Global NEST Journal, Vol 24, No 4, pp 607-612

Evaluation of wastewater treatment technologies by combined analytical hierarchy process and grey relational analysis

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Received: 17/06/2022, Accepted: 11/10/2022, Available online: 16/10/2022

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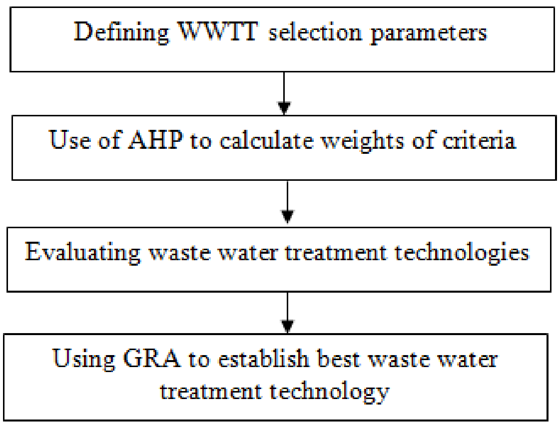
https://doi.org/10.30955/gnj.004373

Graphical abstract



Abstract

Recycling of wastewater is an important issue as it is used for many important applications such as industries, agriculture, household applications and due to water scarcity across the different countries. Wastewater treatment is an important activity as it protects human being and the ecosystem from harmful and toxic elements present in wastewater. Performance evaluation of wastewater treatment technologies being complex Multi-criteria Decision Making (MCDM) problem that has contradictory evaluation factors. This paper is focused on the analysis of factors that affect evaluation of wastewater treatment technologies and their impact by developing a model which combine Analytical Hierarchy Process (AHP) and Grey Relational Analysis (GRA) for the assessment and ranking wastewater treatment technologies (WWTTs) respectively. The best WWTT is chosen based on data acquired through a case study. AHP is applied for computing criteria weights based on comparative significance while Grey Relational Analysis method is applied for ranking and selecting the wastewater treatment technologies. Sensitivity analysis is performed to show the impact of grey relational scores of alternatives in line with variations of distinguished coefficients.

Keywords: Wastewater treatment, MCDM, analytical hierarchy process, sensitivity analysis, GRA.

1. Introduction

The recycling of wastewater and maintaining the environment neat and clean is essential for meeting the challenges caused by increase in population, rapid industrialization and mitigating water scarcity across the globe. Most of the wastewater treatment plants work with the removal of solids, reeking gases and bacteria. The performance of each unit is evaluated by monitoring inlet and outlet characteristics. Performance evaluation of a WWTT is complex due to variations in inlet characteristics, seasonal variations, unbalanced sampling and characterization process. This paper deals with performance evaluation of WWTTs utilizing integrated AHP-GRA approach. In the proposed model, AHP method is utilized for computing criteria weights to make prioritization whereas ranking of wastewater treatment technologies such as activated sludge, membrane bio-reactor, waste stabilization ponds and constructed wetlands is computed by GRA method. The criteria that are considered for this study include: hydraulic retention time, water flow, biochemical oxygen demand (BOD) efficiency, aesthetics, space requirements and energy requirement.

Activated sludge is a popular WWTT which is cost effective, producing better effluent, consume less space and has no odor comparing to other WWTTs (M.J. Hammer Sr., M.J. Hammer Jr.,2006). An integrated AHP and ANP was applied to a decision problem to rank best WWTT (Bottero, et al. 2011). Volcke et al. (2002) reported biological wastewater treatment assessment using simulation benchmark control strategies. An entropy method was proposed to solve MCDM problem (Hwang and Yoon, 2012). Seow, Ta Wee et al. (2016) described the wastewater treatment methods such as biofilm technology, aerobic granulation and microbial fuel cell.

