [49] can be meet in megacities. By implementation of bio-recovery of plastic waste by fungus activities, circularity is operated, and it is introduction of green economy, smart business and SDGs concepts meeting [48]. Likewise, based on a research which is done in Indonesian cities, because of complexity of biological treatment operation, it needs to develop smart infrastructure, and it leads to SDGs as a sustainable plastic waste approach [47]. Whereas, according to research in Russia, with the operation of a recycling economy, some aspects of smart cities are developed [49]. As per the declared Fig., with usages of biodegraded plastic wastes in agricultural soil as a fertilizer [50], the consumption of chemical fertilizer is reduced and finally, hazardous material emissions will be controlled in water and soil resources [51]. In a parallel way, optimizing fertilizer production will reduce the energy consumption for the enricher generation [52]. Therefore, in this CE model, water and energy saving will occur as a green city framework [53]. Looking at Fig. 25, it is clear that the scheme of CE concept can be proven and determined in the present research with different aspects. On the other words, this Fig. has scrutinized the effects of plastic wastes bio-recovery on the food, water and energy supply chains [80-83]. Through research in India, based on some criteria containing heterogeneity, waste, energy, process, toxic gas, and supply, the mechanical treatment system is selected as the best recovery method of plastic waste. But, the Environmental Impact Assessment (EIA) is not argued and Also, the biological methods are not discussed [80]. Also, based on some investigations about the application of MCDM scheduling computations in green supply chain programming, it is concluded that with the mentioned systems, comprehensive aspects of environmental problems can be solved [84-90].

In the last section of this research, the PFF assessment of plastic wastes biodegradation by fungus' activities and green fertilizer generation from municipal solid wastes is summarized in Fig. 26. As per the agreements of experts' ideas, the most important bargaining power of suppliers is biodegradability and clean production of fertilizer in fungus-based procedures. Whereas the least degree of importance is related to low energy consumption in recovery facilities because of the cheap value of energy in Iran. In the following, the main threat of substitute products is connected to inventing furniture, especially, roof covering and bags from plastic wastes, which is approved by different studies [54-56]. Research reviewed incineration, recycling, hydrogenation, landfilling, and gasification of plastic wastes. Finally, the mentioned study evaluated the novel approaches of plastic waste in megacities. Based on the outputs, conversion of plastic wastes to raw materials for production of new products is assumed as one of the best solutions which approve the outcomes of present research [55]. Plus, the other investigation presented a novel framework for smart green enterprises of plastic waste-based products in developing countries [56]. Likewise, the main threat of new entrance is linked to present a novel biodegrading system with low cost and high-quality products [57-60]. Based on research done in Tehran city, Iran for reaching to low-cost sustainable waste-based products, multi-objective optimization computations can be used [58] and through the present study it can reduce the new entrance possible problems PFF model. Also, the other researches proves the high performance of metaheuristic computations for waste management systems [57-63]. Plus, buyers' most and least importance of bargaining power are related to the probability of aflatoxin production from *Aspergillus* flavus bio-activities and fluctuation of bio decomposition outcomes from quality viewpoint during a year, correspondingly [91-95].

