Optimization of process variables for enhanced organic matter degradation and nitrogen conservation during food waste composting at an academic campus

Tandra Mohanta* and Sudha Goel

*Author 1 and corresponding author
Name: Tandra Mohanta
Advanced Technology Development Centre,
Indian Institute of Technology, Kharagpur, India
Email: tandramohanta1102@gmail.com
Mobile: +91-9679085379

Author 2
Name: Sudha Goel
Department of Civil Engineering,
Indian Institute of Technology, Kharagpur, India

Abstract

Fractional factorial design based methodology was adopted to investigate the effects of operational factors and their interactions on the performance of a food waste bin composting process. Moreover, the objective of this study was to produce high quality compost by identifying the optimum combination of the operating factors in aerobic batch reactors. The four factors studied include feedstock ratio (FR), moisture content (MC), mixing time (MT) and with or without starter culture (SC) addition and their effects was observed on three responses namely final C/N ratio, organic matter decomposition (OM) and nitrogen loss. The statistically significant factors were identified and the regression models obtained. The optimal combinations obtained after numerical optimization of all dependent functions using the response optimizer function in Minitab are: 1:1 ratio of foodwaste: cow dung for feedstock ratio, 70% for moisture content, a mixing time of 60 minutes/day and addition of microbial inoculum. The results provided guidance to optimize a composting system that will lead to generation of a stable, mature compost with lower final C/N ratio, minimal nitrogen loss and increase decomposition rate. This study demonstrated that fractional factorial design can be an effective tool to model food waste composting and it can also be utilized for different types of waste.

Keywords: fractional factorial, C/N ratio, food waste, nitrogen loss, organic matter

Introduction

Nearly 1.6 billion tons of food waste (FW) are generated globally and is one of the major environmental concern. Decentralised modes of treatment such as bin composting can be effective solutions to recycle food waste and produce a stabilized and nutrient enriched soil amendment. This can also help tackle waste at the generation point and serve as a potential treatment option at individual or community level. Composting is an inexpensive, environmental-friendly aerobic process which employs microorganisms to convert a mixed complex organic substrates into carbon dioxide (CO_2), water, minerals and a stabilized end product, compost that can be used as a soil conditioner [1]. The end product compost must be of high quality, i.e., stable, mature and free of toxicity both to plants and environment to be considered beneficial for the soil [2,3]. The composting process is governed by various chemical, physical and microbiological factors. The lack of understanding of the complexity of biological, chemical, and physical processes can result in malfunctioning of a composting system. The microbial and physicochemical environment in composting is affected by both environmental conditions such as diversity of microbial population, temperature, aeration, and the chemical properties of raw material such as the C/N ratio, feedstock and moisture content. Studying the interactions between these factors are crucial to understanding the biodegradation process. This in turn helps in successively determining compost maturity and stability.

In order to obtain high quality, stabilized compost, operating conditions should be optimized, which plays a vital role in the degradation process. Variation in feedstock ratio affects the organic matter availability and its degradation and differs with the type of raw material. MC is another important factor responsible for efficient composting. It halts microbial activity when it is low and limits oxygen exchange when it is high. The aeration rate determines the amount of oxygen, which affects the MC and temperature of the system [4]. Also in the recent years, several studies have been conducted to study the effect of inoculation during composting [5-13]. Various studies have shown that addition of beneficial microbes and their products to organic wastes had little effect on the decomposition process [14-16]. However, researchers Singh & Sharma observed that treating organic waste with effective microorganisms, i.e., bacteria, actinomycetes and various groups of fungi accelerated the decomposition process [17]. Their studies have shown that inoculation with *Azotobacter* during composting accelerates the decomposition process and improves the quality of compost. Most results indicated that improvement of composting processes by means of inoculation seemed to depend on the properties of raw materials and microorganisms applied. Most studies deal with only one or two pure cultures [18,19].

Many studies have been conducted to determine effects of these design factors on the composting performance and compost maturity and quality. However, majority of these studies include single-factor or two factor optimization to evaluate the optimum process conditions using the conventional and classical ‘one factor at a time’ approach which is time-consuming [20-22]. It demands more number of experiments, which is neither desirable nor reliable [23]. In addition, the method doesn’t consider the interactive effects of different parameters. To overcome these limitations of a single factor optimization process, empirical methods such as fractional optimization can be employed. In this study, statistically significant factors that affect the performance of a composting system and it its product quality were screened and identified based on the design of experiment (DOE) technique. A two level fractional factorial (2^{4-1}) design was employed to study the effects of four factors-FR, MC, MT and SC on the quality of compost by evaluating their impact on final C/N ratio, OM decomposition and N loss as responses.

Materials and methods

1. Experimental design (24-1 Fractional Factorial design) and statistical analysis

In order to study the effects of operational design parameters on the quality of compost generated with the minimum possible number of experiments, 2^{4-1} fractional factorial design method was selected with four factors, three responses, 4 centre points and 3 replications. The four factors to be investigated are presented in Table 2 along with their high and low levels. The responses recorded include final C/N ratio, Nitrogen loss and organic matter (OM) decomposition.