Membrane bioreactor method has merits such as reduced footprint, removal of filtration, good efficiency & less sludge creation and having disadvantages such as high energy costs, complex and costly membrane (T. Yeit Haan et al. 2017 and M. Djun Lee et al. 2018). Waste stabilization ponds are designed and built to treat wastewater for decreasing organic content by natural treatment using bacteria, fungi, and algae (D. Recio-Garrido et al. 2018). Constructed wetlands uses porous media that lead to clogging with merits like ease of operation & maintenance, less costs and good aesthetic view (Q. Yang et al. 2018). Solutions for Agricultural reuse of the water in a sustainable way using a software was proposed (Hidalgo et al. 2007). Fuzzy TOPSIS was used to prioritize the optimal sites for wastewater treatment (Kim et al. 2013). A comprehensive report on industrial wastewater treatment dealing with ELECTRE method was proposed (Ranade and Bhandari 2014). An integrated fuzzy AHP is proposed to identify best wastewater treatment selection by a case study (Ouyang et al. 2015). Selecting a right wastewater treatment technology will facilitate sustainable development and requires a decision support system (M.N. Yahya et al. 2020).

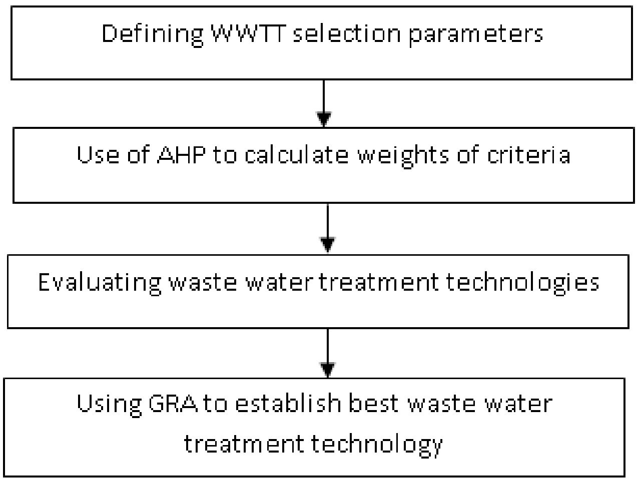


Figure 1 Evaluation of WWTT by integrated AHP-GRA method.

The literature review reveals that many works are reported for WWTTs and their evaluation methods. Analysis of wastewater treatment technologies consists of selection of right type of technologies based on the requirements of regional and application as well. It falls under MCDM that covers both subjective and objective parameters with conflicting goals. Based on the literature, it is found that limited number of works are reported for waster water treatment technologies (WWTT) selection problem, though the availability of MCDM methods are plenty. In this paper, an integrated AHP-GRA methodology is proposed to make a multi-criteria selection among various WWTTs. The views of the decision makers' for comparative position of the selection parameters are calculated by AHP method and by GRA technique ranks of the alternatives are obtained. This paper is organized in to five parts. While part 1 discusses overview of the paper, part 2 focuses on existing practices of various methods of wastewater treatment and application of MCDM methods for ranking the alternatives. Part 3 describes suggested AHP and GRA methods and steps involved. A typical WWTT problem is explained to support the intended model which is discussed in part 4. Lastly, conclusion and scope for future investigation are explained in part 5.

2. Development of AHP-GRA method for WWTT selection

The suggested model deals with the determination of relative weights of criteria by AHP method as part 1 and application of GRA method for ranking and selecting best wastewater treatment technology as part 2. Figure 1 depicts the steps in the proposed method:

2.1. Utilizing AHP to calculate criteria weights

AHP is a Multi-Criteria Decision Making (MCDM) technique that includes converting complicated decision making in a structured form with a sequence of matrix arrived by pair-wise comparison. The various criteria weights are obtained by synthesizing the results Emovon et al (2016).

The AHP model has following phases:

Phase 1: Defining selection parameters of WWTTs selection

Phase 2: Developing a hierarchical framework

Phase 3: Establishing pairwise comparison matrix using equation 3.1:

$$X=[x_{ij}]=\begin{matrix} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix}\begin{bmatrix} C_1 & C_2 & \cdots & C_n \\ 1 & x_{12} & \cdots & x_{1n} \\ 1/x_{12} & 1 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/x_{1n} & 1/x_{2n} & \cdots & 1 \end{bmatrix} \quad (3.1)$$

where $x_{ij}=1$ and $x_{ji}=1/x_{ij}$, $i,j=1,2,\cdots,n$

$C_{1,2,\ldots,}C_n$ represents criteria, while x_{ij} indicates choice on criteria.