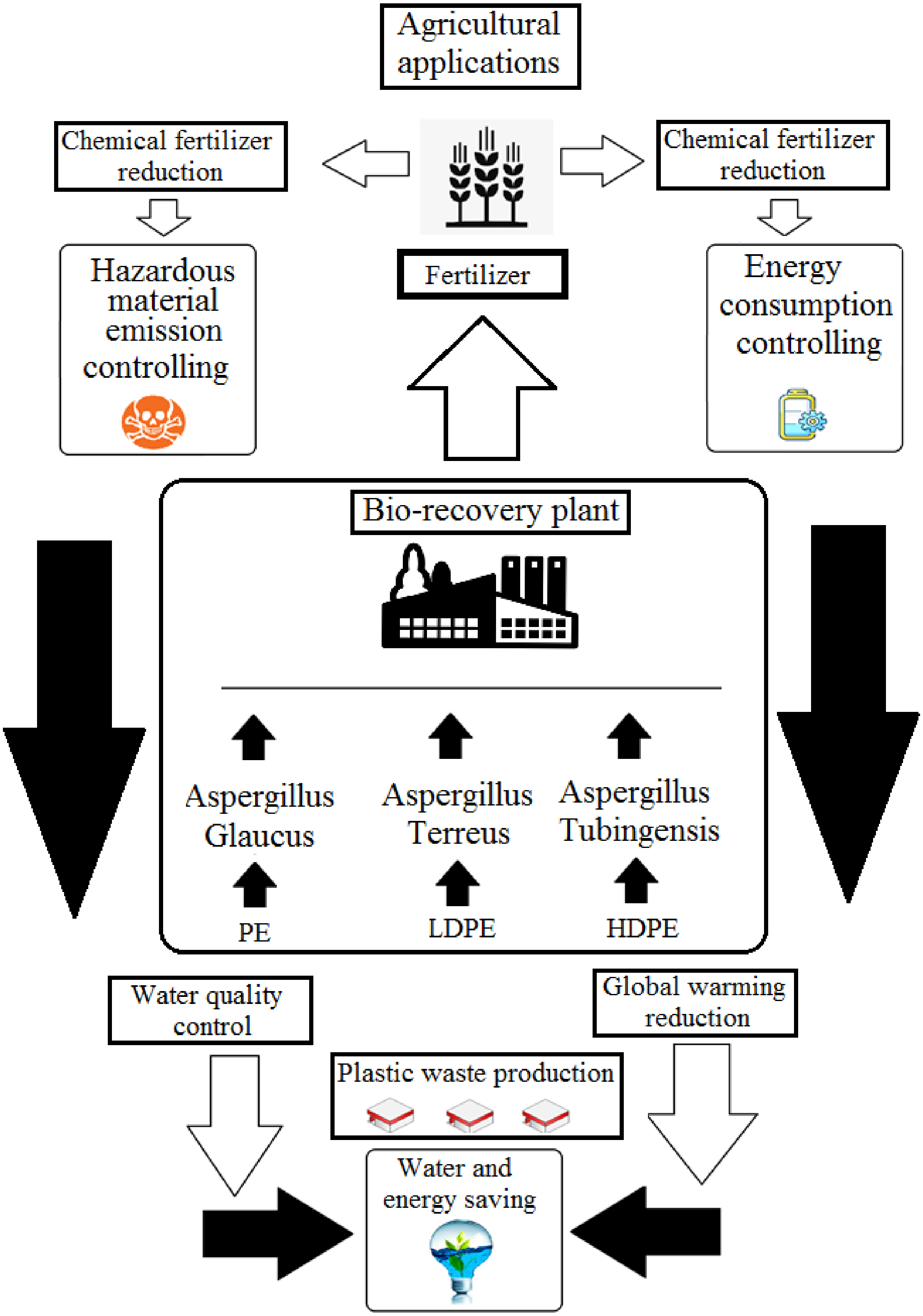


Fig. 25. The scheme of bio-engine application for plastic waste recovery process.

