Experiment and Coupling Analysis of Municipal Solid Waste Degradation Under Multiple Influencing Factors

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Acknowledgements

This work was supported by the Natural Science Foundation of Shaanxi Province (No. 2022JM-262), Excellent Expert Studio Project in Bazhou of Xinjiang (No. 211828240614).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Highlights

- The study carries out a multi-factor coupling analysis of factors affecting Municipal Solid Waste degradation.
- 45% organic matter, 35-45℃ and 120-150% moisture content are suitable for degradation.
- pH goes down and then rise while conductivity and salinity continuously rise over time.
- Equations are given based on SPSS analysis to forecast pH, conductivity and salinity.
- Automatic Linear Modeling models are produced to predict the trends of the leachate characteristics of Municipal Solid Waste.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abstract

The increase in municipal solid waste (MSW) in northwest China has been substantial, with a significant portion primarily treated in landfills. This rapid growth in waste generation presents considerable challenges for landfill management and treatment. The factors affecting MSW degradation are diverse and complex. This study prepares MSW samples based on on-site measured data and conducts a 190-day degradation experiment to analyze the leachate characteristics. By determining the pH, conductivity, and salinity values of the leachate, the effects of temperature (10~65℃), organic matter content (15~75%), moisture content (30~230%), and time (15~190 d) on degradation characteristics which plays a crucial role in understanding the degradation dynamics of MSW under real-world conditions. Throughout the experiment, pH was observed to peak at 7.91 on day 15 and decrease to a low of 5.33 by day 40. Meanwhile, conductivity and salinity showed a steady increase, with values ranging from 1.17 dS/m to 41.65 dS/m and 0.03 ppt to 29.67 ppt, respectively. Generally, the pH value is higher at 65 ℃, while the salinity and conductivity are higher between 35 ℃ and 45 ℃. Coupling analysis shows that temperature, time, and moisture content are positively correlated with salinity, Organic matter has a negative impact on salinity. Therefore, by adjusting the parameters of MSW, its degradation characteristics can be regulated and can be used as backfill material in construction works. A multiple linear regression equation and automatic linear modeling (ALM) were proposed for predicting pH, conductivity, and salinity values.

Keywords: Landfill; Solid waste; Organic matter; Moisture content; Temperature; Salinity; Conductivity; pH

1. Introduction

The generation of MSW has rapidly enlarged due to global economic development and the accelerated pace of urbanization. In developing countries, the quantity of MSW generation has increased from 0.64 billion metric tons in 1970 to 2 billion metric tons in 2019 (Maalouf 2023). According to Global Waste Management Outlook 2024 reports, total global MSW generation is forecasted to grow to 3.8 billion tons by 2050. The volume of waste being disposed of in China has increased dramatically over the past several decades, and as of 2022, it was estimated to be

244.5 million tons (Steele 2022). The primary MSW treatment techniques include incineration, composting, and sanitary landfill (NBS of China 2018). Among them, the sanitary landfill method is considered the most economical method to dispose of MSW due to its large total amount of treatment, low operating cost, good economic applicability, and convenient management (Mor S. 2023). Therefore, landfills remain the primary treatment method for MSW in most developing countries, including China. The complexity of landfills makes it possible for them to cause certain environmental disasters during the construction, service, and closure phases, jeopardizing the environment and the safety of people and property. For example, on July 10, 2000, a landslide occurred at the Manila landfill in the Philippines due to heavy rainfall, killed ten people and injured more than 100 (Jafari N. H. 2013); on June 15, 2002, a large landslide of 50,000 m^3 at the Gele Shan landfill in Chongqing (J. S. Li 2018) had buried 10 people to death. In February 2005, a large-scale landslide occurred at the Bandung landfill in India that resulted in 61 deaths and more than 90 people missing. On August 23, 2017, a landfill landslide in the capital of Guinea resulted in at least eight deaths (The Straits Times 2017). The stability of landfill sites is mainly related to MSW's engineering properties. The degradation of MSW is a unique characteristic that significantly impacts the engineering properties of landfill. The degradation is influenced by the landfill's age, organic content, temperature, and moisture content, resulting in complex coupling effects (Abdel-Shafy 2023, Koda 2023). Therefore, studying the factors that impact the degradation of MSW has crucial academic value and practical significance.

Some scholars have analyzed and studied this area mainly from the perspective of environmental engineering while some scholars have studied MSW's degradation and engineering characteristics under the influence of a single variable (Juarez 2023, Hu 2024, Tupsakhare 2020). However, from the geotechnical engineering perspective, there is relatively little research on the multi-factor coupling effects of MSW degradation, especially on strength indicators. Considering the complexity and regional differences of MSW components, such research needs to be conducted in conjunction with the characteristics of each region. This paper aims to explore the impact of biodegradation on the mechanical properties of MSW, so as to provide reference and guidance for the construction and long-term operation of landfills. To achieve this objective, the research focuses on Xi'an, the largest city in Northwest China, which was chosen for its distinctive combination of high waste generation and a semi-arid climate. Xi'an's status as a rapidly urbanizing metropolis with a high proportion of Municipal Solid Waste makes it a representative case to examine MSW degradation characteristics.

In the study of the effect of temperature on degradation, some research data show that the temperature inside the landfills ranges between 20-65 °C. Zhao et al. (2016) have explored the influence of temperature on settlement and biodegradation properties of MSW, and they found that 22 °C to 45 °C temperature is the most suitable temperature for enhancing the biodegradation of refuse. Wang et al. (2012) examined the impact of temperature on MSW degradation ranging from (20 - 46 °C) for 1400 days and concluded that higher temperatures accelerated the waste degradation. Shu et al. (2023) also examined the highest heat generation, which occurred at 40°C initial temperature in the first 200 h of the degradation. MANNA et al. (1999) used a drilling rig to determine the temperature of the garbage at different depths of a landfill in Italy in October 1993 and May 1994. Still, there was no in-depth study on the temperature change inside the landfill. Chaiampo F. (1996) studied the temperature changes inside a landfill in Italy, and the temperature of the MSW was 10-15 °C at a depth of 1-2 m, 35-40 °C at a depth of 3-5 m, and 45-65 °C at a depth of 5-20 m. The heat generated from the decomposition of organic materials in MSW often leads to higher landfill temperatures (Shu 2023). Rugebregt, M. J et al. (2023) have suggested that temperature significantly affects changes in pH.

Organic matter is a prominent factor influencing the degradation of MSW. Lu J C S et al. (1981) tested the degradation products of the organic matter in leachate from the landfill. Chen Jidong et al. (2105) took a sanitary landfill site in Shenzhen Xiaping and proposed the relevant calculation formula for organic matter by establishing the stabilization calculation model of MSW. Luo Feng et al. (2004) found that 65% moisture content is the most suitable for the biodegradation of organic matter. Lou et al. (2024) have studied the effect of organic matter and other factors on the decomposition of MSW. Zhang L. et al. (2024) studied the influence of volatile organic compounds in large MSW landfills.

Some scholars have also studied the correlation between moisture content and MSW degradation. Giannis et al. (2008) and Swati, M., & Joseph, K. (2008) analyzed the effect of water and leachate on the degradation of MSW and found that a certain degree of increase in moisture content can increase the sub-sedimentation of waste samples. Tang et al. (2023) have studied the effect of moisture content (55%, 60%, 65%) on the compost of kitchen waste. Sue et al. (2023) have proposed a method to compute the heat generation during MSW degradation after examining the impact of starting temperature and moisture content on heat generation. Eckenfelder and

Musterman (1998) identified landfill age, ambient air temperature, precipitation and refuse permeability, depth, and MSW type as factors that impact leachate amount and composition. By studying the changing law of pH, conductivity, and salinity values under the change of time, moisture content, temperature, organic matter content, the correlation law between different degradation influencing factors and the indicators of garbage soil leachate will provide experimental bases for judging and evaluating the degree of degradation of MSW, which can help to enrich and develop the theory of degradation and strength of MSW, and provide experimental data support for the rational design of landfills, later expansion and secondary development after closure.

Many scholars have researched urban household waste's engineering and degradation characteristics and achieved fruitful results (Rawat 2023, Gao 2022, Chetri 2022, Lee 2022, Berge n.d., D. J. Li 2024). Previous studies have shown that the degradation of MSW significantly impacts its engineering properties. However, the existing research on MSW degradation has problems such as single parameters, weak correlation, and incomplete understanding of the coupling effect of degradation influencing factors. It is also challenging to analyze the changes in engineering properties of MSW. Moreover, due to MSW's prominent regional characteristics and multiple environmental factors, its degradation is a complex multi-factor coupling problem that requires targeted and in-depth research. Given this, based on previous research, this study is the first to systematically explore the effects of varying temperature, organic matter content, moisture content, and degradation time on the pH, conductivity, and salinity of municipal solid waste (MSW) leachate, providing a comprehensive coupling analysis that highlights the complex interactions between these factors, which can be utilized to regulate MSW degradation and optimize its use as a construction backfill material. The study provides the in-depth understanding to better manage the degradation and stability conditions of landfills. Moreover, the outcomes of the study are helpful to foresee the degradation of MSW depending upon the input variables of the study. The research has clear academic value and practical significance for MSW landfill engineering.

2. Test Materials, Methods, and Plan

2.1 Field Investigation of Municipal Solid Waste

Seven MSW collection locations were chosen based on the population distribution, urban structure, and level of development of the study area to investigate the composition of urban residential garbage in Xi'an. The positions of these chosen MSW collection sites are displayed in

Fig 1, together with information on the Jiangcungou dump, the sole landfill in Xi'an (Figure 2). Table 1a shows the mass percentages of the various MSW compositions. In Xi'an, soil, metals, plastics, food waste, paper, and fiber are the principal constituents of MSW. Food waste, paper, and fiber types are among these compositions that can decompose; as a result, Xi'an's overall mass percentage of degradable compositions is 55.2%. The most significant component in this specific MSW is food waste, which has an average mass percent of 37.4%. Generally speaking, more developed areas have more excellent rates of food waste. This implies that a considerable rise in the organic matter content of MSW will result from an increase in urban infrastructure projects. Table 1b displays the density and moisture content of MSW in Xi'an. MSW typically has a high moisture content; however, regional differences can be significant. This study's highest moisture content value is 2.6 times higher than the lowest. Density was measured to a maximum of 1.7 times the minimal value. The density in Table 1b indicates the natural accumulation density of waste. The Jangcungou landfill reported compacted densities ranging from 1.06 to 1.75 g/cm^3, with an average of 1.28 g/cm^3. As a result, the compacted density is nearly three times higher than the average accumulation density, suggesting that fresh MSW has a very high compressibility (Kong 2020).