The relative position of adjacent elements are evaluated thro values 1, 3, 5, 7, and 9 Saaty (2000), in which 1 specifies "similar important", 3 shows "marginally more important", 5 signifies "considerably more important", 7 shows "firmly more important", and 9 means "exceptionally more important".

Phase 4: Testing the comparison matrix dependability to ensure specialist judgement reliability through estimating consistency ratio by equations 3.2 and 3.3 Saaty (1980, 2008):

Consistency ratio = consistency index/random index (3.2)

$$CI=\frac{(\lambda_{\max}-n)}{(n-1)} \quad (3.3)$$

$\lambda_{\max}$, 'n' and CI indicate the Eigen value, matrix size (1 to 10) and consistency index respectively. Decision consistency is tested using consistency ratio (*CR*) of *CI* with relevant RI value. The consistency ratio is agreed if it is not more than 0.10 Lee (2012).

Phase 5: Computing weight of each pairwise comparison matrix w by divide up elements of each column of matrix A by the column total. Then adding the elements in each resultant row and divide up the sum with number of row elements.

2.2. Grey relational method (GRA)

The GRA method was proposed by Deng (1982) combining theories of system, space and control. It is used to determine grey relational grade and influence measure of performance of the system or between the system factors. It is applied to correlate the reference and compared factors of a system (Deng, 1989). GRA evaluates ambiguous associations among various factors of a system (Liang, 1999). GRA is applied in areas like forecasting, system control, data-processing, modeling and decision making (Chang et al., 1996; Hsu and Wen, 2000). GRA is also used for hydroelectricity production planning (Liang, 1999), image compression (Hsu et al., 2000) and MCDM problems (Wu, 2003).

The steps in GRA method are illustrated in the following stages (Wu and Chen, 1999):

Stage 1:

Generation of referential series v_0 = ($v_0(1)$,$v_0(2)$,…, $v_0(j)$,…,$v_0(n)$) where v_i indicates compared series v_i = ($v_i(1)$,$v_i(2)$,…,$v_i(j)$,…,$v_i(n)$) where 'i' ranges from 1 to m. The compared series v_i is characterized through matrix format.

Stage 2:

Normalization of data set for "larger-is-better" and "smaller-is-better". For "larger-is-better", $v_i(j)$ is converted as $v_i^*(j)$ by equation (3.4):

$$v_i^*(j) = \frac{v_i(j) - \min\limits_i v_i(j)}{\max\limits_i v_i(j) - \min\limits_i v_i(j)} \quad (3.4)$$

$\max\limits_i v_i(j)$ indicates maximum and minimum j value.

For "smaller-is-better", $v_i(j)$ is translated to $v_i^*(j)$ using equation (3.5):

$$v_i^*(j) = \frac{\max\limits_i v_i(j) - v_i(j)}{\max\limits_i v_i(j) - \min\limits_i v_i(j)} \quad (3.5)$$

Then, normalized referential series of v_0 becomes v_0^*.

Stage 3:

Calculation of difference between v_0^* and v_i^* at j.

Stage 4:

Calculation of grey relational coefficient $\tau_{0i}(j)$ by (3.6):

$$\tau_{0i}(j) = \frac{\Delta\min + \delta\max}{\Delta_{0i}(j) + \Delta\delta\max} \quad (3.6)$$

where $\Delta\min = \min\limits_i - \min\limits_j \Delta_{0i}(j)$, $\Delta\max = \max\limits_i - \max\limits_j \Delta_{0i}(j)$ and δ is the distinguished coefficient (δ ε [0,1]).

Stage 5:

Calculation of degree of grey equation coefficient (ρ_{0i}) using (3.7):

$$\rho_{0i} = \sum_{j=1}^{n} [Wi(j) \times \tau_{0i}(j)] \quad (3.7)$$

W_i indicates weights of criteria.