Table 2. Design factors and their high and low level

Independent variables	**Code**	**Units**	**Low level (-1)**	**High level (+1)**
Feed stock ratio	FR		1:1	3:1
Moisture content	MC	%	50	70
Mixing time	MT	minutes/day	20	60
Starter culture	SC	ml/kg	No	Yes

Based on the analysis of variance (ANOVA), the significant factors with respect to each response are determined and used to produce the factorial model. The experimental data obtained after the completion of the composting were subjected to regression analysis and fit to the following second-order polynomial equation:

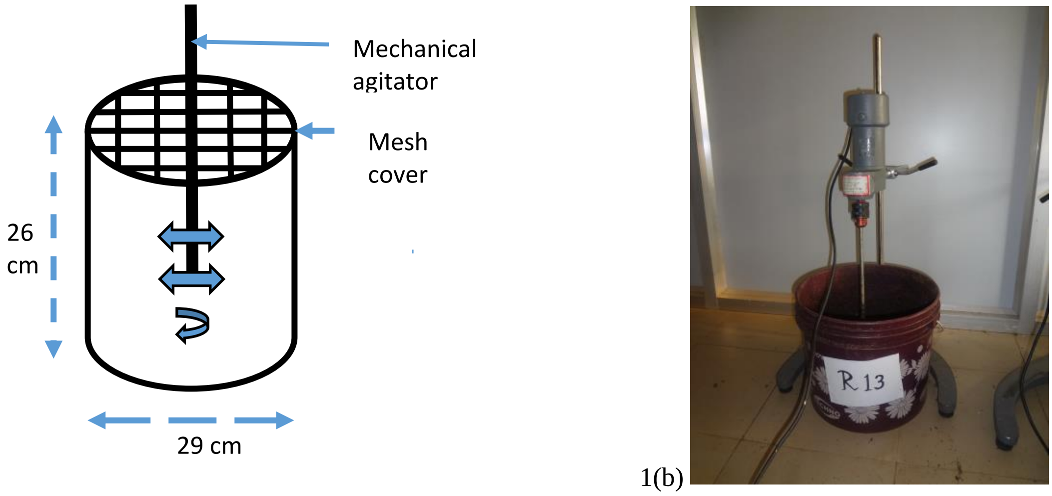
$$Y = \beta 0 + \sum_{i=4}^{4} \beta iXi + \sum_{j=4}^{4} \beta jXj + \sum_{i=1,j=1}^{4} \beta ijXiXj \text{ (i < j)} \qquad (1)$$

where Y is the response or dependent variable [C/N ratio, OM degradation and N loss]; X_i, X_j is the value of the independent variable concerned; and β_0, βi, βj and βij are unknown characteristic constants estimated from the experimental data. Table 2 shows the complete set of run with measured and predicted values of each response variable

2. Composting process

Food waste (FW) was treated by composting process. Cow manure was mixed with food waste to provide the required C/N ratio at the start of the process. The FW mainly comprised of kitchen waste and cooked vegetables, rice and ..salads discarded post consumption and were collected from messes of halls of residences in IIT Kharagpur campus.

A laboratory scale composting reactor (shown in Fig 1(a) and (b)) was used for the study. The cylindrical reactor is made up of HDPE and measures 29 cm internal diameter × 26 cm height (volume 18 litres). For mixing and turning, a rotatory stirrer (REMI RQG-120D) at a constant speed of 800 rpm is used. Mixing was performed once a day for the 1st 30 days and every alternate day for the remaining 60 days. The open end of the reactor was covered by a mesh cover when it is not being stirred. A digital thermometer was inserted into the reactor to record temperature readings every day. The reactors were run in triplicates.



1(a)

1(b)

Fig 1(a). Schematic diagram of the bin reactor used. (b)Actual reactor setup used

A mixed microbial consortium as a starter culture was used in selected bioreactors. The consortium was prepared from pure cultures isolated from soil as well as from previously run composting experiments.

3. *Analytical methods*

For monitoring the composting process, samples were collected at three randomised points in each reactor and then mixed together to form a homogenised mixture which were then assessed in triplicates for various maturity parameters.

Results and discussion

1. *Initial waste characteristics*

The raw material used for the study were characterized physico-chemically and the results are provided in Table 1.

Table 1. Physico-chemical characterization of food waste and cow manure used in the study

Parameters	***Units***	***Food waste***	***Cow manure***
Wet bulk density	g/cm^3	0.625	0.83
pH	-	7.11	6.87
Moisture Content	%	86.9	24.5
TC	%	42.95	17.44
TN	%	1.72	1.58
Total Phosphorous	mg/kg	1.2	1.12
C/N ratio	-	24.97	11.04
Total solids	%	13.1	75.5
Volatile solids	%	44.95	31.39
Fixed solids	%	55.05	68.61

2. *Screening of factors affecting responses*

The factorial design and all statistical analysis was computed using the Minitab v18. The analysis of variance (ANOVA) was performed to determine the statistically significant design parameters affecting the three responses and to produce the regression prediction model. In addition, significance of the regression models obtained was also screened. ANOVA analysis summary for each of the three responses include coefficient estimate of the model, the significance of each parameter and also the interaction effects of the two or more parameters. The significance of a regression equation was checked using F-values while the p-values were used to check the significance of each coefficient (Wang et al., 2013). **P-values** less than 0.05 indicate model terms are significant while values greater than 0.1 indicate the model terms are not significant. The R-squared from the ANOVA indicates how close the data is to the fitted regression line.