Table 1a. Mass percentage (%) of MSW components in Xi'an City

Refuse collection point	Sludge	Food waste	Paper	Fiber	Plastics	Metals	other
Jingkai District	48.3	28.0	10.3	3.4	7.6	2.1	0.3
Lianhu Road	22.3	37.9	6.8	16.5	16.5	0.0	0.0
Yuxiangmen	48.4	22.8	11.4	7.0	8.8	1.6	0.0
Xingqing Road	10.1	56.5	11.3	2.3	14.7	3.4	1.7
Jiandong Road	26.2	46.3	9.5	7.4	9.5	1.1	0.0
Dabaiyang	40.1	29.0	11.2	10.3	7.5	1.9	0.0
Ziqiang Road	28.2	40.6	8.3	9.4	12.5	1.0	0.0
Mean	31.9	37.4	9.8	8.0	11.0	1.6	0.3

Table 1b. Moisture content and density of MSW in Xi'an City

Garbage collection site	Jingkai	Lianhu Road	Yuxiangmen	Xingqing Road	Jiandong Road	Dabaiyang	Ziqiang Road	average value
Moisture content (%)	54.4	111.4	75.2	45.6	120.8	84.4	91.6	83.3
Density (g/cm^3)	0.58	0.41	0.46	0.35	0.38	0.43	0.38	0.43

Table 1c. Dynamic Conditions of Test Samples

Sr. No	Moisture Content (%)	Organic Matter Content (%)																			
		15%				30%				45%				60%				75%			
		Temperature (°C)																			
		10	35	45	65	10	35	45	65	10	35	45	65	10	35	45	65	10	35	45	65
1	30%	S1	S2	S3	S4	S21	S22	S23	S24	S41	S42	S43	S44	S61	S62	S63	S64	S81	S82	S83	S84
2	80%	S5	S6	S7	S8	S25	S26	S27	S28	S45	S46	S47	S48	S65	S66	S67	S68	S85	S86	S87	S88
3	130%	S9	S10	S11	S12	S29	S30	S31	S32	S49	S50	S51	S52	S69	S70	S71	S72	S89	S90	S91	S92
4	180%	S13	S14	S15	S16	S33	S34	S35	S36	S53	S54	S55	S56	S73	S74	S75	S76	S93	S94	S95	S96
5	230%	S17	S18	S19	S20	S37	S38	S39	S40	S57	S58	S59	S60	S77	S78	S79	S80	S97	S98	S99	S100

*Note: S1, S2, S3 shows sample 1, sample 2, sample 3 and so on for all samples 1-100

2.2 Preparation of test materials and Testing Equipment's

In this research, the MWS samples were manually prepared according to the results of the compositional research on MSW in Xi'an City (Hanlong Liu 2005). To simulate the landfill situation of the actual garbage and to facilitate the operation of the indoor test instrument, the test materials were selected as follows: the food waste was made up of meat and cooked rice; the grass was made up of crushed weeds harvested by the lawn mower; the fabric was made from discarded old clothes; paper was taken from shredded paper strips in the office shredder; metal was made from broken iron shavings; slag was made from loess from the excavation at the local construction site, and plastics were made from broken plastic bottles, the composition of each component is shown in Fig. 3 (i, ii, iii, iv and v) and mixed sample is shown in Fig. 3 (vi).

The MSW in Xi'an is the research object and conducts field research on the composition of MSW in different areas of Xi'an; the comparison tests were made for four different temperatures (10 °C, 35 °C, 45 °C, 65 °C), five different organic matter contents (15%, 30%, 45%, 60%, and 75%), and five different moisture contents (30%, 80%, 130%, 180%, 230%), considering the interaction of the factors in the scheme, a total of 100 sets of comparative tests were produced and the mass of the samples, leachate pH, conductivity, salinity, were measured at specific intervals for testing MSW with different degradation levels at different time points. The samples were prepared by wet method (Kong 2020) and packed in a polyvinyl chloride (PVC) plastic box. The outer side of the box is wrapped with plastic film to ensure its sealing and simulate the anaerobic degradation environment at landfill sites. Part of the sample in the box is shown in Fig. 3 (vii), and part of the sample in degradation is shown in Fig. 3 (viii). Table 1c gives the different dynamic conditions of the samples under this study. The pH, conductivity, and salinity characteristics of leachate are measured by the Hengxin AZ86505 benchtop pH meter measuring instrument, and the leachate was guaranteed to submerge the probes during the measurement to ensure the reliability of the measurement results. The degradation environment control of the samples is carried out by the environmental testing equipment. Samples were taken from the equipment regularly, and leachate was collected from the sample box for pH, conductivity, and salinity tests.

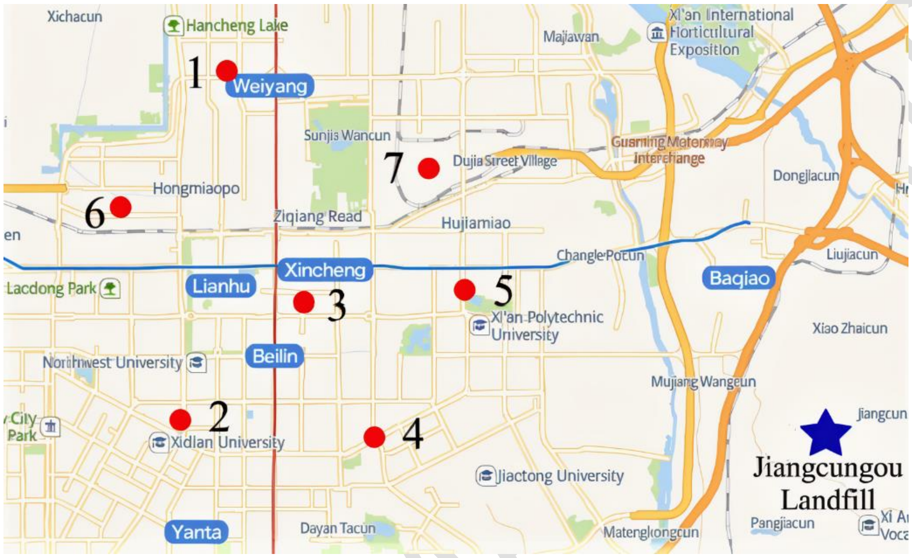


Figure 1. Location of MSW collection stations in Xi'an (sampling points for municipal solid waste composition surveys)

Figure 2. Jiangcungou Landfil, Xi'an, China

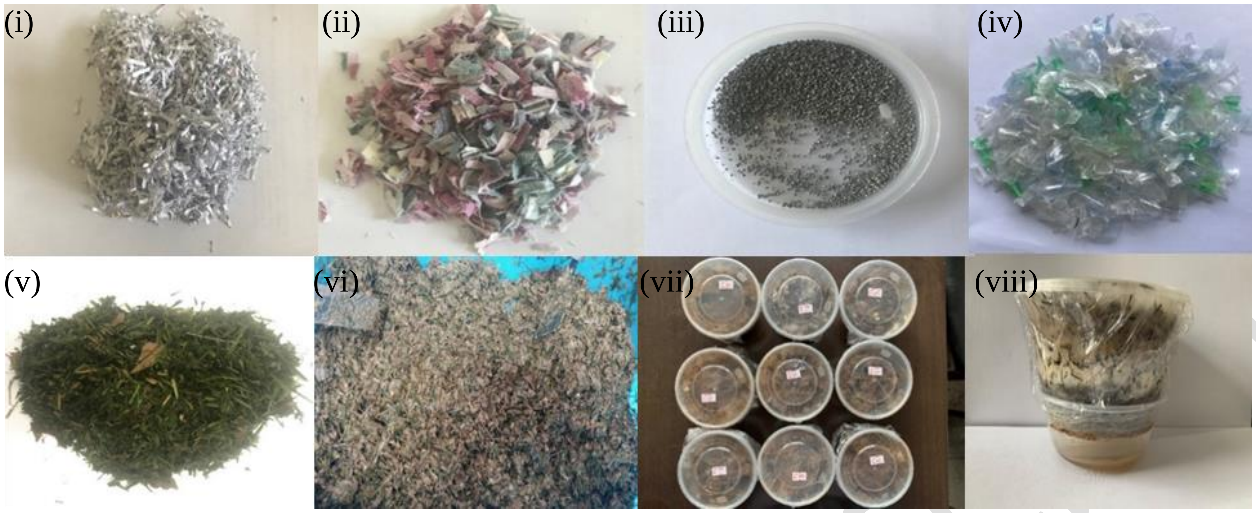


Figure 3. (i. shredded paper; ii. shredded cloth; iii. iron filings; iv. plastic; v. grass; vi. prepared MSW; vii. some samples after packing; viii. degradation and leachate collection)