3. Case study

The integrated AHP and GRA method consists of computation of criteria weights by AHP method incorporating judgments from various specialists. Subsequently, GRA method is applied to get the assessment values based on ratio system in order to rank the four different WWTT s.

3.1. Defining the selection criteria for WWTTs

This case study deals with four prospective wastewater treatment technologies and seven selection criteria such as hydraulic retention time, water flow, BOD elimination effectiveness, space requisite, aesthetics, space requirements and power requisite are considered. The set of criteria used in this study are defined as follows:

Hydraulic retention time (HRT): This parameter is used to calculate the contact time between the pollutant and the microorganisms and affects the efficiency of wastewater treatment. The time varies from 2 to 24 hours.

Table 1. Saaty's 9-point scale

Amount of comparative significance	Description
1	equal significance
3	low significance
5	great significance
7	proven significance
9	definite significance
2, 4, 6, 8	Intermediate significance

Water flow: It ensures clean and safe disposal of wastewater.

BOD elimination effectiveness: The BoD value signifies purification level of waster water.

Efficiency: The removal efficiency in a treatment plant is stated as the percentage removal efficiency.

Aesthetics: appearance and external condition of the treatment plants.

Space requirements: Construction area required for a particular WWT technology.

Power requisite: Amount of energy required for treatment.

Figure 2 shows the hierarchy of WWTTs.

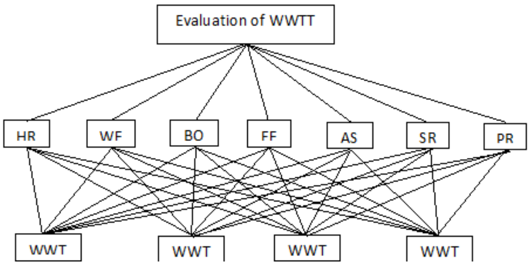


Figure 2. Hierarchy of wastewater treatment technologies.

3.2. Utilizing AHP to get criteria weights

The AHP estimation process was conducted and a program is used to collect evaluators' decisions and compute criteria weights by EXCEL. The judgement matrix dimension (n) is 7x7. The eigenvalue $\lambda_{max} = 8$, consistency index (CI) = 0.167, random index (RI) = 1.32 and consistency ratio (CR) of pairwise comparison matrix is 0.09<0.1 are calculated using the following formulae:

Consistency index CI = $(\lambda_{max} - n)/(n-1)$; Consistency ratio CR=CI/RI where RI is a random index. It implies consistency of judgment matrix. Saaty's 9-point scale and criteria weights calculated by means of pairwise comparisons are presented in Tables 1 and 2 respectively.

From the Table 2, it can be seen that BOD is very essential criterion in WWTTs performance evaluation. Subjective and analytical assessment of WWTTs alternatives is presented in Table 3. A subjective ranking is awarded through technical group which is converted using one to five score (larger-the-better).

3.3. Assessment of prospective WWTTs

The subjective and quantifiable data to assess WWTTs are presented in Table 3. To validate the GRA model for choosing proper WWTTs, the WWTTs are regarded as choices 1 to 4 while assessing elements are perceived as criteria j for alternatives 1 to 7. As low energy consumption and low space requirement are certainly advantages to the end user, these are categorized under "smaller-is-better". High values of Hydraulic retention time, Water flow, Aesthetics, efficiency and BOD removal are preferred and hence identified as "larger-is-better" case.

3.4. Applying GRA to decide the best WWTT

As mentioned in section 3.2, GRA technique is applied to combine the subjective assessment by evaluators by applying AHP and numerical data as shown in Table 3.

