Environmental Management: Modelling Plants Nutrients Values During the Composting Process

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Abstract: - Composting of domestic wastes is one of the natural methods of eliminating foods wastes without damaging the environment. This process provides plants nutrients in the form of hygienic products, similar to mineral-rich soil called agricultural compost. The content of these formed components depends on several factors in the process, such as the humidity, the rejects quantities, their ratios to each other, the type of waste, the composting temperature and the elements interactions during the physico-chemical transformations. The innovation in this study, which remains the essential aim of this work, is to show how the formed essential plants nutrients, such as potassium, nitrogen, and phosphorus, depend not only on the humidity of the environment, the aeration by oxygen and the composition of the domestic wastes, but also on the interaction between them combined with the transformation time. Mathematical modelling using the design of experiments method, revealing that the presence of one element of three in the compost is a function of the two others in time, shows this. The mathematical model showing the variation of composting time as function of the minerals presence in the compost by graphs, contours and response surfaces; they simultaneously interprets the results of this process.
One of the final objectives is to estimate by prediction the values of composting days without new experiments.

Key Words: - Domestic wastes, composting, Chimico-physical transformation, Fermentation, Natural fertiliser, Mathematical modelling

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1 Introduction

In the following, one shows that some of the mineral elements necessary for plant nutrition that conserve during the degradation and fermentation of food and plant wastes vary with time. They depend, not only on the quantities of the various wastes, the humidity, the oxygen rate and the alteration time [1][2][3] but also, they depend of the conserved elements quantities and their interactions during the processes in the compost as potassium, nitrogen, phosphorus etc. One interests here in the three components because their rate in the compost is significant, and their nutritive role is important. The obtained product, is a very useful fertiliser for agriculture and gardening since it nourishes the plants and develops them [4][5][6]. Each element acts on the other in their formation, according to the time of degradation; the mathematical model, which takes into account the percent of each of them, shows this, as one sees later in the text. The modelling of this chimico-physical behaviour is done by the design of experiments method using the Modde 6.0 software. This mathematical model has several advantages over other models. In addition to being based on experiments: a- It is simple and polynomial form. b- It does not include any difficult trigonometric or logarithmic functions. c- It has the ability to be descriptive and predictive at the same time in the experimental field. d- It has an interactive correlation between the factors and finally, e- It does not require a high number of experiments. This is here, where the innovative aspect of this paper resides in other complicated models, more involving difficult and complicated mathematical functions are used in many sciences, but describe only the process without any prediction. The used polynomial model has this faculty with the ability to introduce interactions between the factors and choose the estimated level coefficient in our work at 95% to get closer to the truth and real behaviour. All this cannot be done with other modelling. However, before this stage, experiments and measurements must be carried out and the process of natural composting must be successfully started, passing through the oxidative phase where the temperature reaches 70 °C, then through the maturation phase where it drops to 30 °C with a stabilised pH between 7.3 and 7.8. Sixteen different parameters are measured every 30 days, but the study focuses on three of them, which enter into the composition of the KNOP compound used by biologists. These are the quantities of potassium, nitrogen and phosphorus, whose variation should not be too pronounced because they tend to fall with time [7][8][9][10][11]. The composting time is analysed and optimised according to the variation of these three elements. This analysis is possible using the cited software, which allows to find the behavioural model, but also to predict results not known experimentally.

2 Preparation of the Experimental Environment and Measurements

Biodegradable wastes are collected in a container (composter) with side holes for aeration and a cover to protect the residues from the weather conditions. It also has a drain hole at the bottom to drain off the nutrient-rich liquid from the process. Compost material consists mainly of a mixture of kitchen waste such as peelings and fruit and vegetable residues, cellulose products such as paper, wet plants and garden wastes, nutshells, and small amounts of eggshells and coffee marc. To get the process started quickly, already formed compost, soil earthworms are added. Finally, it is important to note that no fish, meat and plastics should be added, because they prevent or slow down the degradation of the other components [12][13]. Sewage sludge is also added because it contains microorganisms that accelerate the process. The humidity level must be strictly controlled at each
stage by the wrist test, because too much humidity causes rotting, and too less humidity causes drying out; in both cases composting is not successful. This conditions permit to the compost to be formed under good circumstances in a quasi-neutral or slightly acidic environment, and a humidity rate favouring the proliferation of the bacteria, the fermentation and the fertilisation of the environment. This method eliminates between 30% and 50% of the waste contents, as a function of its composition.