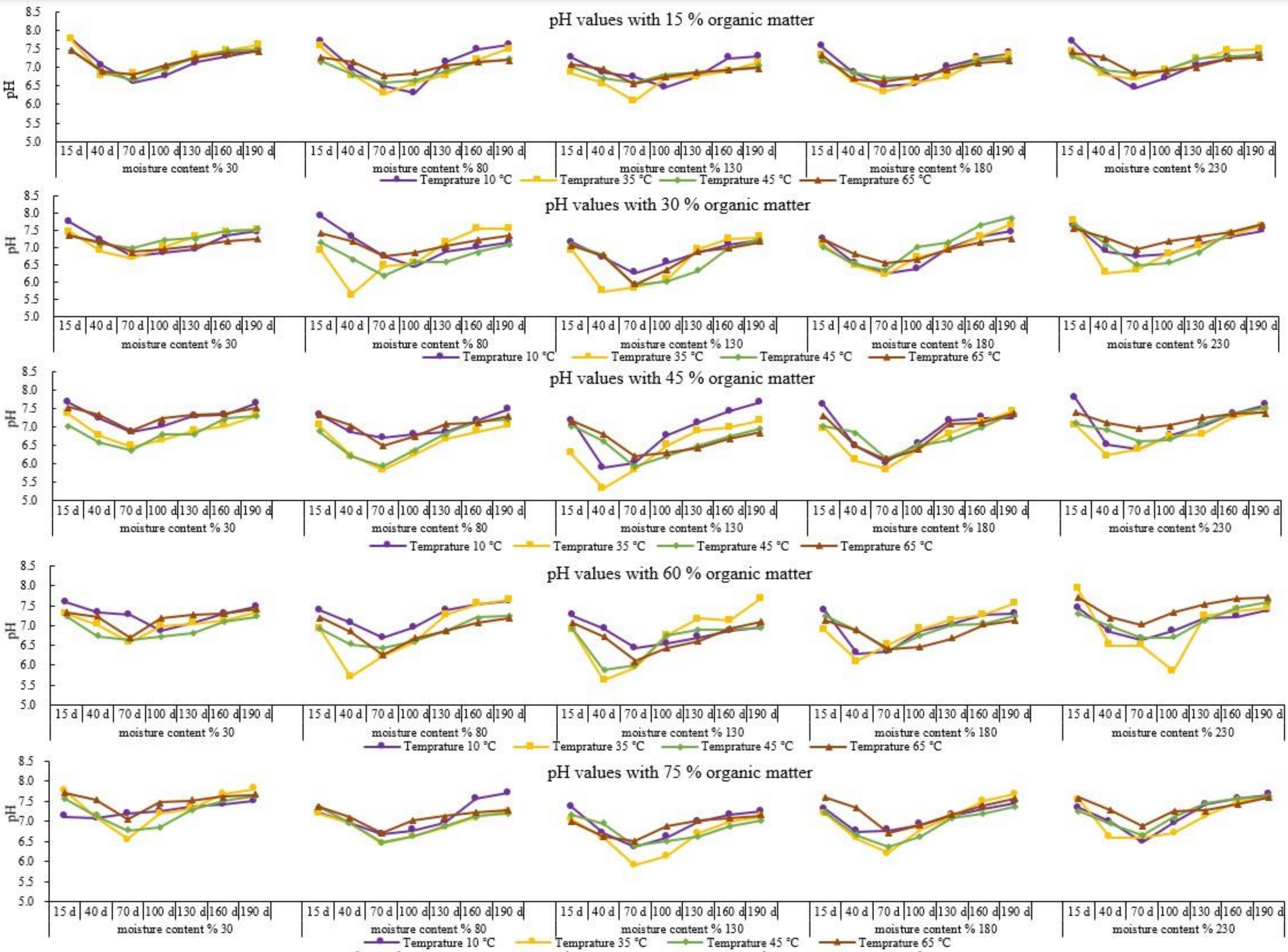
3 Results and Discussions

In landfills, MSW is subjected to intricate chemical, physical, and biological processes that lead to its breakdown. The primary consequence of MSW breakdown is landfill leachate (Youcai 2018). Landfill leachate is generated due to water percolation through the MSW, oxidation of the MSW, and corrosion. Since leachate is a product of MSW degradation, changes in leachate-related parameters also characterize and reflect the degree of degradation of the sample. Therefore, multiple parameter measurements were conducted on the leachate of MSW with different time intervals, degradation temperatures, organic matter content, and moisture content.

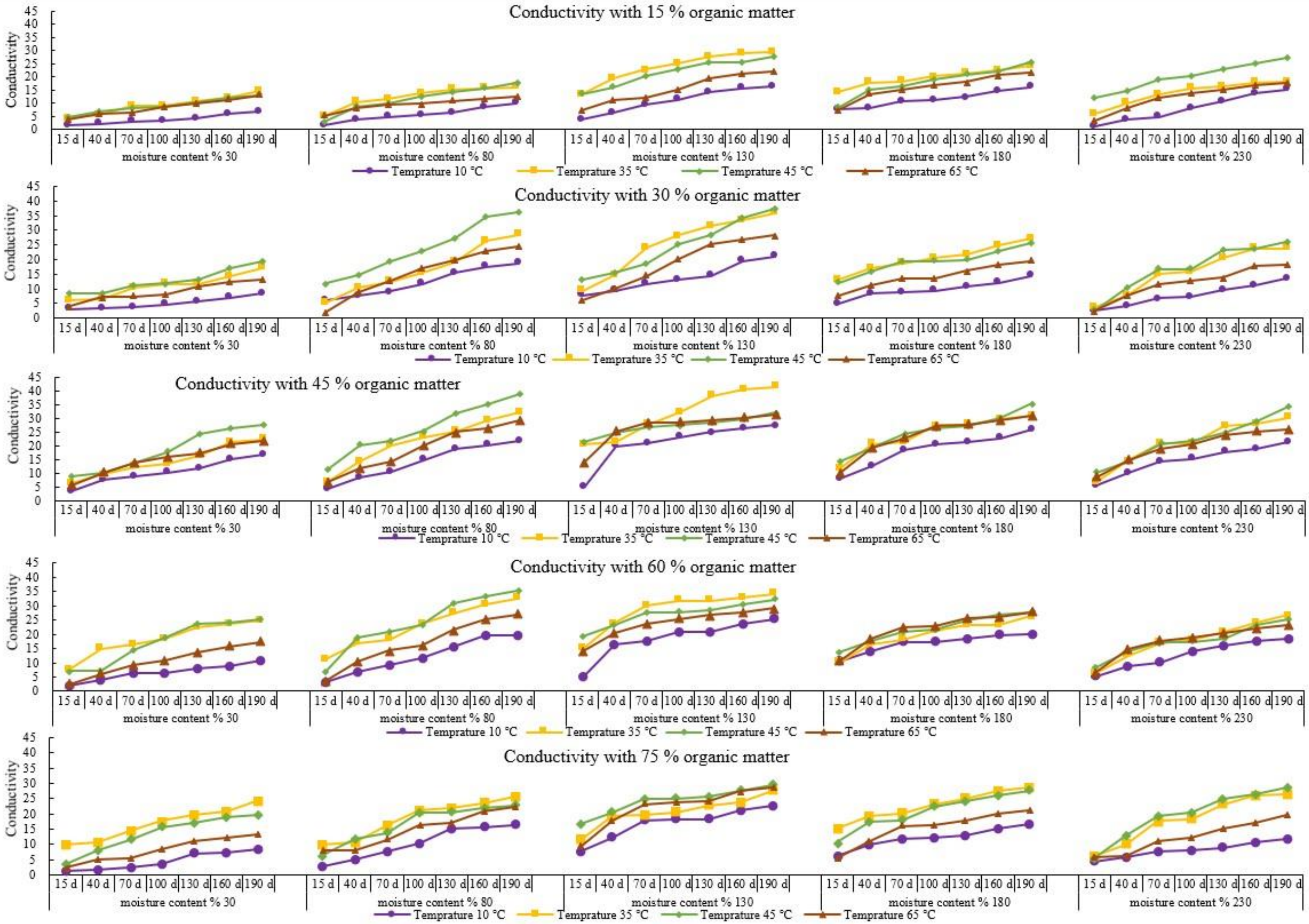
3.1. pH, conductivity, and salinity of MWS leachate under different degradation conditions

A total of one hundred samples were prepared and observed to the changing behavior of the degradation properties of leachate mentioned in Table 1c. The results of the experimental work on pH values and their changing trends with the several conditions of the effecting factors are given in Fig. 4a. The pH value is highest at all temperatures after the fifteen days of MSW formation. pH gradually decreases till 70 days and then increases, this trend of pH values remains the same for all dynamic conditions of organic matter content, moisture content, and temperature with minor fluctuations. It indicates that the pH is mainly dependent on MSW age. The pH readings at 130% moisture content are lower than the other values. The pH values are observed to be relatively small as the organic matter content is increased. Organic matter in MSW undergoes decomposition by microorganisms, producing organic acids as byproducts. When these organic acids dissolve in water, the pH of the leachate may be lowered. The generation of organic acids is often enhanced by higher quantities of organic matter, which reduces the pH of the leachate. There is comparatively little higher turbulence in pH values with increasing moisture content values, which may be described as moisture content influencing the rate of MSW decomposition and the mobility of substances within the landfill. Higher moisture content promotes microbial activity and accelerates the decomposition of organic matter, potentially leading to increased acid production and decreased leachate pH. Conversely, low moisture content may slow decomposition and reduce acid production, leading to higher pH levels in the leachate. The pH at temperature 35 ºC have shown more variance than other temperatures. Temperature affects microbial activity and the rate of chemical reactions in the landfill. Warmer temperatures generally accelerate the decomposition of organic matter, leading to increased production of organic acids and lower pH in the leachate. Cooler temperatures may slow decomposition and acid production, producing higher leachate pH. As MSW ages and decomposes, the organic matter content decreases, leading to changes in leachate characteristics, including pH. Over time, leachate pH may gradually increase as decomposition slows and the organic matter is depleted. The literature shows pH ranging from 7.0 to 7.5 are most suitable for microorganism reproduction and efficient digestion and methane production. The test results of this study show that the pH is closer to this range when the moisture content is 30% or 230%, the organic matter content is 75%, and the temperature is 65 ºC. Thus, the pH levels in landfills may be maintained under these conditions.

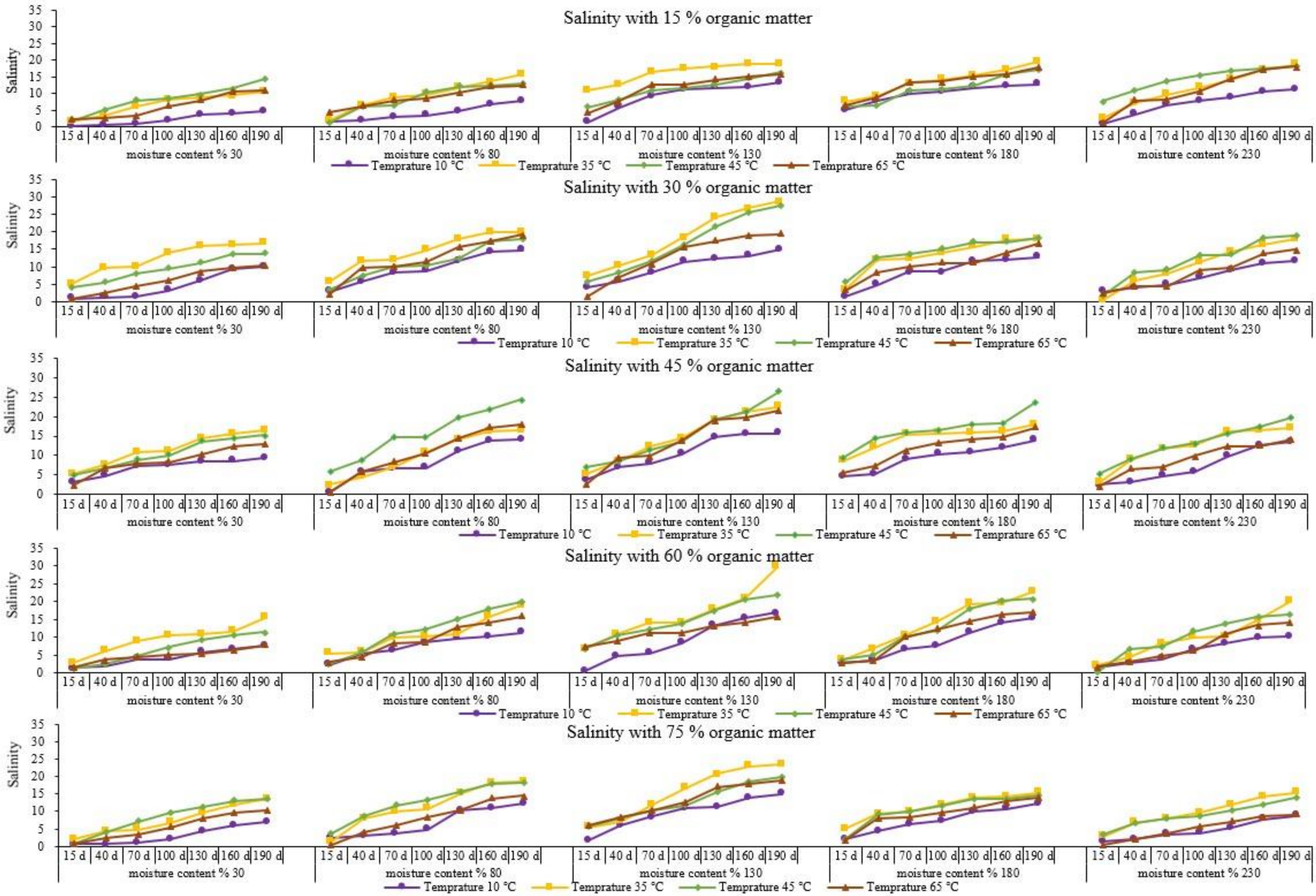
MSW's conductivity is paramount because it is a valuable metric for managing and treating MSW, as it offers vital information for sustainable MSW management techniques and environmental preservation. The outcomes of this study are presented in Fig. 4b. Higher moisture levels generally lead to higher conductivity. Within each moisture level, conductivity tends to increase as the temperature rises. For instance, it is noticed that conductivity is generally higher at 65 °C than at other temperatures. The impact of temperature on conductivity is more pronounced at higher moisture levels and the conductivity gradually increases with the age of MSW. The increase in conductivity over time in MSW leachate results from ongoing MSW decomposition, microbial activity, chemical reactions, changes in MSW composition, and leachate accumulation. These processes collectively lead to higher concentrations of dissolved ions in the leachate, thereby increasing its conductivity. There is a significant increase in conductivity across the entire temperature range as moisture content goes from 30% to 230%. Similarly, conductivity increases at each moisture content level as the temperature goes from 10 °C to 65 °C. The number of dissolved salts and ions in the leachate from MSW is referred as its salinity. Fig. 4c provides the study outcomes on the salinity of MSW leachate. Generally, higher temperatures appear to correlate with higher salinity levels. This trend suggests that increased temperatures may enhance the dissolution of salts and ions from the MSW into the leachate, leading to higher salinity. The influence of moisture content on leachate salinity is less straightforward but can still be observed. The dependence of leachate salinity on both temperature and moisture content underscores the complex interactions between these factors within the landfill environment. The salinity of MSW leachate is influenced by the combined effects of temperature, moisture content, and time. Higher salinity levels can raise the danger of groundwater contamination and adversely affect the efficiency of leachate treatment procedures; thus, it is important to comprehend these dependencies to manage and mitigate the environmental effects of landfill leachate.