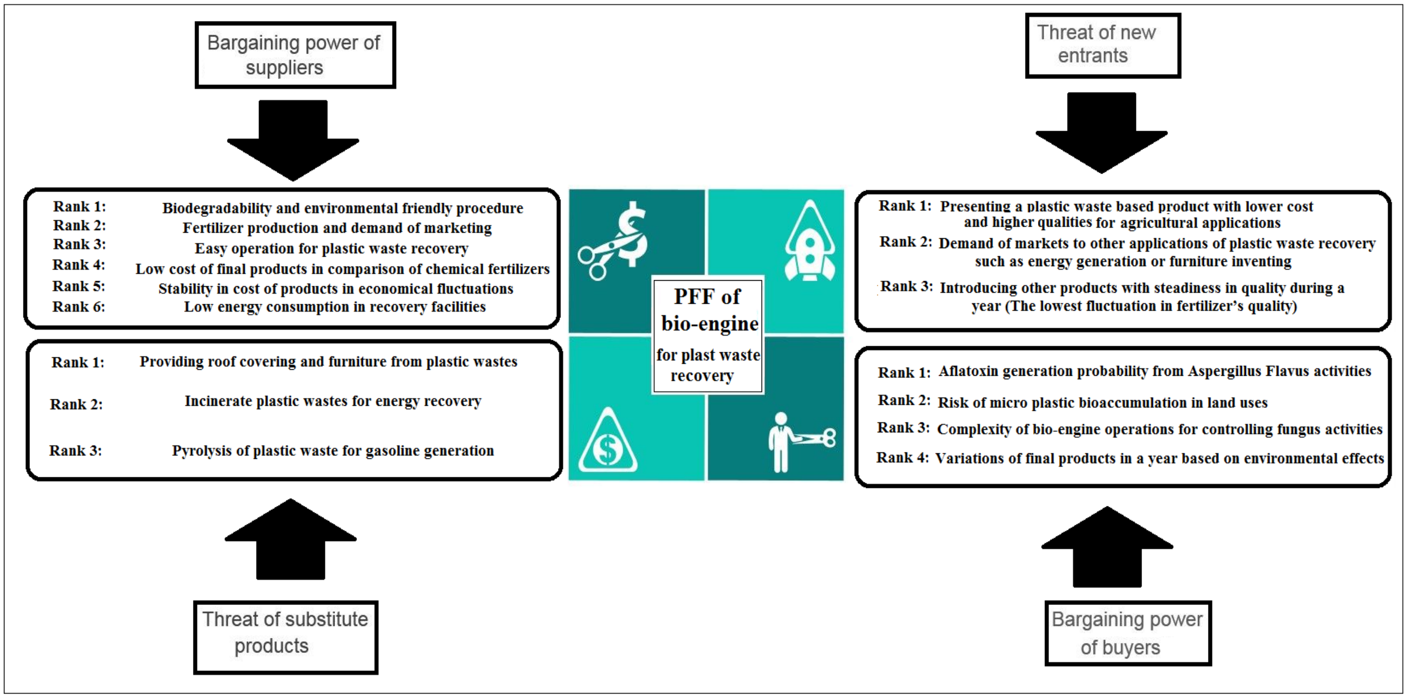


Fig. 26. The PPF of PE, LDPE and HDPE decomposition by bio-engines in present research.

With the application of the decision system in the present study, it is predicted that around 300 thousand tons'/year plastic waste can be recovered to agricultural products [58], hazardous material emission can be controlled and it causes energy optimization through the waste management procedure [59-68]. For the mentioned outcomes, the rate of waste production is assumed equal to 2000 ton/day as per physical measurement of Mashhad city municipality, which is reported generally in 2020, value of plastic waste is considered equal to 51% (Fig. 4) and the mass equivalent of bio-recovery process is set in 80% with considering safety factor [69]. Finally, the surveying of this study has been done by online citizen system of Mashhad city and 42138 persons patriate on it. In the mentioned survey that is done with corporation of the municipality of Mashhad city, citizens' satisfaction after implementing the bio-recovery process of plastic waste are asked. The main question of the mentioned query was "Satisfaction level of citizens about environmental management and urban services" after and before implementation of bio-recovery of plastic waste in Mashhad city. The outcomes of the mentioned online survey are illustrated according to Fig. 27. As per the declared Fig., after implementation of plastic bio-recovery system in Mashhad city, regards of people to urban management organization is increased from 49% to 64%. Also, dissatisfaction rate is reduced from 31% to 16% by application of biological procedure of plastic wastes. Therefore, satisfaction of citizens about urban management system will be improved through the suggestion of present investigation.