2.1 Measurements Results

The 127 experiments below in Table 1 are developed under the surveillance of 2 essential parameters which are the humidity rate with an average of 37.9, and the pH with an average of 7.5. These two values permit to the compost to be formed under good conditions in a quasi-neutral or slightly acidic environment, and a humidity rate favouring the proliferation of the bacteria, the fermentation and the fertilization of the environment. Table 1 shows the cited values; they are taken every 30 days from the composting beginning to 210 days. In this table, one notes that the K, N and P decrease at 210 days.

Table 1. Masses of mineral components and parameters rates of the compost during 210 days

Parameters	0 day	30 days	60 days	90 days	120 days	150 days	180 days	210 days
Humidity (%)	53.8	42.2	39.4	36.7	35.2	33.1	32.	31.1
pH (-)	7.4	7.3	7.1	7.6	7.4	7.8	7.7	7.7
E.C (mS cm^{-1})	2.2	1.8	1.8	1.8	1.7	1.8	1.8	1.8
TOC %	35.5	36.6	41	42	35.2	29.3	29.1	29
TKN %	1.3	1.4	1.7	1.9	1.9	1.9	1.9	1.9
MO %	52.2	52.1 0	50.0 2	50.5	48.9	46.4	42.8 4	40.
Ash (g kg^{-1})	32.8	34.3	36.32	42.4	46.2	50.5	51.5 1	52.5
C/N	27.3	26.1	24.5	22.7	18.7	15.4	15.1	15
Dec % (1)	-	6.5	14.3	33.6	43.6	62.1	61.1	61.1
$N\text{-}NH^{+}$ (mg g^{-1})	2.5	2.3	2.6	1.9	1.3	1.2	1.1	1.1
$N\text{-}NO^{-}_{3}$ (mg g^{-1})	2.7	2.5	1.5	1.6	0.9	0.6	0.6	0.6
Mg total (g kg^{-1})	2.5	2.6	2.8	2.8	3.1	3.5	3.3	3.3

K total (g kg^{-1})	13.6	9.9	8.7	8.7	9.7	9.6	9.4	9.1
P total (g kg^{-1})	2.3	2.2	2.5	1.9	1.9	2.1	2.2	2.2
Mn total (mg kg^{-1})	48.6	50.6	50.6	78.8	79.8	60.3	56.1	55.1
Fe total (mg kg^{-1})	4875	4777	3058	3703	4057	4464	4304	4350

One notes that k, N and P decrease respectively of 33.08%, 48.07% and 4.34% of their initial values. Our aim is to keep them high while forming this natural fertilizer. This requires an optimisation between the composting time and the elements percentage in fertiliser.

3 Modelling of the Composting Process

The chosen model differs from the others [8] [10] by its polynomial form, which describes the composting time as a function of the variation of the three minerals K, N and P. It consists of a sum of 7 monomials in which the 3 elements x_i (the factors) are coded values multiplied by coefficients a_i that must be determined, while the time y (the response) is represented in its real value, [14] [15][16][17] (formula 1).

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 \quad (1)$$

However, the mentioned factors (x_i) are expressed with various units, and with a values range very different from each other; they cannot be represented by their real values in the model because it is a sum of monoms. In order to satisfy the model equation (1), there is a need for normalisation for obtain the factors without unit and situated between two extreme values "-1" and "+1", using the following coding relation (coded values) [17]:

$$x_i = \frac{u_i - \left(\frac{u_{\max} + u_{\min}}{2}\right)}{\left(\frac{u_{\max} - u_{\min}}{2}\right)} \quad (2)$$

Where: x_i is the coded parameters value, u_i is the real parameter value, u_{max} is the maximal real value of all parameters, and u_{min} is the minimal real value of all parameters. The coded values of the parameters are given in Table 2 from 0 day to 210 days.

Table 2. The coded values of parameters

Experiments	Coded value of K	Coded value of N	Coded value of P
1	1	1	0,333
2	-0,51	0,771	0
3	-1	0,371	1
4	-1	0,0286	-1
5	-0,592	-0,714	-1
6	-0,633	-0,943	-0,333
7	-0,714	-1	0
8	-0,837	-1	0

3.1 Determination of the Coefficients Values a_{ij}

By replacing these coded values in model (1), 8 different equations are formed and expressed in matrix form; the solution of this equations system is given by expression (3) [17]:

$$a_{ij} = \left(X^t X\right)^{-1} \left(X^t\right)(Y) \quad (3)$$

Where: X: Factors model matrix, X^t: Transpose of the factor model matrix, $(X^tX)^{-1}$: Information matrix, (Y) is response matrix. Thus, model (1) takes the equation form (4) [14][15][16][17]:

$$y = -208.736 - 125.149x_1 + 0.162633x_2 - 32.8015x_3 + 78.359x_1^2 + 259.387x_2^2 + 62.1935x_3^2 \quad (4)$$