a. pH value changes w.r.t Organic Matter Content, Moisture Content and Temperature



b. Conductivity changes w.r.t Organic Matter Content, Moisture Content and Temperature



c. Salinity observations w.r.t Organic Matter Content, Moisture Content and Temperature

Figure 4. pH, conductivity, and salinity of MWS leachate under different degradation conditions

3.2 Effect of temperature on the degradation characteristics of MSW

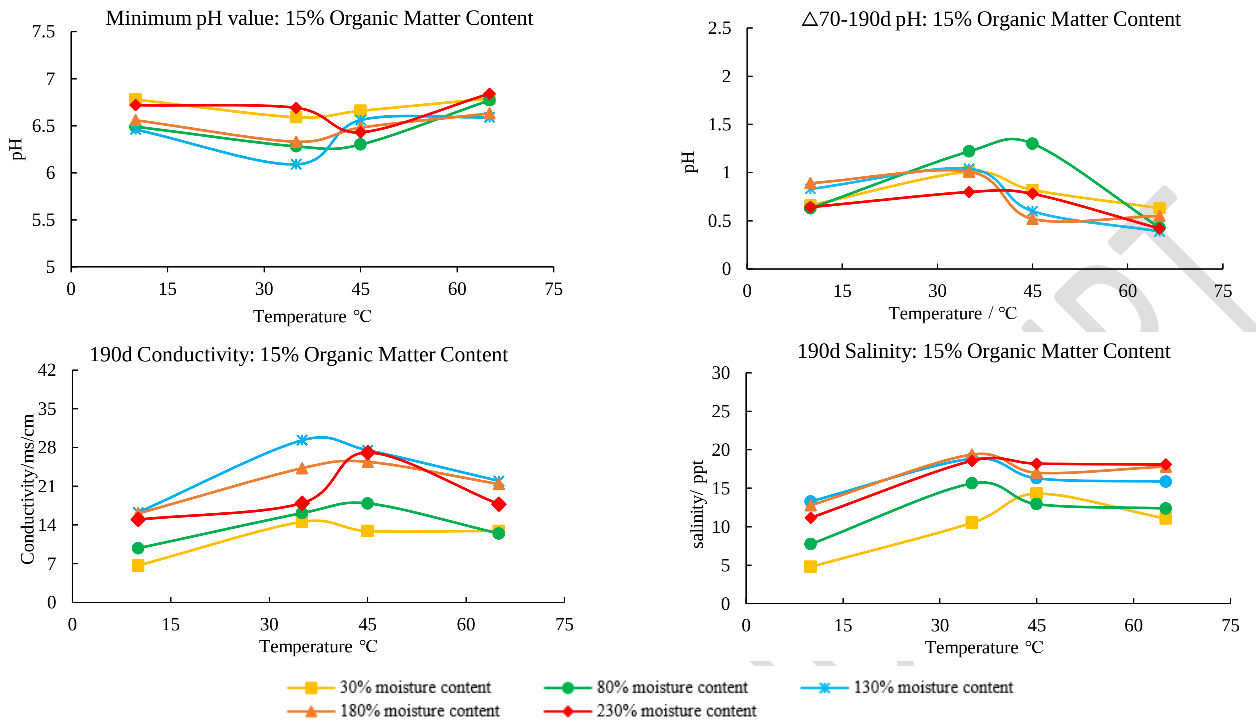
The analysis in the previous section shows that during the degradation process, the pH of the sample leachate reached a minimum value at about 70 days. This minimum value and the increase at a later stage can be used as a reference to characterize the rate or degree of degradation. Similarly, the sample leachate conductivity and salinity increased monotonically, and the values can also be used to reflect the degree of degradation. Figs. 5a – 5e summarizes the curves of degraded leachate pH minima, pH rises from 70 to 190 days, and the maximum values of conductivity and salinity as a function of temperature for samples of various moisture contents at different temperatures of organic matter content for comparative analysis. The variation curves of pH minima for each sample, reveal that most samples reach their lowest pH at degradation temperatures between 35 °C and 45 °C under identical test conditions. This suggests that at about 40 °C, municipal solid waste (MSW) degrades more quickly and thoroughly. Therefore, 40 °C is likely an optimal temperature for the growth of various degradation bacteria, including methanogenic bacteria. The microbial flora in the waste samples develops slowly at degradation temperatures of 10 °C or 65 °C. The lowest pH occurs later at 10 °C and 65 °C than at 35°C and 45°C. Furthermore, these temperatures have larger minimum pH, which suggests that internal processes are occurring at a lesser intensity. The conductivity and salinity at 10 °C and 65 °C also stay elevated for longer, indicating inadequate internal degradation and an excess of organic matter in the MSW samples. At the same time, such test results are closely related to the effect of temperature on organic matter. However, organic matter degradation in landfills is a multi-stage, highly complex biochemical process involving diverse microorganisms. Biochemical reactions catalyzed by biological enzymes do not have their equilibrium constants altered by these enzymes. Nonetheless, due to their excellent catalytic activity and high efficiency, enzymes significantly accelerate the biochemical reaction rate of organic matter.

3.3 Effect of organic matter content on the degradation characteristics of MSW

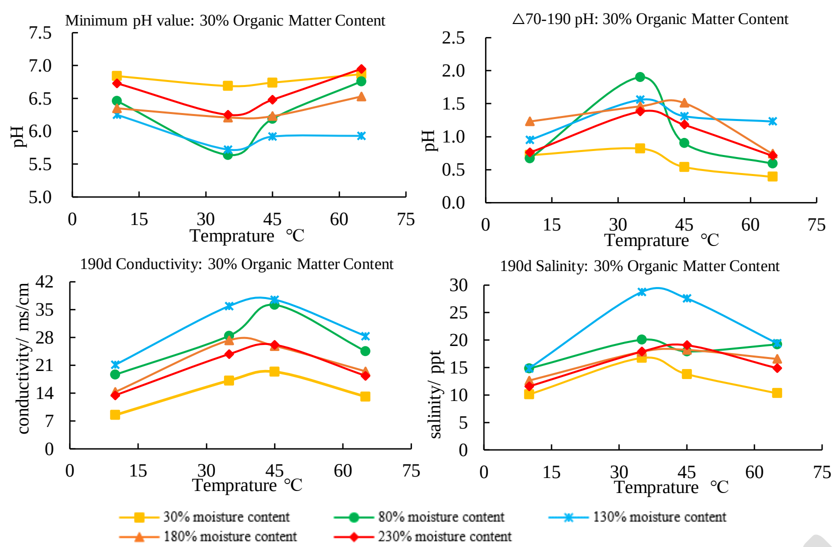
Figs. 6a – 6d show the curves of degraded leachate pH minima, pH increases from 70 to 190 days, and conductivity and salinity maxima as a function of organic matter content for each moisture content sample at different degradation temperatures, respectively. The lowest pH value is reached for most samples with various variable combinations when the organic matter concentration is 45%. This indicates that the maximum bacterial generation, development, and reproduction occurs in the sample at around 45% organic matter concentration. A sample with an organic matter concentration of less than 45% will have a higher pH value because there won't be as much organic material present during the acid-producing transition period. The pH difference graph from 70 to 190 days demonstrates that the sample pH differences' peak points are dispersed throughout the region. Nonetheless, samples with 45% organic matter have the most peak locations. There are fewer peak spots in samples containing 30% and 60% organic matter. The plots of the maximum values of conductivity and salinity for the samples show that those with an organic matter content of about 45% experience a rapid rise in conductivity and salinity during the acid production transition phase and enter the stabilization phase earlier. In contrast, samples with lower or higher organic matter content maintain an increasing trend in conductivity and salinity for longer. However, due to slower internal degradation reactions compared to the 45% organic matter content samples, the conductivity and salinity in these samples remain lower.