After approving the all suggested strategies from TOPSIS, AHP, ELECTRE and OWA computations by 12 retired managers as senior experts (Table 4), they have predicted the progress of Mashhad city's plans as the upstream documents after implementation of the bio-recovery process which are illustrated in Fig. 28. According to the mentioned Fig., the rate of municipal waste industries development has increased from 30% (2016) to 58% (After bio-recovery process implementation) based on senior experts' idea. The mentioned specialists have expressed the improvement percentage of the mentioned process according to their experiences and the mean amount is reposted. Also, in the same way, through the bio-recovery procedure, smart city goals as an internal program in Mashhad city will be increased from 20.32% in 2018 to 25% in 2025 (one year after finishing the bio-recovery system setting up). According to different research about Mashhad city [70-74] and empirical knowledge of senior experts, the rate of hazardous material emission from municipal solid wastes will be controlled around 25% from 2016 to end of the plastic waste bio-recovery process set up. The twelve senior experts in this part of study are available knowledge management banks found in Mashhad city with appropriate background according to HR of the municipality in the case study.

Table 4. Specification of experts for MCDM computations in the present research.

Selection criteria	Main experience	Position levels	Number of experts
Experiences and academic educations	Scientific researches on the similar topics	Formers Dean of the Faculties of Engineering, agriculture and Environment, Ferdowsi University of Mashhad	3
Experiences and holistic view in megacity environmental management	Political decision about similar issues in Khorasan Razavi Province	Deputies Governor of Khorasan Razavi Province	2

Experiences, academic educations and wisdom	Macro-management in the field of metropolises	The mayors of four cities in Khorasan Razavi Province	4
Experiences	Expert view on the field of municipal solid waste management	Managing Directors of Mashhad Waste Management Company	2
Experiences	Expert and managerial view on the environmental protection issues	Deputy of Environmental Protection Organization of Iran	1

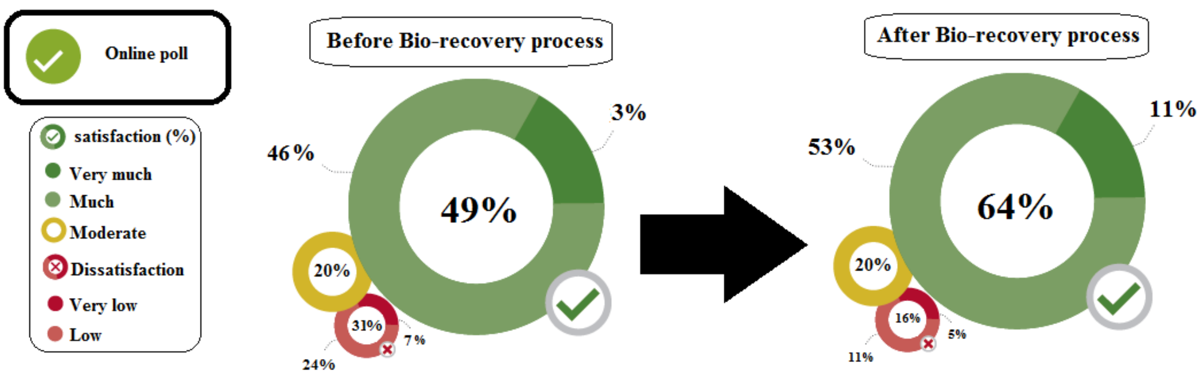


Fig. 27. Citizens' satisfaction to implementation of plastic waste bio-recovery process by Online platform in Mashhad city.