3.2 Model Quality Analysis

Several indicator coefficients and quality tests show the ability of the model to describe correctly the composting process. The indicator of the descriptive quality of the model R2 ($0 \le R2 \le +1$) is in our case equal at 0.999, the indicator of the predictive quality of the model Q2 ($-\infty < Q2 \le +1$) is 0.993; they are both close to +1, which indicate the very good quality of the model.

3.3 Evaluation Tests

3.3.1 Coefficients Significance

The Student test shows the significance of the coefficients a_{ij} that compose the mathematical model. The statistical calculation [15], which consists of comparing the absolute values of the model coefficients and the variance S_i multiplied by the Student number t_{crit} ($t_{crit}*S_i$) taken from the

Student table for each coefficient [16][17][18] gives the following results:

Table 3. Significance of model factors

Coef	Values	$t_{crit}*S_i$	Significance
a_0	208,736		Significant factor
a_1	125,149		Significant factor
a_2	0,162633		Non-significant factor
a_3	32,8015	0,79635	Significant factor
a_{11}	78,359		Significant factor
a_{22}	259,387		Significant factor
a_{33}	62,1935		Significant factor

Table 3 shows that only the factor a_2=0.162633 does not predominate in model (4), because it is inferior to $t_{crit}*S_i$, it means that its effect on the response y (composting time) is negligible, its action does not change so much the value of y. The model is therefore well developed because there are not many insignificant factors. All the 6 other remained factors (Table 3) are significant in model (4); when they have a negative sign it means that they decrease the value of the number of composting days in the expression and vice versa.

3.3.2 The Fisher-Snedecor Test

The Fisher-Snedecor test is a statistical hypothesis test, which permits to compare 2 variances by doing their ratio which must not exceed a certain theoretical value [17][18][19][20]. It depends on the differences between the observed measurements and the predicted values.

The comparison between the observed Fisher number and the one from the theoretical tables explains the regression of the composting time of the wastes y in xi (factors: quantities of minerals**).** In our case F_{obs}=200472 and F_{crit}=233.99 (F_{obs}>F_{crit}). This demonstrates that the proposed model is globally significant with a 95% chance of being realised.

4 Results, Analysing and Discussion

One sees from Figure 1 that the maximum deviation of wastes composting time between measuring values and theoretical value is 0.07% (for experiment 7: 180 days), while the minimum is 0.009% (for experiment 2: 30 days), compared to initial values. This is an insignificant deviations; the proposed model (4) is perfectly adapted to the measured values of wastes composting. The 6 other values are therefore between these 2 values.

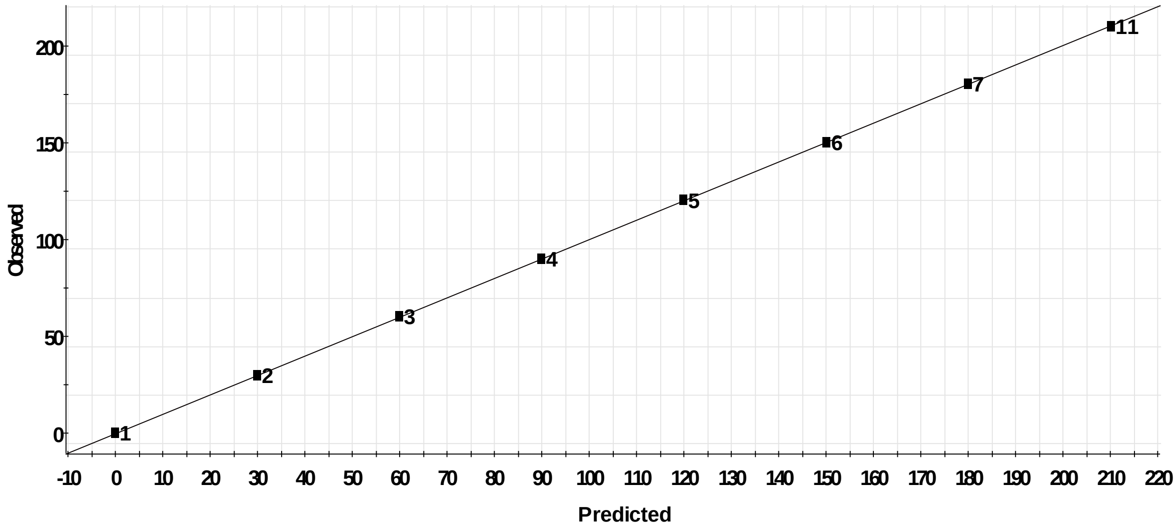


Fig. 1: Illustration of the deviations between observed and predicted model values