Response 1: C/N ratio

ANOVA analysis for final C/N ratio delivered the model F-value to be 21.87, which implies that the model is significant. The significant model terms (p-values <0.05) is shown in the pareto chart (Fig 2). The pareto chart demonstrates the main and interaction effects of the independent process parameters by ranking them according to their contribution in affecting the response variable-final C/N ratio. The factors lying above the t-value limit are considered significant contributors. For C/N ratio, SC and FR were the significant contributors. However, SC negatively affects C/N ratio while FR has a positive effect. Positive effects leads to an increase in the dependent or response variable with a unit increase in the independent variable and vice versa. On the other hand in case of negative effects, a unit increase in an independent variable causes a unit decrease in the dependent variable and vice versa.

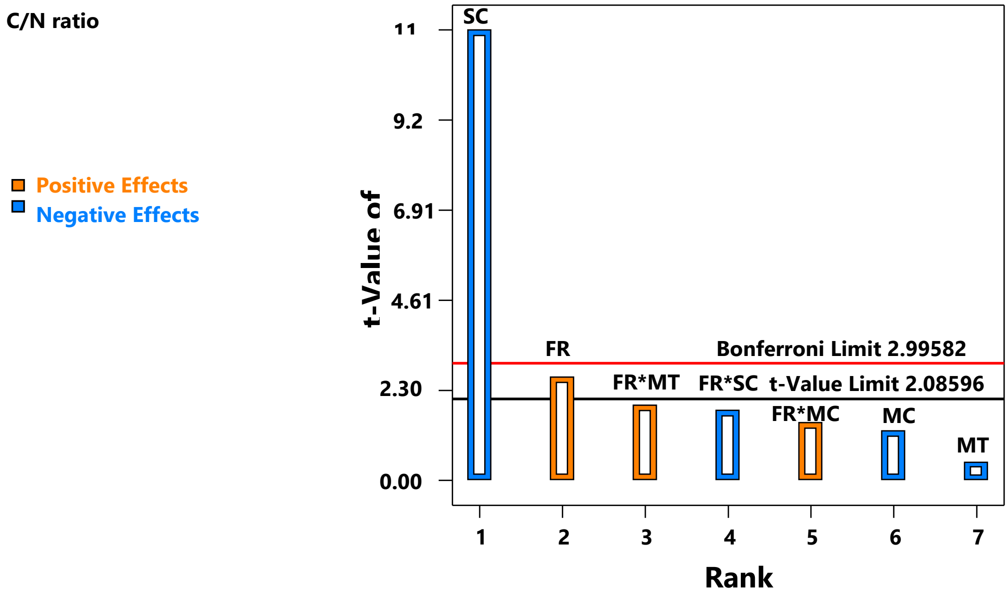


Fig 2: Pareto chart ranking effects according to their contribution to final C/N ratio