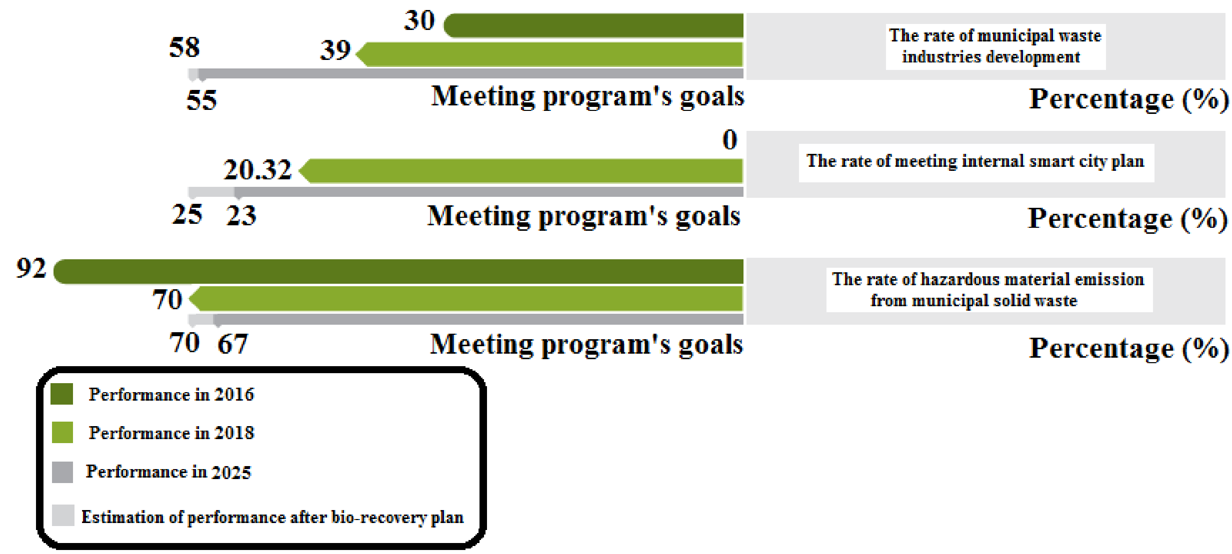


Fig. 28. Evaluation of meeting solid waste management goals of plastic waste bio-recovery process in the present study.

The outcomes of the present study with other researches in this field are compared and summarized in Table 5. According to the mentioned achievements, the present study emphasized on application of MCDM algorithms for the determination of best fungus-based systems as the bio-engine through plastic waste biodegradation. Then, with a query in the online platform, feedback of the action is appraised according to citizens' satisfaction percentages. Likewise, the PFF model could scrutinize the economic aspects of the present research. Therefore, with achievements of the research, plastic waste recovery can be programmed by considering environmental, social, political, and economic issues simultaneously. Thus, with these findings of present efforts, the research gap is filled in the field of plastic waste management. While the other researches have considered to technical aspects of plastic waste biodegradation. But, the present investigation has utilized the outcomes of all technical studies for real field planning in Mashhad city.

Table 5. Comparison the outcomes of different studies.

No.	Description	Reference
1	Evaluation of the best process for plastic waste recycling by integrated fuzzy AHP-TOPSIS methods	[75]
2	Application of MCDM for management of hazardous materials	[76]

3	Integration of Life Cycle Assessment (LCA) and MCDM for solid waste collection system appraisal	[77]
4	Application of Hesitant Fuzzy Multi-Objective Optimization system for medical waste management	[78]
5	Creating the framework for solid waste management by MCDM	[79]
6	Application of AHP for plastic waste recycling methods ranking	[80]
7	Green planning for plastic waste management by integration of MCDM, PFF, scenario building and with consideration of social satisfaction	Present study and filling the research gap

Specifically, the plastic waste management issue is scrutinized in the United Kingdom [84], United State [85], and Denmark [86]. But, they appraised the different subjects of this research area as below:

- United Kingdom: Application of political approaches for managing marine plastic wastes with focusing on tax approving [84]. Likewise, the present research is concentrated on technical and managerial aspects of plastic waste, and it can cover comprehensive viewpoints of the declared challenge area.
- United State: Assessment of incineration technique for implementation of waste to energy concept as a recovery based solution [85]. Besides, the direct recycling approaches of plastic waste are not argued in the declared investigation. Reversely, the present effort concentrates on applying biological procedures for applying the environmentally friendly recycling concept as a technique through plastic waste management.
- Denmark: Evaluation of Environmental Impact Assessment in the Aarhus, Denmark case study with focusing on Circular Economy issues [86]. But, the managerial insights are not discussed in this study like present research.