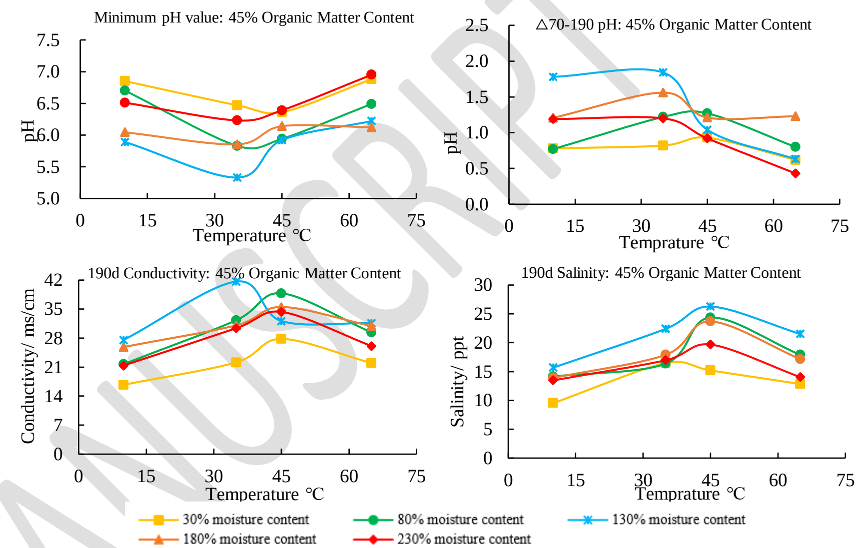
3.4 Effect of moisture content on the degradation characteristics of MSW

Figs. 7a – 7d show the curves of leachate pH minima, pH increases from 70 to 190 days, and conductivity and salinity maxima as a function of moisture content for each organic matter content sample at different degradation temperatures, respectively. The minimum leachate pH first decreases and then increases as the moisture content is increased from 30% to 230% for samples with the same organic matter content and degradation temperature. The pH is lowest when the moisture level is between 120% and 150%. When the sample's organic matter content is minimal, the peak pH difference usually arises between 70 and 120 days, according to the graphs of pH over 70 to 190 days. On the other hand, the most remarkable difference often happens between 120 and 180 days when the organic matter content is also added in large quantity. The moisture content dramatically influences the environment in which organic matter degrades. Bacterial growth and the breakdown of organic materials depend on water. A sample with the proper moisture level will quickly develop a degraded environment, transmit nutrients and microorganisms essential for the process, and ensure complete contact between the bacterial flora and degradable organic matter.



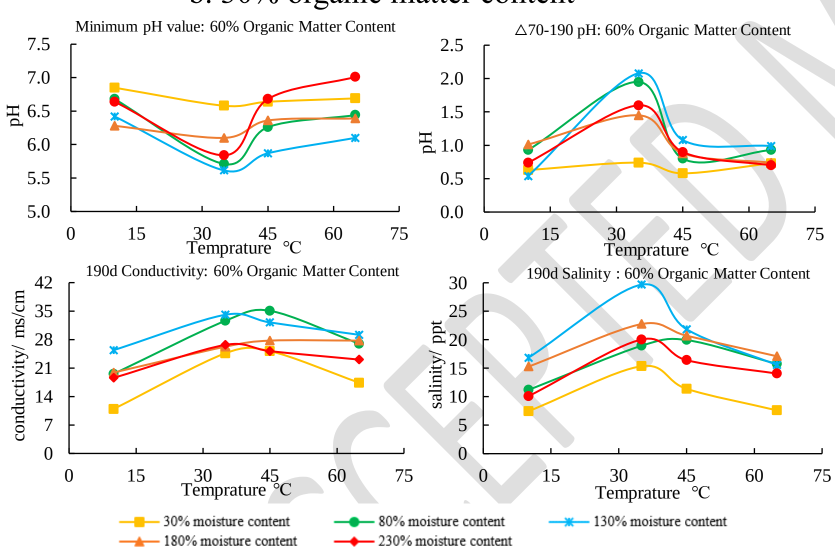
a.15% organic matter content

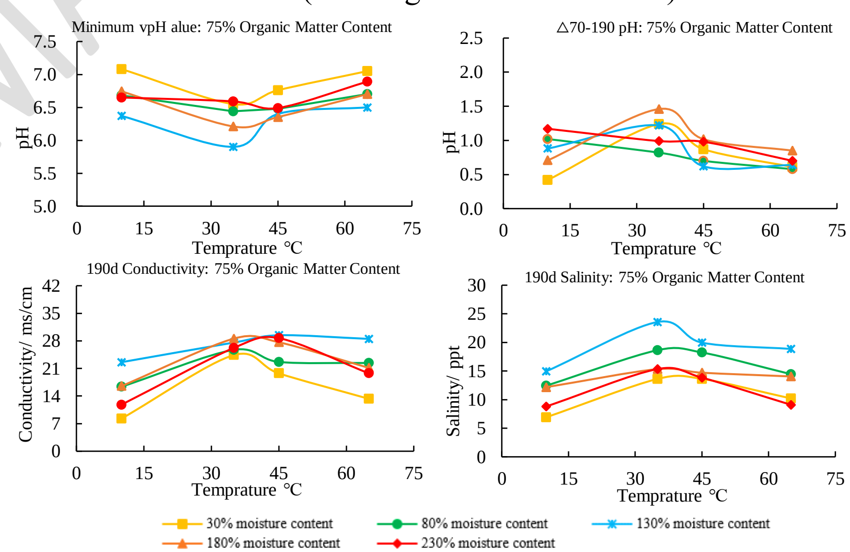




b. 30% organic matter content

c. (45% organic matter content)

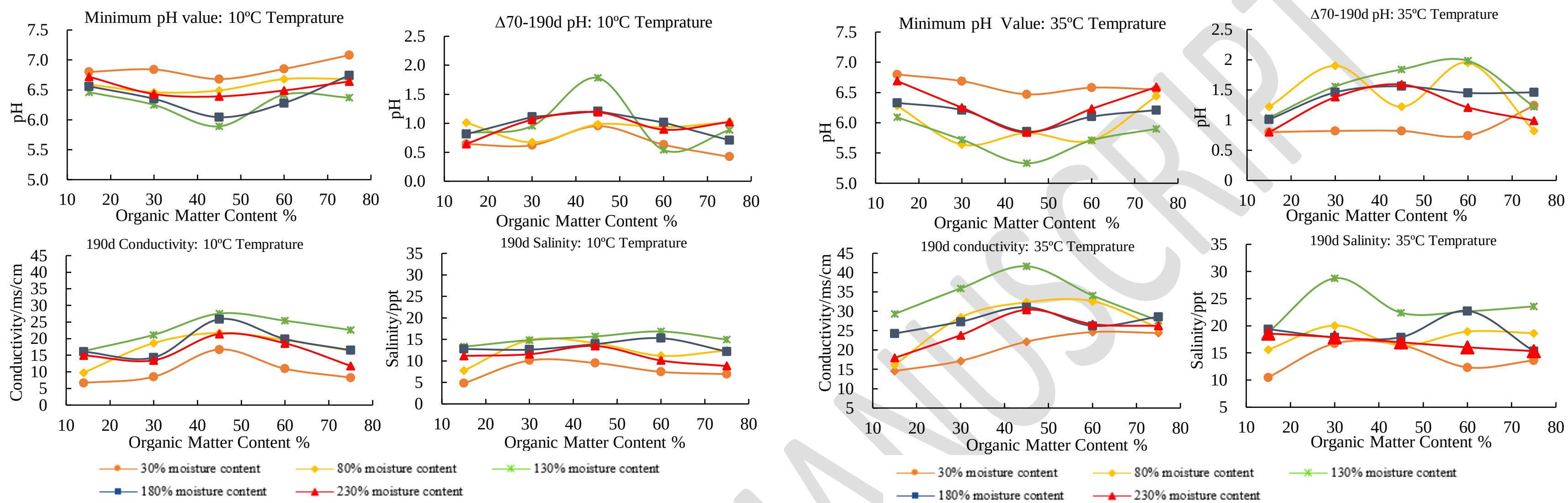




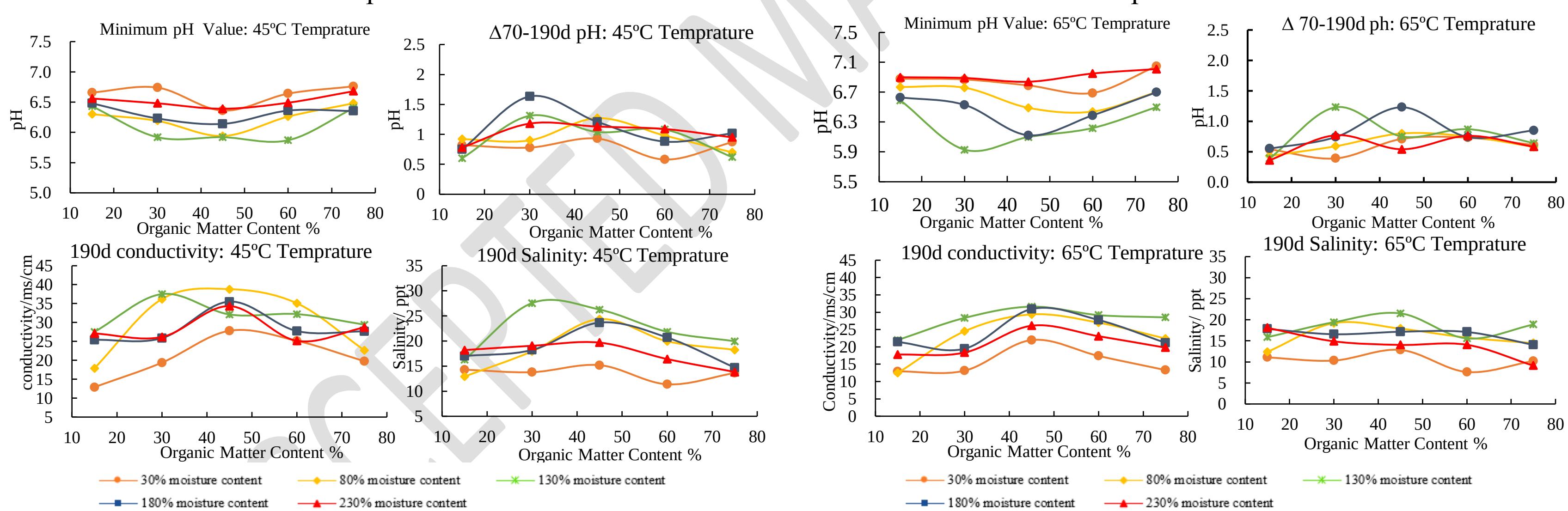
d. 30% organic matter content

c. (45% organic matter content)