Effect of independent design parameters on C/N ratio

- ***Single factor or main effects***

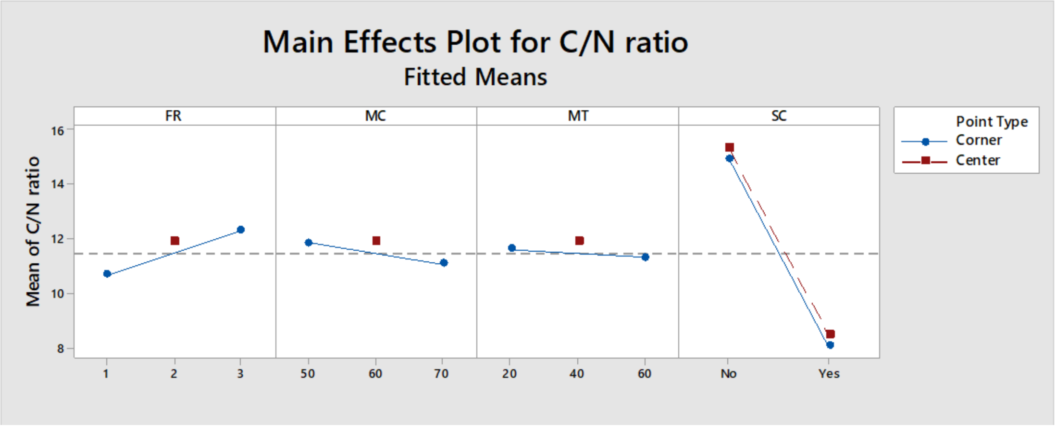
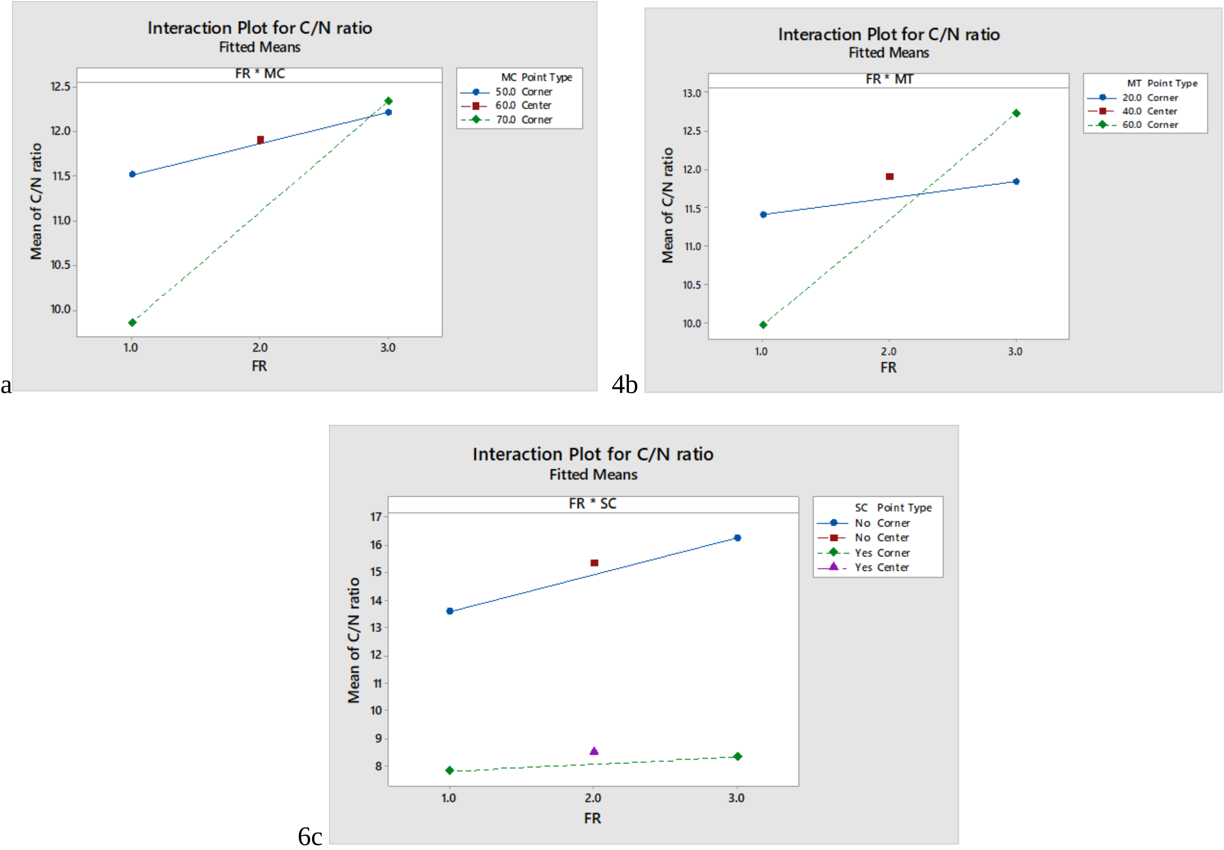


Fig 3 Main effects plot for C/N ratio

The effect of all four independent process parameters on the C/N ratio is shown in Fig 3. The final C/N ratio decreases with decrease in the feedstock ratio and with addition of microbes during the start of composting. The average final C/N ratio was found to be 10.68 and 12.28 when FR=1 and FR=3 respectively. Similarly,final C/N was found to be 8.05 when starter culture was added and 14.91 in case of no addition of starter culture. Therefore, it has significant difference with 13.03% reduction when FR is reduced from 3 to 1 and 46.01% reduction when starter culture is used.

- ***Interaction effects between independent factors***

Figure a-c shows the interaction effects between the four operational parameters. An interaction occurs when the response is different depending on the settings of two factors and appear with two non-parallel lines, indicating that the effect of one factor depends on the level of the other.



4a 4b

6c

Figure 4a-c. Plots showing the interaction effects between the design factors

From figure 6a, lower C/N ratio at the end of composting was achieved when FR was reduced from 3 to 1 at 70% MC as compared to when MC was maintained at 60 and 50%. Similarly, for interactions between FR and MT (figure 6b), it can be observed that final C/N ratio increases as the FR is increased from 1 to 3 at a constant mixing time. However, the difference in increase is greater when MT is 60 minutes/day in comparison to 20 minutes/day. Fig 4c shows little interaction between FR and SC. However, addition of starter culture had a greater impact in C/N reduction when FR was reduced from 3 to 1 than without its addition.

Response 2: OM decomposition

For OM decomposition, FR, SC, FR*MT and FR*SC are significant model terms and is visually represented in the pareto chart (Fig 5). From the figure, interaction effects of FR*MT and FR is a positive contributor while FR and FR*SC have negative effects on final OM degradation.