4 Technology, social and economic aspects

The outputs of the present study are appraised from technology, social and economic aspects for waste management subject [84-88]. For the mentioned goals, the results are compared with some different studies according to Fig. 29. Based on this scheme, from a technology aspect, the bio-recovery of plastic wastes is safe and environmentally friendly against other techniques such as incineration, landfilling, and anaerobic digestion, which is concluded from the Life Cycle Assessment of each method [87-89]. Also, it is clear that for enhancement of the bio-recovery process, the mentioned plastic waste should be mixed with 84% organic compounds, and then it can be utilized as liquid fuel through biological treatment [90,91]. Finally, the usage of hydrothermal for mixed plastic-organic wastes can be useful as another application through the CE process, and it causes the industrial ecology concept [92].

In developing countries, especially Iran, the economic subject is the main area of SDGs and with the execution of CE in the environmental issues, the economic aspect can be met. Likewise, with green management of plastic waste as an income resource in Iran, economic issues are tied to environmental concepts. Based on Fig. 29, the economic issues are frontier of SDGs in developing countries, and they should be satisfied before all aspects for the continuation of the designed plan.

Finally, as per Fig. 27, with the execution of present study outcomes, social satisfaction increases because of confidence in local government promotion based on green city grantee. In other words, transformational participation occurs in the city, and bio-recovery issues after public announcement become a public demand from the government.