3.4.1. Making referential series of v_0

The subjective and quantifiable assessment of four prospective WWTTs is characterized by the following matrix:

$$V_i = \begin{bmatrix} 2.5 & 220 & 4 & 3 & 85 & 0.3 & 90 \\ 0.8 & 157 & 5 & 37 & 80 & 0.4 & 85 \\ 45 & 20 & 5 & 4 & 90 & 0.3 & 85 \\ 0.8 & 24 & 5 & 3 & 80 & 1.2 & 80 \end{bmatrix}$$

The referential series of V_0 is (45, 220, 5, 3, 90, 0.3, 90) and compared series of V_1= (2.5, 220, 4, 3, 85, 0.3, 90)

V_2 = (0.8,157,5,3,80,0.4,85)

V_3=(45,20,5,4,90, 0.3, 85) and

V_4 = (0.8,24,5,3,80,1.2,80)

3.4.2. Standardizing data series

The series data are normalized by larger-is-better and smaller-is-better cases. Hence, standardized referential series of v_0 develop into v_0^*: The "larger-is-better" case is utilized to qualitative criteria through equation (3.4) whereas "smaller-is-better" for energy consumption and space requirement are converted by equation (3.5). In accordance with computational steps, the referential series of v_0^* converts (1, 1, 1, 1):

$v_1^*(1)$= 220-20/220-20=1

$v_2^*(1)$= 157-20/220-20= 0.685

$v_3^*(1)$ = 20-20/220-20=0

$v_4^*(1)$ = 24-20/220-20=0.02

The similar process is adopted for calculating the remaining normalization data set.

3.4.3. Computation of grey relational coefficient $\tau_{0i}(j)$

The grey relational coefficient is computed by equation (3.6) through setting the distinguished coefficient as 0.5. The remaining values of $\tau_{0i}(j)$ is calculated and are depicted in Table 4.

Table 2. Criteria weights of WWTT

Criteria	**Water flow**	**Hydraulic retention time**	**Aesthetics**	**Energy consumption**	**Efficiency**	**Space requirement**	**BOD**
Weight	0.14	0.16	0.06	0.13	0.21	0.05	0.25

Table 3. Assessment of prospective WWTTs

WWTT	**Water flow (lmh)**	**Hydraulic retention time (hr)**	**Aesthetics**	**Energy consumption**	**Efficiency (%)**	**Space requirement (m^2/inhabitant)**	**BOD (%)**
AS	2.5	220	4	3	85	0.3	90
WSPs	0.8	157	5	3	80	0.4	85
CWs	45	20	5	4	90	0.3	85
MBR	0.8	24	5	3	80	1.2	80

Table 4. The Grey relational coefficient values

	Water flow (lmh)	Hydraulic retention time (hr)	Aesthetics	Energy consumption	Efficiency (%)	Space requirement (m^2/inhabitant)	BOD (%)
Weight	0.14	0.16	0.06	0.13	0.21	0.05	0.25
AS	1	0.473	1	1	0.483	0.642	1
WSPs	0.740	1	1	0.890	0.473	0.473	0.642
CWs	0.473	1	0.473	1	1	1	0.642
MBR	0.478	1	1	0.4736	0.473	0.473	0.473

Table 5. Grades of the grey relational coefficient for various WWTTs

WWTT	Grades of the grey relational coefficient
Activated sludge (AS)	0.8711
Waste stabilization ponds (WSPs)	0.7091
Constructed wetlands (CWs)	0.7866
Membrane bioreactor (MBR)	0.5981

Table 6. Grey relational grades of WWTT alternatives

Alternaties	Value of distinguished co-efficient									
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
AS	0.643	0.734	0.765	0.791	0.812	0.830	0.846	0.859	0.871	0.881
WSPs	0.325	0.424	0.494	0.548	0.592	0.629	0.659	0.686	0.709	0.729
CWs	0.528	0.586	0.633	0.670	0.701	0.727	0.750	0.769	0.786	0.801
MBR	0.263	0.333	0.389	0.436	0.477	0.513	0.544	0.573	0.598	0.620

3.4.4. Calculation of degree of grey relational coefficient (ρ_{0i})

The Grey relational grade indicates relationship between two series. The grade of the grey relational coefficient ρ_{0i} is calculated by equation (3.7). Based on the grades, the alternatives are ranked based on grey relational grade. The best alternative will have high grey relational coefficient grade (Wu and Chen, 1999). The values of the grey relational grade calculation of the four WWTTs are represented in Table 5.