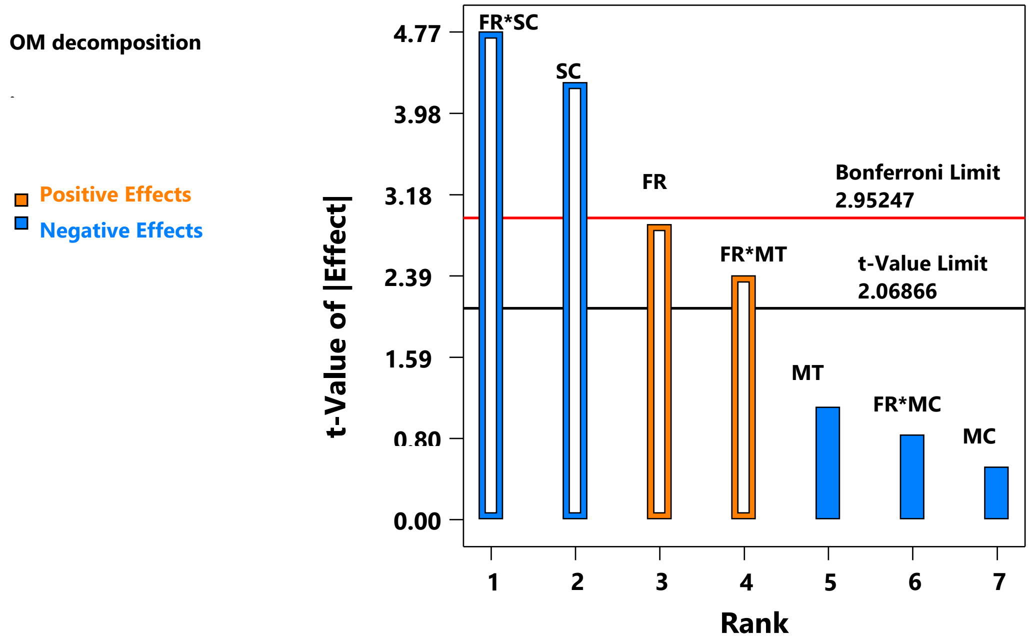


Fig 5. Pareto chart ranking effects according to their contribution to OM decomposition

Effect of independent process parameters on OM decomposition

- ***Single factor or main effects***

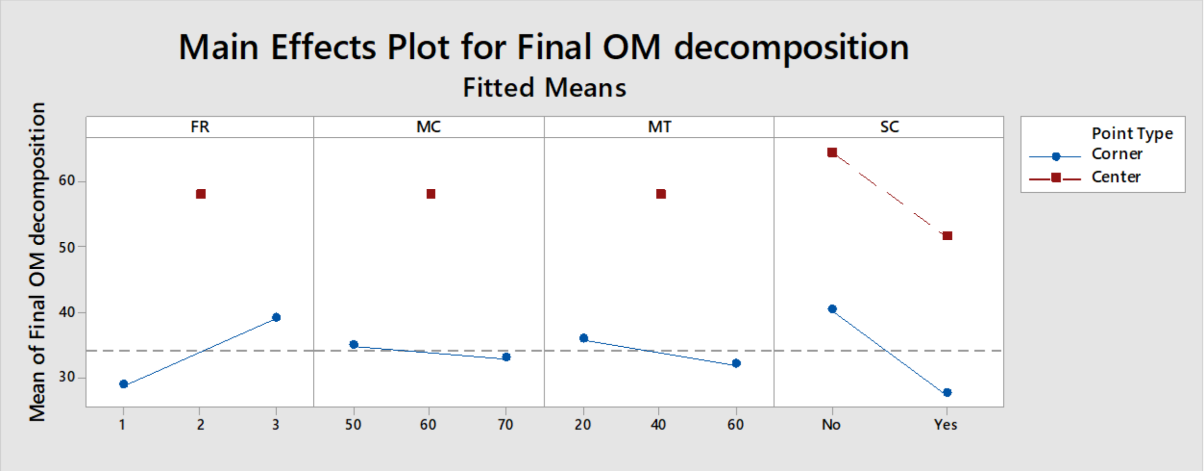


Fig 6. Plot showing the main effects for OM decomposition

The effect of all four independent process parameters on the OM decomposition is shown in Fig 6. As per the model, only FR and SC were considered significant.