Figure 5. Effect of temperature on the degradation characteristics of MSW

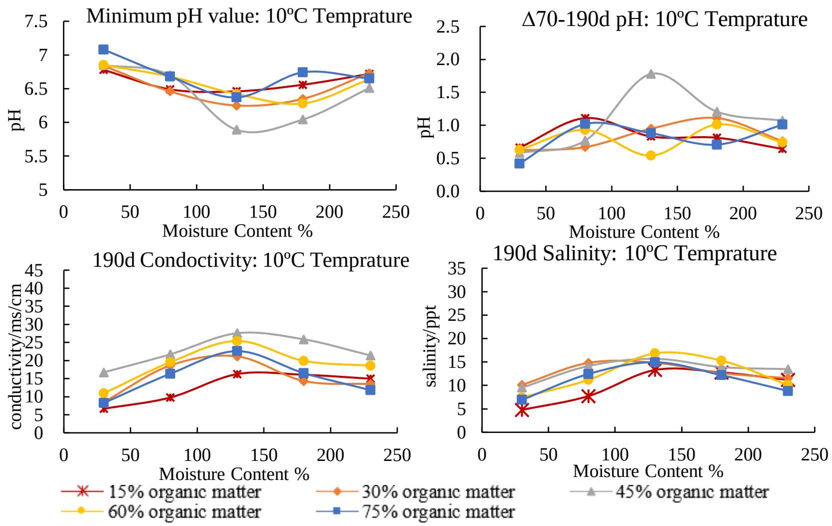


a. temperature 10 °C b. temperature 35 °C

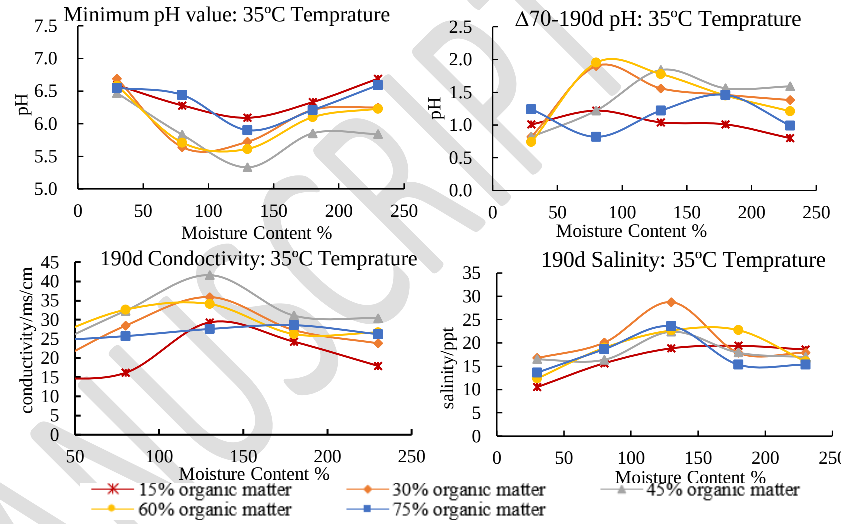


c. temperature 45 °C d. temperature 65 °C

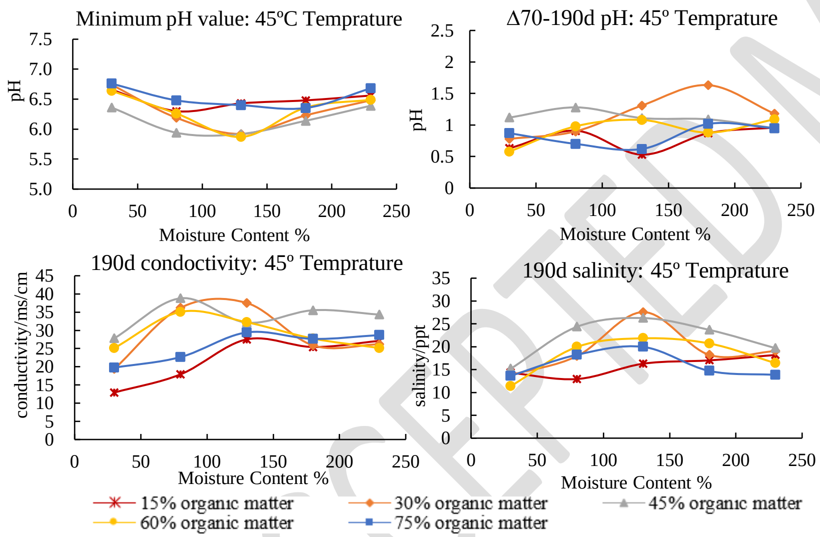
Figure 6. Effect of organic matter content on the degradation characteristics of MSW



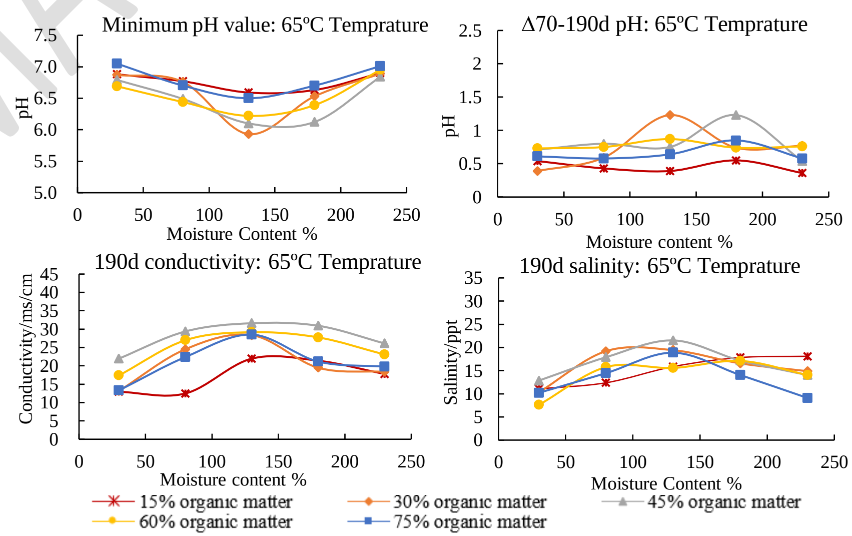
a. temperature 10 °C



b. temperature 35 °C



c. temperature 45 °C



d. temperature 65 °C

Figure 7. Effect of moisture content on the degradation characteristics of MSW

4. Statistical Effect of Different Factors on the Degradation of MSW

The results obtained from the experiments are further analyzed statistically to understand the relationships between different factors of leachate more deeply. The data obtained were computerized and statistically analyzed using SPSS v22. Correlation analysis is applied to find out the nature of the relationship between the factors under study. Some previous studies have also followed this statistical analysis to describe the characteristics of leachate and MSW (Banch 2019, De Side 2021, Gupta 2017, Pablos 2011).

Table 2a presents the data, revealing a modest positive association between temperature and salinity (0.162) and conductivity (0.220). This implies that the environment's conductivity and salinity rise together with temperature. Only marginally favorable relationships exist between pH (0.041), conductivity (0.152) and organic matter content suggests that greater organic matter concentration may somewhat impact conductivity and pH. There are slightly favorable relationships between Moisture Content and Salinity (0.145) and Conductivity (0.192). Significant positive relationships exist between the Number of Days and Salinity (0.752) and Conductivity (0.624). The pH show weak negative relationships with Temperature (-0.007), Moisture Content (-0.040), Conductivity (-0.139), and high positive correlations with Number of Days (0.306). This suggests that pH rises with longer exposure times but also marginally falls with increased conductivity, moisture content, and temperatures. Temperature (0.220), organic matter content (0.152), moisture content (0.192), number of days (0.624), and salinity (0.862) all show strong positive correlations with conductivity. Salinity exhibits a moderate positive association with temperature (0.162) and high positive relationships with Moisture Content (0.145), Number of Days (0.752), and Conductivity (0.862). All of these variables affect the salinity value.

4.1 Regression Analysis

Several researchers, i.e. (Lak 2012, Ergene 2022, Dhiman 2024) applied statistical analysis to study the leachate and its characteristics. Ergene D. et al. (2022) have applied correlation analysis to study the relationships between alkalinity and electric conductivity (from 0.7 to 0.9), alkalinity and potassium (from 0.4 to 0.8), and Carbon and Electric Conductivity (from 0.8 to 0.9). Using regression analysis, Ramesh, N. et al. (2016) have predicted that Methane content, Influent pH and Influent CO significantly influence COD Removal. Babu, G. S. et al. (2013) suggested a newly created constitutive model used to represent the complex behavior of MSW utilizing regression equations based on the response surface method (RSM). Several researchers, i.e. (Kumar 2016, Chen 2020, Lebersorger 2011, Chhay 2018, Al-Jarallah 2014, Araiza-Aguilar 2020, Miezah 2015, Supangkat 2020, Ayeleru 2023), have used statistical tools like regression models and equations to study the different perspectives of MSW. Still, no previous study has primarily focused on the degradation characteristics of MSW under dynamic conditions. Thus, the study uses regression analysis to understand the impact of different dynamic conditions (independent factors) on the degradation characteristics of MSW (dependent factors). The outcomes are given in Tables 2b, 2c, and 2d.

4.1.1 Dependence of pH on the Predictors

Table 2b presents the regression analysis results and sheds light on the correlations between the predictors and pH levels. Since the R=.312 and F= 18.699 values indicate that the whole model is efficient in predicting pH. However, temperature, moisture, and organic matter content do not substantially predict pH for each regression weight since their p-values are more than 0.05. With a significant t-value (8.499, p = 0.000) and a Beta coefficient (β) of 0.002, the Number of Days has a noteworthy impact on pH prediction. The general regression equation (i) for this model is given below:

$$y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 \ldots\ldots\ldots\ldots \text{(i)}$$

"Number of Days," that appears to have a meaningful link with the dependent variable, "pH,". The other variables in this model, which include temperature, moisture, and organic matter content, either exhibit zero beta coefficients or high p-values (> 0.05). The regression equation with only the significant predictor "Number of Days" would be, with the value of alpha constant (6.672) as given in eq (ii). For the equations, X1 represent Temperature, X2 represent Organic Matter Content, X3 represent Moisture Content and X4 represent Number of Days:

$$pH = 6.672 + .002 \times X_4 \ \ldots\ldots\ldots \text{(ii)}$$

4.1.2 Dependence of Conductivity on the Predictors

Table 2c clarifies that all four predictors have statistically significant correlations with conductivity, as evidenced by the large F-value of 172.003 and extremely low p-values (all < 0.001). A substantial connection between the variables is shown by the R=.705, indicating that the models are statistically significant. The temperature has the most significant beta coefficient (β = 0.090), followed by the number of days (β = 0.086), the organic matter content (β = 0.058), and the moisture content (β = 0.022). The regression equation (iii) for the conductivity value prediction is as follows, with the value of the alpha constant being (-.913):

$$\text{Conductivity} = -.913 + 0.090 \times X_1 + 0.058 \times X_2 + 0.022 \times X_3 + 0.086 \times X_4 \quad \ldots\ldots\ (iii)$$

4.1.3 Dependence of Salinity on the Predictors

Table 2d gives the outputs of the regression analysis for the salinity. All the predictors significantly affect salinity. Here, organic matter has a negative beta value, which shows a negative correlation between the organic matter and salinity. The regression equation (iv) with alpha constant (.719) is given below:

$$\text{Salinity} = .719 + .045 \times X_1 + (-.017) \times X_2 + .011 \times X_3 + 0.71 \times X_4 \quad \ldots\ldots\ldots\ldots\ (iv)$$

While comparing the actual experimental values and the forecasted values from equations (ii), (iii) and (iv) the average percentile difference is found to be -1.23% in forecasting pH, 20.35% for conductivity and 40.82% was observed in forecasting salinity.