The Grey relational coefficient grade indicates the complete performance which is used for performance evaluation and raking.

3.5. Obtaining the WWTT ranking

From the values of grey relational coefficient grades, it is found that $\rho_{01} > \rho_{03} > \rho_{02} > \rho_{04}$, the ranking order of WWTTs is: (I) WWTT 1 ; (II) WWTT 3; (III) WWTT 2; (IV) WWTT 4. Wastewater treatment technology 1 (Activated sludge method) is the best possible selection by considering all subjective and quantitative criteria. The ranking of alternative will vary based on the criteria weights.

It will be made possible to successfully combine the focused knowledge and capability of all evaluators by the suggested model. Based on the model, GRA method is adaptable for selecting wastewater treatment technology that has both subjective and quantifiable criteria.

4. Sensitivity Analysis

Sensitivity analysis is performed to investigate relationship between grey relational grades of the four WWTTs alternatives and the distinguished coefficients. End user can revisit the referential sequence by using larger-is-better and smaller-is-better conditions. The values of grey relational grades for various distinguished coefficients for WWTT alternatives are depicted in Table 6. Figure 3 shows the features of sensitivity analysis of grey relational grades.

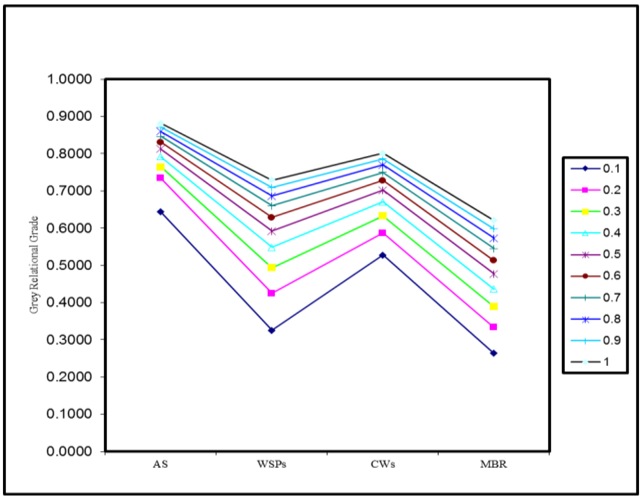


Figure 3 Impact of grey relational grades with various distinguished coefficients

It is observed from the Figure 3 that WWTT selection remains same (1 > 3 > 2 > 4) on the basis of values of grey relational grade with distinguished coefficients from 0.1 to 1.0. Thus, it is determined that the GRA method is consistent for WWTT selection. The new approach can be applied to integrate both qualitative and quantitative criteria involved in WWTT selection. It is evident that supplier selection using the GRA model is consistent and accurate. From the results of the case study, it can be emphasized that the integration of AHP and GRA is an effective and practicable approach to select the wastewater treatment technology.

5. Conclusion and future scope

Evaluation of wastewater treatment technology is a complicated MCDM issue that includes subjective and quantifiable criteria. An integrated AHP and GRA model is developed and utilized for selecting a best wastewater treatment technology. Based on the results obtained from the study, activated sludge method is found to be more effective in terms of all the selection criteria and Membrane bioreactor method is least preferred due to its disadvantages compared to other methods. AHP method is employed to calculate criteria weights by taking into account opinions of experts to estimate the WWTTs.

The proposed model is found to be more effective to solve WWTT selection problem which has qualitative and quantitative factors and facilitates selection of best alternative that has less information. A DSS is developed to select best wastewater treatment technology efficiently and accurately which consumes less time to carry out mathematical calculations. It is found that the proposed method is extensively utilized for selecting best wastewater treatment technology. As there are various methods to assess multiple attributes, wastewater treatment technology selection problem can be extended using the same. The research is extended further with focus on application of various MCDM methods to compare their relative end results and outcomes.

Conflict of interest

The authors declare no conflict of interest.

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