- ***Interaction effects between independent factors***

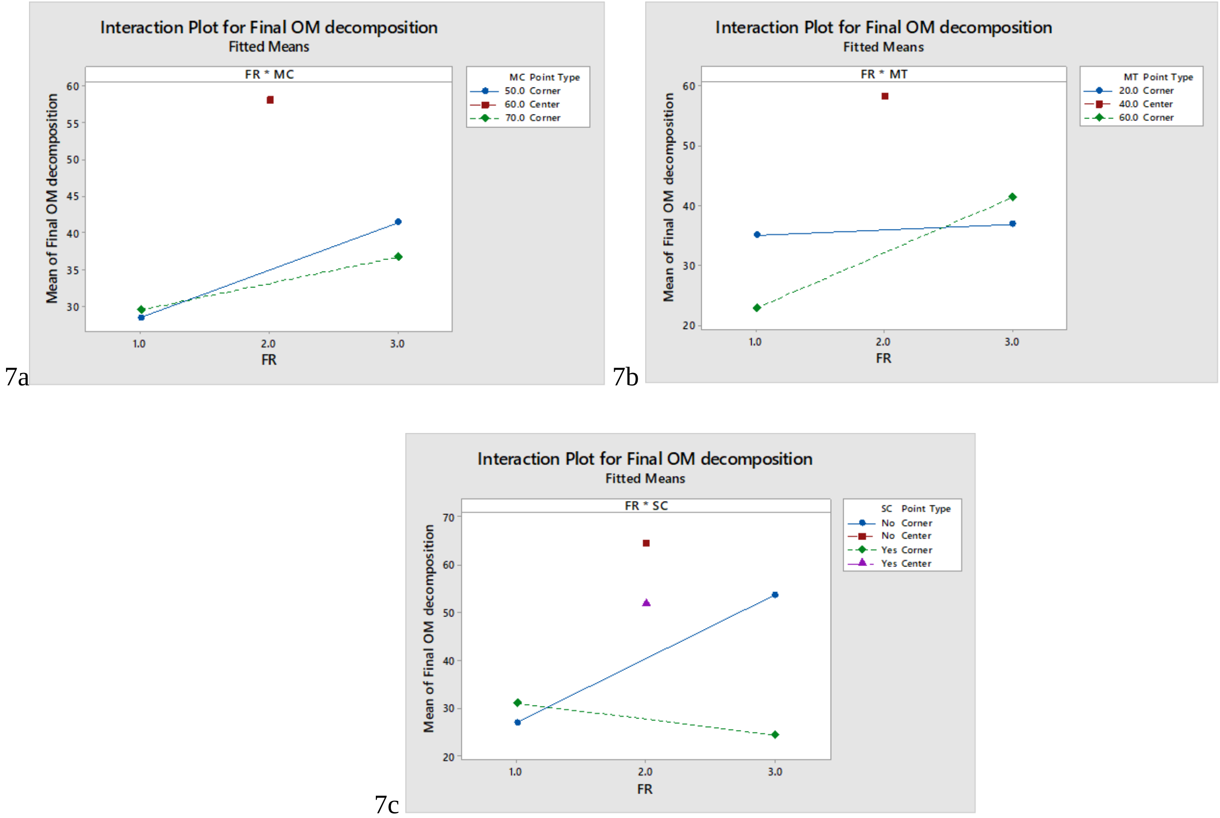


Fig 7a-c. Plots showing interaction effects between all four parameters wrt final OM decomposition

In fig 7a, the representative MC lines (at both levels) almost approach each other which implies that changes in MC had very little effect on OM decomposition when FR=1. However, OM loss significantly increases from 36.71 % to 41.42% as MC changes from 70% to 60% when FR=3. Interaction between FR and MT (Fig 7b) shows that mixing time of 20 min/day did not have a remarkable effect on the final OM loss as FR changes from 1 to 3. However, final OM degradation significantly increases with FR increases at higher mixing time (i.e. 60 min/day). At FR=1, OM decomposition increases from 22.84 % to 35.05% as MT is reduced from 60 min/day to 20 min/day. On the contrary, higher mixing time of 60 min/day increased OM degradation from 36.81 to 41.32 % (at FR=3). Interaction between FR and SC had the most significant positive effects on the response OM decomposition (Fig 7c).

Response 3: N loss

For the response N loss, ANOVA delivered the model F-value of 5.65 implying the model is significant. In this case FR, MC, FR*MT and FR*SC are significant model terms.

Effect of independent process parameters on N loss

- ***Single factor or main effects***

Fig 8 shows the variations in total N loss as a result of single factor variations at both high and level levels. N loss is most affected by FR and MC and is observed to be directly proportional to FR and indirectly proportional to MC. Nitrogen was conserved in majority reactors. MT and SC didnot have a significant effect on N loss.