4.2 Automatic Linear Modeling

Automatic linear modelling (ALM) is favored when evaluating data sets because it is easier to analyze and comprehend the findings, can graphically portray the results, and provides more thorough information, especially when investigating massive, complicated data sets (Genç 2024). Panneerselvam B. et al. (2021) have used ALM to predict the significant influence parameters on the groundwater. The influence of predictors is observed by using ALM as the data set is complex, and there are 700 changing dynamic conditions for 100 samples. In the following proposed models, the influences of predictors on MSW degradation characteristics were analyzed using the ALM method (Murugesan 2022, Karuppannan 2019, Panneerselvam 2021).

The model fit structure for the Dependence of pH, Conductivity and salinity shows that R^2 values are 74.2%, 87.9% and 86.1%, respectively, as shown in Fig. 8a. These values show that the model fits the observed data and provides insights into the overall strength of the relationships between predictors and the target variables. The predictor significance charts are displayed in the model summary in Fig. 8b, where the number of days for pH is 0.728, the highest value, indicating that it has the most effect on the forecasting model. When determining pH, the other predictors are less significant. All predictors are essential in predicting the conductivity according to the values for conductivity prediction. The salinity forecasting model describes the impact of the number of days .665 organic matter content. The models offered more information and a clearer knowledge of predicting the dependent variables for the understudy, predicting variables under the given conditions.

The discarded Fig. 8c scatter plot of pH, Conductivity and salinity shows the observed values on the x-axis and the predicted values on the y-axis. A more significant fraction of the sample locations lies on the 45-degree line, which predicts the accuracy of the models. The relationships between the predicted and the observed values are crucial to assess the model performance. Ideally, data points are clustered tightly around the diagonal line (y = x), indicating close agreement between predicted and observed values. The predicted models are well-fitted and exhibit a concentrated cluster of points near the diagonal, reflecting accurate predictions and minimal errors within the ALM framework. Fig. 8d consists of the estimated means charts representing and analyzing the comparison between the mean values of the dependent variable (pH values) across different levels or categories of the predictor's variables. The charts show that pH will have a higher mean value at temperatures 10 ºC and 65 ºC while its value will gradually decrease and will have minimum mean values between 35 ºC and 45 ºC. The pH will also decrease and then increase for several days, and their value will be at least 70 days. pH will have a minimum mean value of 130% moisture content and 45% organic matter content.

The estimated mean values charts for Conductivity are given in Fig. 8e. The predicted charts show that the conductivity will gradually increase with the time. Its mean value will be minimum at 10 ºC temperature and maximum at 35 ºC – 45 ºC and then decrease at 65 ºC. Also, conductivity will be minimum at 30% moisture content and 15% organic matter content. It will have maximum mean values at 130% moisture content and 45% organic matter; with a further increase in the moisture content and organic matter content, the conductivity shows a decreasing trend. Fig. 8f represents the estimated mean charts for salinity. Here, the mean values for salinity will be minimum at 15% - 30% organic matter content, 10 ºC temperature, and 30% moisture content. The salinity will increase gradually till 45% organic matter, 35 ºC – 45 ºC temperature, and 130% moisture content, and then it will decrease with increasing values of these predictors. Moreover, the salinity value will show an increasing trend with the increase in time.

Table 2. Outcomes of Correlation and Regression Analysis

a. Correlation Analysis

No.	Factors	Temperature	Organic Matter Content	Moisture Content	Number of Days	pH	Conductivity	Salinity
1	Temperature	1						
2	Organic Matter Content	.000	1					
3	Moisture Content	.000	.000	1				
4	Number of Days	.000	.000	.000	1			
5	pH	−.007	.041	− .040	.306**	1		
6	Conductivity	.220**	.152**	.192**	.624**	−.139**	1	
7	Salinity	.162**	−.065	.145**	.752**	−.028	.862**	1

b. Regression Analysis for pH

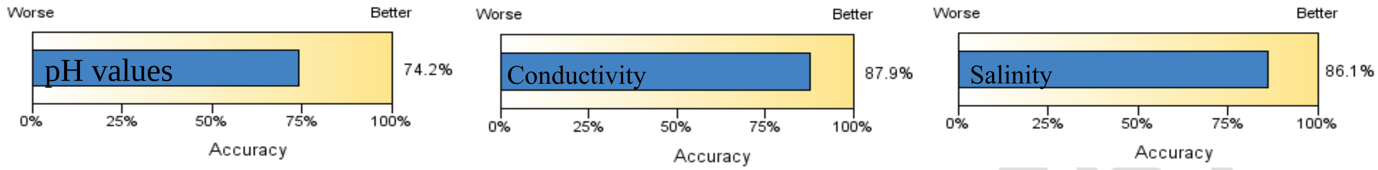
No.	Regression Weights	Beta (β) Coefficient	R	R^2	F	t-Value	*p*-Value
1	Temprature→pH	.000	.312	.097	18.699	−.192	.848
2	Organic Matter Content→pH	.001				1.125	.261
3	Moisture Content→pH	.000				−1.120	.263
4	Number of Days→pH	.002				8.499	.000

c. Regression Analysis for Conductivity

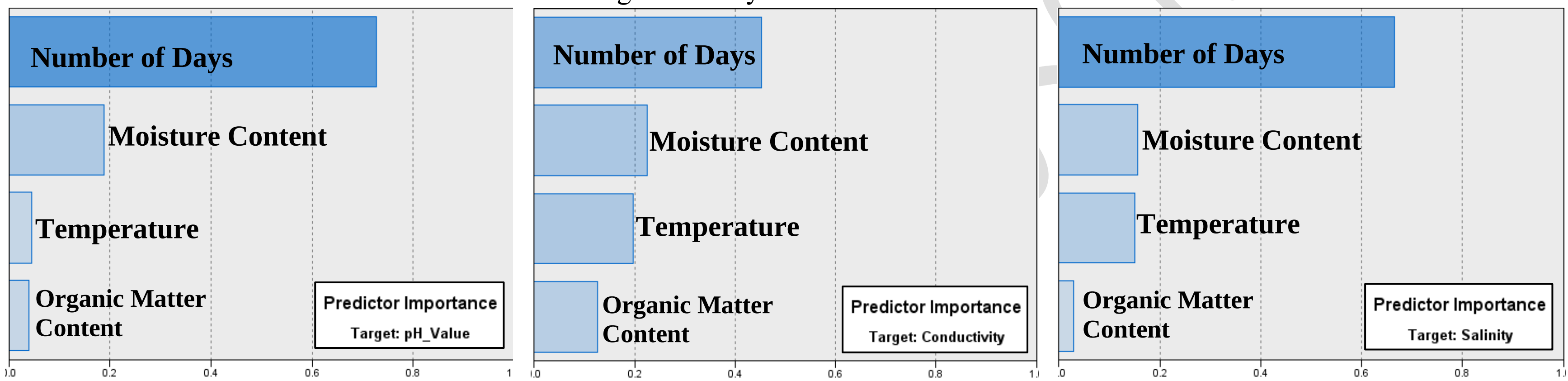
No.	Regression Weights	Beta (β) Coefficient	R	R^2	F	t-Value	*p*-Value
1	Temprature→Concuctivity	.090	.705	.497	172.003	8.173	.000
2	Organic Matter Content→Conductivity	.058				5.645	.000
3	Moisture Content→Conductivity	.022				7.137	.000
4	Number of Days→Conductivity	.086				23.203	.000

d. Regression Analysis for Salinity

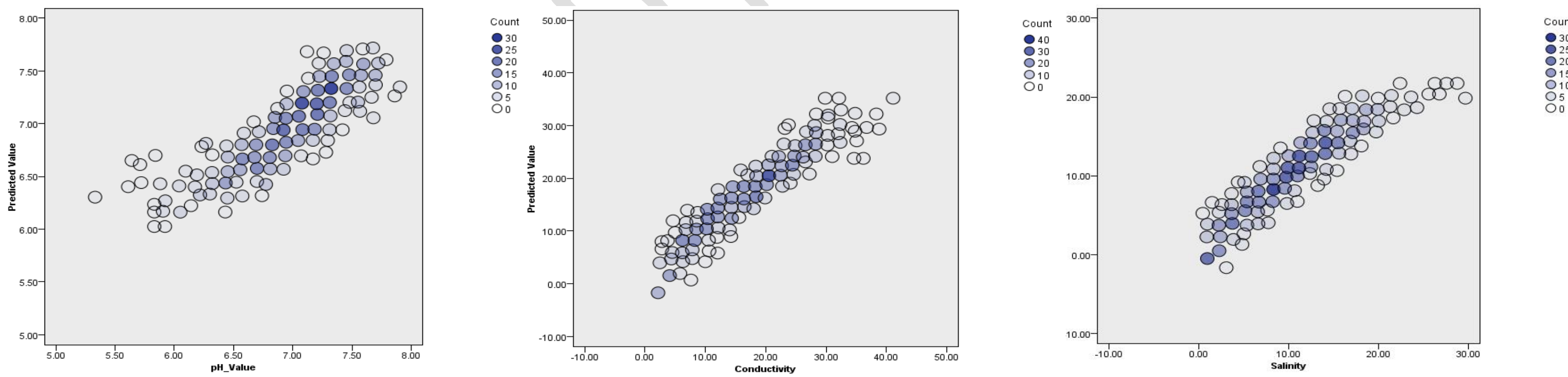
No.	Regression Weights	Beta (β) Coefficient	R	R^2	F	t-Value	*p*-Value
1	Temprature→Salinity	.045	.785	.617	279.502	6.919	.000
2	Organic Matter Content→Salinity	−.017				−2.749	.006
3	Moisture Content→Salinity	.011				6.180	.000
4	Number of Days→Salinity	.071				32.006	.000