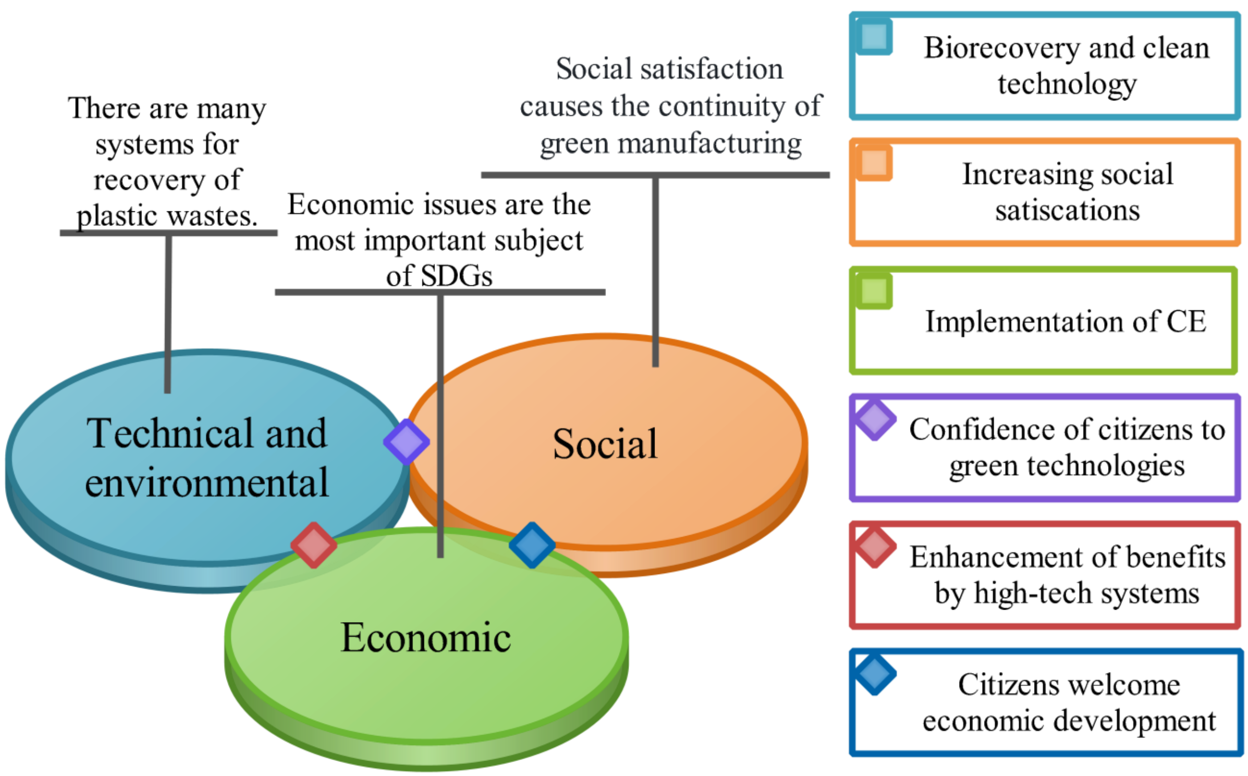


Fig. 29. The scheme of technology, social and economic aspects in the present study.

There are many suggestions as our limitations which can be considered for our future works. Adding more social factors like job opportunities and work's damages is a good suggestion to do an in-depth sensitivity analysis [58-60]. The lost working days for implementing the proposed municipal plastic waste management may be studied in the future [61-63]. It goes without saying that the proposed integrated model can be applied to other applications like supply chains and energy-based systems [64-70]. Developing a conceptual model to create energy policies is another future research direction from our results [71-75]. Last but not least, considering the recent advances in machine learning and the internet-of-things technologies in our conceptual model is another good idea [76-83].

5 Conclusion

Nowadays, plastic wastes are assumed as hazardous emerging pollutants which are not decomposed easily by nature. Likewise, the mentioned contaminations have a lot of different compounds that process of them are dissimilar together and it causes a high level of complexity for plastic waste management. Plastic wastes are converted to microplastic wastes by some human and natural-based activities, and then they will not point source pollutions which is released to water, air, and soil environments. For implementation of GC, there are some features and managing the plastic wastes is one of GC's main aspects. Therefore, in this research, fungus-based biodegradation of PE, LDPE and HDPE are appraised by application of MCDM, including AHP, TOPSIS, ELECTRE, and OWA. Then, the outcomes of AHP, TOPSIS, ELECTRE are analyzed in three economic, energy and environmental crises divided into low and high intensity of catastrophe in each situation. Finally, the CE and PFF techniques for environmental impact assessment and economic scrutinizing are performed.

As per GT computations, with the integration of three stages bioreactor including *Aspergillus* flavus (or *Mucor rouxii* NRRL 1835) as a stage 1, *Consortium* (stage 2) and *Aspergillus flavus* (stage 3) can be useful for recovery of plastic wastes in a normal situation of the GC. But, the sensitivity analysis has demonstrated that in crises (i.e., economical, energy, and environmental impacts), *Aspergillus glaucus* (for PE), *Aspergillus terreus* (for LDPE) and *Aspergillus tubingensis* (for HDPE) has the most resilience, and they were appropriate for the core of bio-engine.

Moreover, with the application of biodegraded plastic wastes as a fertilizer in agricultural land uses, the quality controlling in water/soil resources and energy saving will occur. The PFF demonstrates that for implementation of fungus-based plastic biodegradation, the most significant parameters in the bargaining power of suppliers and buyers contain environmental-friendly procedures based on biological process and toxic substance generation probability as per Aspergillus flavus bio-decomposition.

For future studies, the present research suggests evaluating energy consumption for bio-recovery of plastic waste and scheduling the renewable energy resources for use in the declared procedure. Job opportunities and lost workdays can be contributed to our proposed framework. It goes without saying that with developing renewable energy through plastic waste management, other aspects of green manufacturing can be implemented.

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