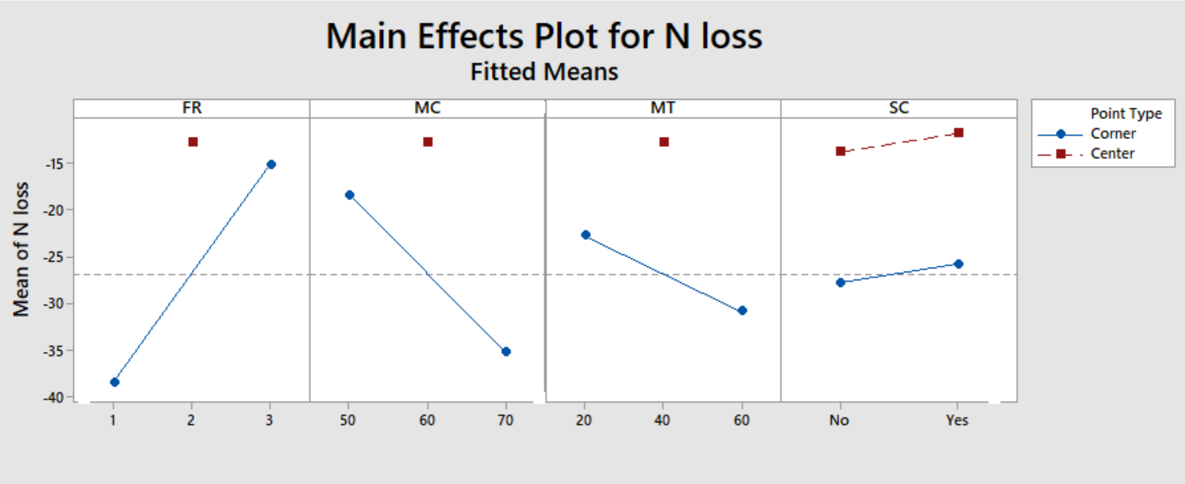


Fig 8. Plot showing main effects of independent variables to N loss

Interaction effects between independent factors

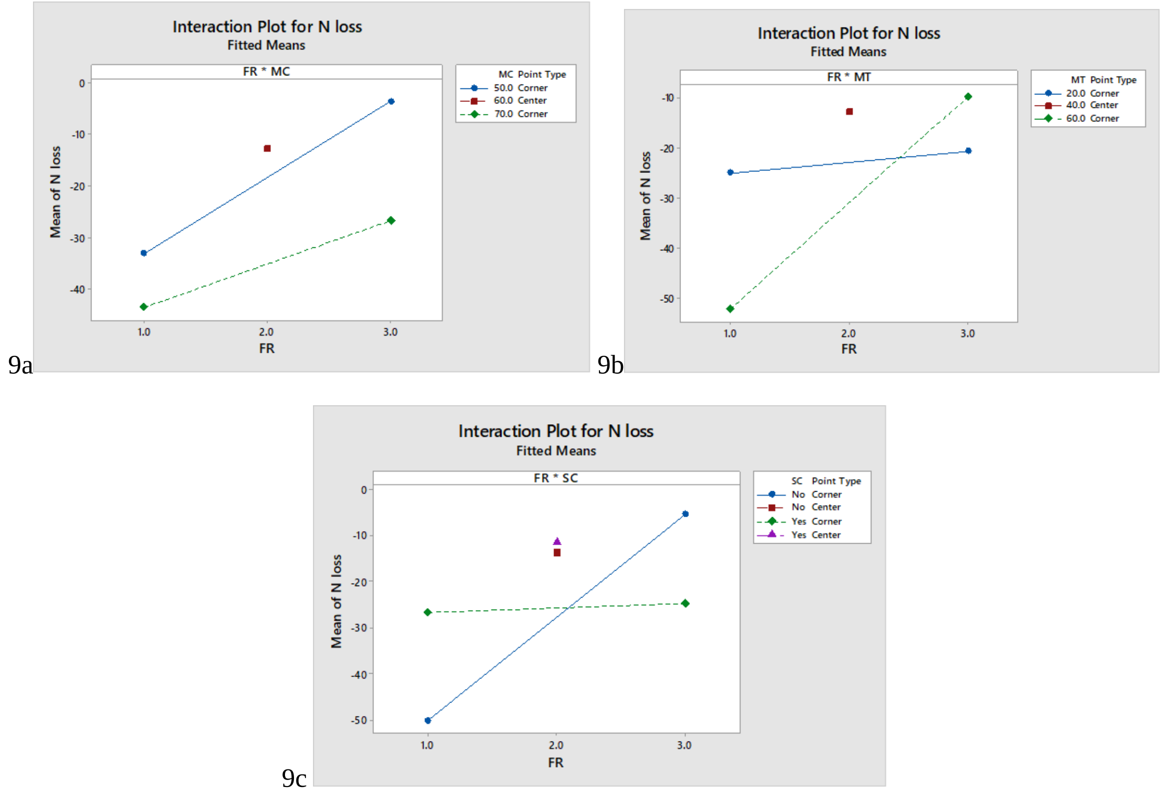


Figure 9a-c. Plots showing interaction effects between four operational parameters wrt N loss

Figure 9a-c shows the interaction plot for N loss. FR and MC have very little interaction with each other (as evident by parallel lines). Higher moisture content prevents N loss at lower FR and viceversa. Lower mixing time of 20 min/day (figure 9b) didnot have a remarkable effect on N loss at different FR levels as does addition of SC in figure 9c.

Regression Analysis

Regression equations yielded for each dependent variable as a function of independent variables are presented in Table 2

Table 2. Regression equations for each dependent variable

Eq No	Equations	Df	F value	R(sq)
(2)	$\frac{C}{N} ratio = 20.16 - 3.04\,FR - 0.1277\,MC - 0.0652\,MT - 2.345\,SC + 0.0447\,FR * MC + 0.0291\,FR * MT - 0.542\,FR * SC + 0.419\,Ct\,Pt$	8	21.87	90.2 %
(3)	$OM\ decomposition = 32.5 + 5.4\,FR + 0.200\,MC - 0.514\,MT + 10.39\,SC - 0.145\,FR * MC + 0.2090\,FR * MT - 8.37\,FR * SC + 24.05\,Ct\,Pt$	8	8.8	78.74 %
(4)	$N\ loss = 8.6 + 11.6\,FR - 0.211\,MC - 1.154\,MT + 22.36\,SC - 0.315\,FR * MC + 0.475\,FR * MT - 10.67\,FR * SC + 14.04\,Ct\,Pt$	8	5.65	70.4 %

These equations can be used to estimate the variation of dependent variables with changes in the independent variables over the ranges considered the other two variables are kept constant. Only the terms with statistically significant coefficients are shown according to the proposed methodology. Table 3 presents the measured vs predicted values for each of the responses against the 28 runs.