4.1 Response Surfaces and Contours of Wastes Composting Process

The graphs below in Figure 2 in the form of response surfaces and contours are graphic illustrations of the mathematical model (4). They show how the composting time is a function of the relative masses of the mineral elements in the compost (Potassium, Nitrogen and Phosphorus). The analysis is based on the formation time of the natural

fertilizer and its fermentation and fertilisation, keeping the quantities of these mineral plant nutrients acceptable because they tend to decrease (Table 1). In these graphs, the values of 2 elements K and N (in the ions form of NH^+ and NO_3^-) are introduced, while keeping the 3rd mineral P invariable at its minimum, medium and maximum values.

The response surfaces (3D graphs) and their projection (contours) are graphical representations illustrating according to the mathematical model (4) how the composting time in days varies according to the 3 parameters initially described.

The contour is a curvilinear line on which the number of days of composting stays the same; therefore, it is an iso-time in our case.

The negative values of the iso-lines are purely theoretical, they have no real meaning. The ideal is to have a very short composting time, i.e. to approach the "zero" iso line by changing the values of the 3 parameters, one of which remains stable and the 2 other are variable factors.

All 3 response surfaces have the same shape and aspect, they are convex downwards to the minimum point of curvature which shows that a minimum point of theoretically negative number of days of composting without physical significance is reached.