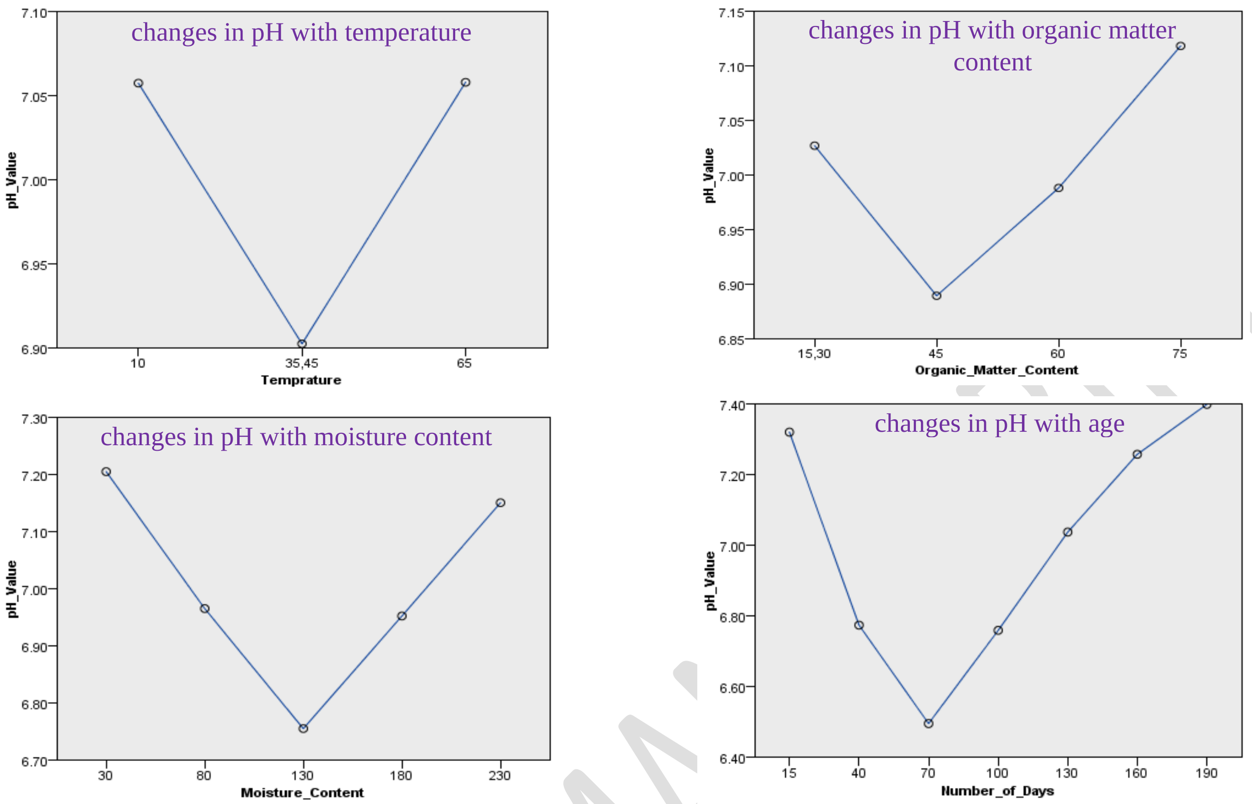
a. Percentage Accuracy for Predicted data for the models



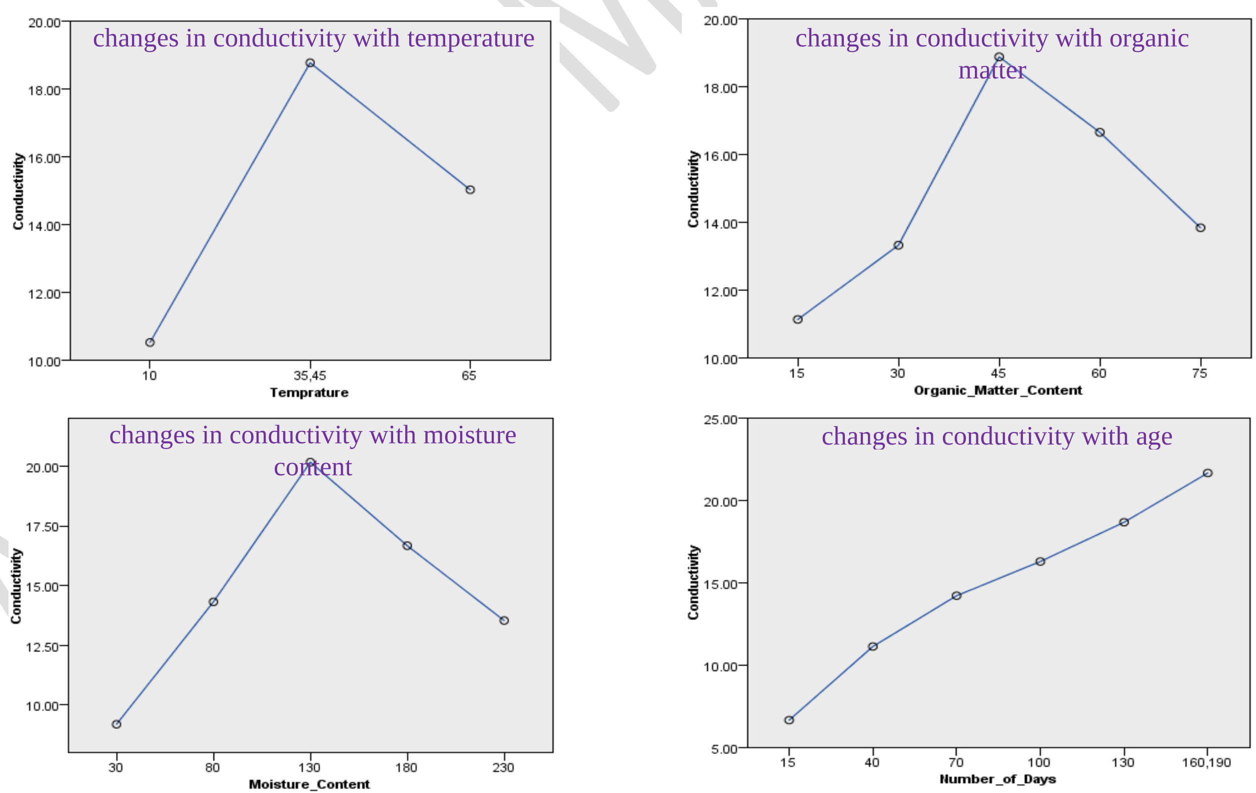
b. Predictor's importance in the estimating models



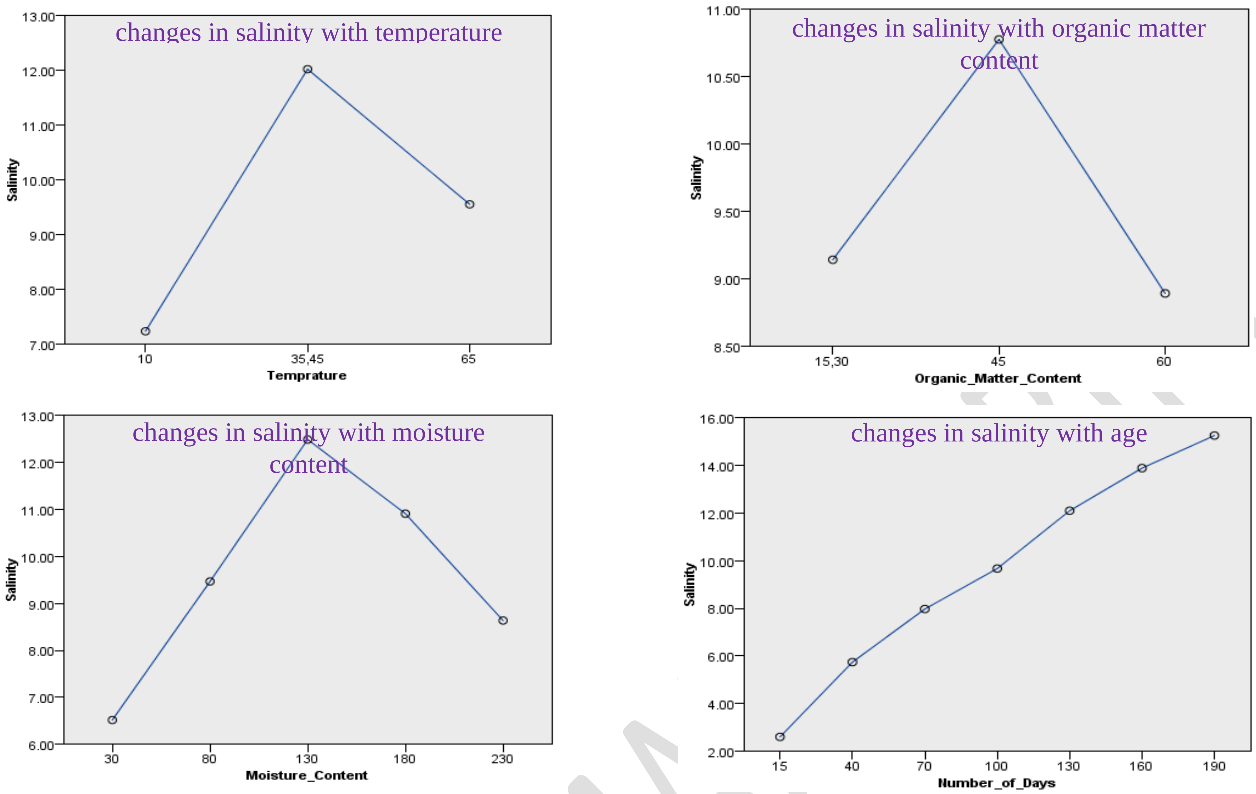
c. Discarded scatterplot of observed vs predicted values



d. Estimated Mean Values (pH)



e. Estimated Mean Values (Conductivity)



f. Estimated Mean Values (Conductivity)

Figure 8. Outcomes of Automatic Linear Regression Analysis

5. Conclusion

This study examined the degradation characteristics of municipal solid waste (MSW) by analyzing leachate pH, conductivity, and salinity over a 190-day period under varying conditions of temperature, moisture content, organic matter content, and degradation time. The results indicate that:

1) pH decreases and then increases with time, while conductivity and salinity increase monotonically and stabilize at later stages. The optimal conditions for MSW degradation were found to be 35–45°C, 120–150% moisture content, and 45% organic matter.
2) Statistical analysis reveals that temperature is positively correlated with conductivity and salinity, while organic matter content has a negative effect on salinity. Longer degradation times lead to higher conductivity and salinity.
3) Regression analysis shows that pH is primarily influenced by the number of days, while conductivity is affected by all factors. Salinity is negatively influenced by organic matter content.

These findings emphasize the importance of temperature, moisture, and organic matter content in regulating MSW degradation, which can enhance landfill management and backfill material utilization.

While this study provides valuable insights into MSW degradation, further research is needed to explore landfill gas emissions, which are crucial for environmental pollution control and assessing MSW degradation stages. Additionally, investigating the compressive strength, mass, and volume changes of leachate would further enhance our understanding of the engineering properties of MSW landfills.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Natural Science Foundation of Shaanxi Province (No. 2022JM-262), Excellent Expert Studio Project in Bazhou of Xinjiang (No. 211828240614).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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