Table 3. Total runs with different factor combinations with measured and predicted values of each response variable

Std	Run	A:FR	B:MC	C:MT	D:SC	Measured C/N ratio	Predicted C/N ratio	Measured OM decomposition	Predicted OM decomposition	Measured N loss	Predicted N loss
		Independent variables				*Response variables*					
1	4	1	50	20	No	15.8	15.18	30.87	32.48	-39.2	-29.35
2	13	1	50	20	No	13.4	15.18	26.07	32.48	-27.2	-29.35
3	19	1	50	20	No	16.33	15.18	43.96	32.48	-32.2	-29.35
4	5	3	50	20	Yes	9.15	7.87	21.8	24.46	-24.3	-16.70
5	14	3	50	20	Yes	7.3	7.87	25.3	24.46	-4.5	-16.70
6	26	3	50	20	Yes	6.8	7.87	22.8	24.46	-22.8	-16.70
7	7	1	70	20	Yes	9.1	7.75	37.5	37.62	-32.2	-16.50
8	8	1	70	20	Yes	7.99	7.75	33.3	37.62	-15.5	-16.50
9	16	1	70	20	Yes	5.8	7.75	38.6	37.62	-3.3	-16.50
10	17	3	70	20	No	16.74	15.93	53.56	49.17	-19.3	-20.48
11	20	3	70	20	No	14.08	15.93	40.63	49.17	-33.8	-20.48
12	21	3	70	20	No	16.96	15.93	56.79	49.17	-18.9	-20.48
13	15	1	50	60	Yes	7.97	7.96	22.06	24.31	-39.7	-33.14
14	18	1	50	60	Yes	6.67	7.96	23.6	24.31	-42.3	-33.14
15	23	1	50	60	Yes	8.9	7.96	23.8	24.31	-18.9	-33.14
16	1	3	50	60	No	16.33	16.69	66.19	58.38	20.6	13.48
17	2	3	50	60	No	18.55	16.69	77.67	58.38	-7.7	13.48
18	27	3	50	60	No	15.18	16.69	34.76	58.38	17	13.48
19	6	1	70	60	No	10.1	12.07	21.47	21.36	-77.2	-67.02
20	9	1	70	60	No	13.71	12.07	24.5	21.36	-72.7	-67.02
21	24	1	70	60	No	12.4	12.07	21.58	21.36	-61.7	-67.02
22	11	3	70	60	Yes	9.37	8.88	26	24.26	-1.8	-28.97
23	28	3	70	60	Yes	8.2	8.88	23.2	24.26	-54.2	-28.97
24	25	3	70	60	Yes	8.71	8.88	20.1	24.26	-32.4	-28.97
25	3	2	60	40	No	16.58	14.97	54.12	64.40	15.7	-25.84
26	12	2	60	40	Yes	8.73	8.11	61.49	51.71	-33	-23.83
27	10	2	60	40	No	13.4	14.97	60.79	64.40	-25.2	-25.84
28	22	2	60	40	Yes	8.89	8.11	55.82	51.71	-8.7	-23.83

Model fitting and determination of optimum mixture

Eq 2-4 predicts the final C/N ratio, OM decomposition (%) and N loss (%) and the following criteria setup was chosen to obtain the optimized solution as shown in Table 4.

Table 4. Criteria adopted for obtaining optimized set of parameters

Criteria	Goal	Value	Optimized solution
FR	In range	1-3	1
MC	In range	50-70 %	70 %
MT	In range	20-60 minutes	60 minutes
SC	In range	No-Yes	Yes
C/N ratio	Minimize	-	Predicted C/N fit=6.2
OM decomposition	In range	-	-
N loss	Minimize	-	Predicted N loss fit= -45.66
			Composite desirability=0.76

From the table, the optimum mixture suggested was FR to be 1 (i.e. 50% food waste and 50% manure (by weight)), MC to be maintained at 70 %, mixing time of 60 minutes/day and the addition of starter culture. This optimum mixture was tested under the same aeration conditions in the same reactors in three replicates and the results are provided in Table 5

Table 5. Predicted vs measured responses based on the optimized set of parameters

Response	**Predicted Mean**	**95% PI low**	**95% PI high**	**Observed data**	**Observed data Mean**
C/N ratio	6.2	2.74	9.743	Run 1=8.15; Run 2=7.72; Run 3=9.63	8.55
N loss	-45.66	-83.63	-7.68	Run1=-54.07; Run 2=-76.97; Run 3=-58.42	-63.15

Conclusion

The fractional factorial method was found to be promising for optimization. The results suggested an optimum combination of operating factors of FR to be 1, MC to be maintained at 70%, mixing time of 60 minutes/day as well as addition of microbial inoculum as starter culture for the in-vessel composting system under the tested set of conditions. Analytical and microbiological analyses showed expected results in accordance with the FCO standards. Further studies are needed to validate the optimum set of results yielded by the factorial design with different type of wastes to verify its efficacy in obtaining a stable, mature quality compost. In addition, studies including windrow composting with the given optimum conditions are needed for real-world application.

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