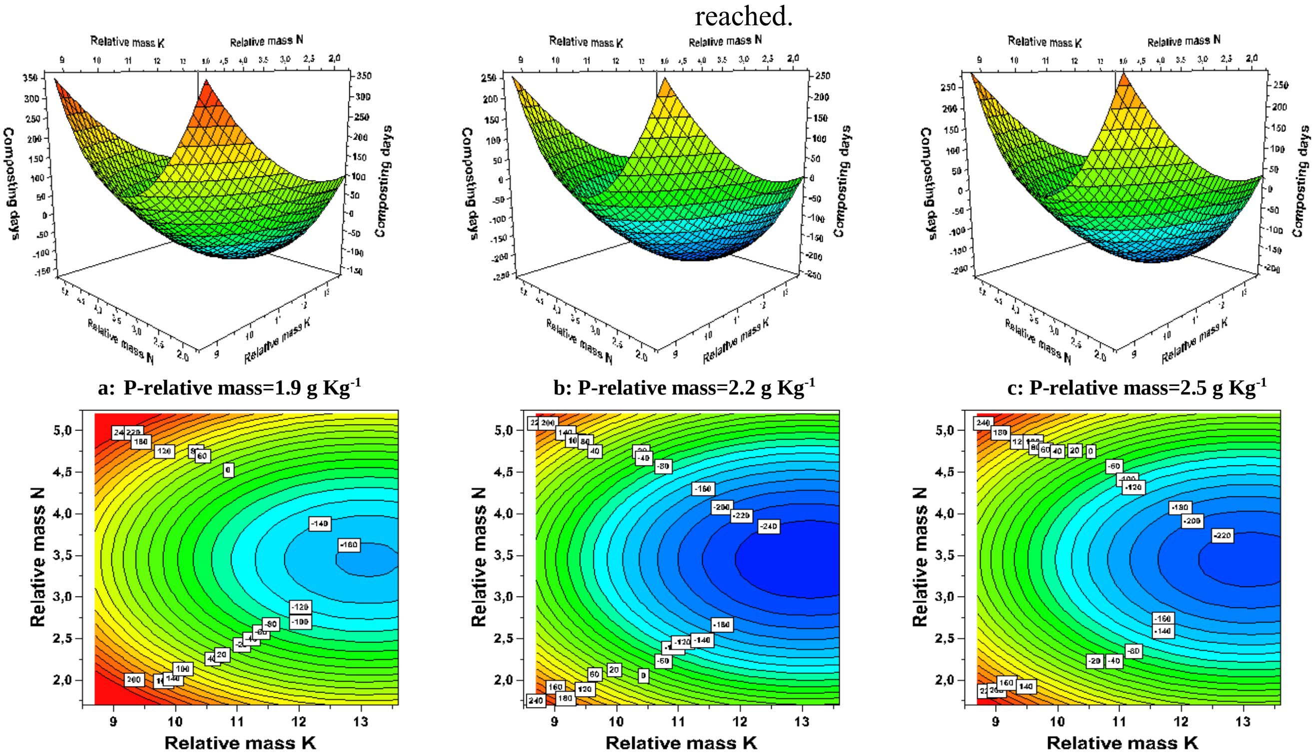


Fig. 2: Illustrative response surfaces and contours of model

It is evident that the representations given by the mathematical model in figure (2) show negative non-real values of the days number. These values are purely theoretical and therefore to be rejected. Therefore, the analysis of the composting process focuses on the positive values, i.e. beyond the zero contour.

4.1.1 For relative Masse of Phosphorus Equal at Minimal Value of 1.9 g kg^{-1}

In order to keep the potassium and nitrogen quantities high (close to the initial values recorded before composting), in the case where the relative mass of phosphorus is 1.9 g kg^{-1} (Figure 2-a), the number of days of fermentation must approach 99 days. Below and above this, the values of these 2 elements are lower than the desired maximum values. In this case, these are some predicted values by the model for the working field (Table 4).

Table 4. Predicted values of compost elements when phosphorus value is 1.9 g kg^{-1}

N°	P-quantities (g kg^{-1})	k-quantities (g kg^{-1})	N-quantities (mg g^{-1})	Composting days -
1			2.0	235
2			2.5	130
3			3.0	74
4		9.0	3.5	57
5			4.0	83

6			4.5	150
7			5.0	264
8			2.0	141
9			2.5	39
10	1.9	10.0	4.5	60
11			5.0	170
12			2.0	69
13			2.25	13
14		11.0	4.75	41
15			5.0	99
16		12.0	2.0	29
17			5.0	54
18		13.0	2.0	23
19			5.0	44

4.1.2 For Relative Masse of Phosphorus Equal at Mean Value of 2.2 g kg^{-1}

In this second case, where the relative mass of phosphorus is 2.2 g kg^{-1} (Figure 2-b), one notices that the elliptical contours have moved to the left compared to the first case; this means that the zero value contour delimits 2 small zones (contours in yellow and red colours), one at the top left, the other at the bottom left, where there is presence of phosphorus, potassium and nitrogen in the compost. The green and blue zones (Figure 2-b) are purely theoretical and are to be rejected because the number of days is negative. Table 5 shows the values predicted by model (4), where one sees that for the phosphorus relative mass of 2.2 g kg^{-1}, and from the relative potassium mass of 11 g kg^{-1}, it is impossible to predict the composting days giving real values of the 3 minerals.

Table 5. Predicted values of compost elements when phosphorus value is 2.2 g kg^{-1}

N°	P-quantities (g kg^{-1})	k-quantities (g kg^{-1})	N-quantities (mg g^{-1})	Composting days -
1			2.0	140
2			2.5	38
3		9.0	4.25	16
4	2.2		4.5	55
5			5.0	163
6			2.0	42
7		10.0	4.75	13
8			5.0	75

4.1.3 For Relative Masse of Phosphorus Equal at Maximal Value of 2.5 g kg^{-1}

In this situation, when the relative mass of phosphorus is maximum and equal to 2.5 g kg^{-1}, the contours (Figure 2-c) are in an intermediate position compared to the 2 previous cases since the area of composting days beyond the zero contour is lower than the case of 1.9 g kg^{-1}, but higher than 2.2 g kg^{-1}. In theoretical zone predicted by the mathematical model (4) below the zero-contour is relatively large and should be rejected because it is not a true representation of reality. Table 6 shows some predicted values of the number of composting days as function to the relative masses of the 3 plant nutrients in the natural fertiliser when the relative mass of phosphorus is 2.5 g kg^{-1}.

Table 6. Predicted values of compost elements when phosphorus value is 2.5 g kg^{-1}

N°	P-quantities (g kg^{-1})	k-quantities (g kg^{-1})	N-quantities (mg g^{-1})	Composting days -
1			2.0	170
2			2.5	68
3		9.0	3.0	8
4			4.0	16
5	2.5		4.5	85
6			5.0	199
7		10.0	2.0	76

8		5.0	104
9	11.0	2.0	8
10		5	37

Comparing the 3 studied situations, it is easy to see in case 3, that the relative masses of the mineral elements in the compost are very close to the initial state, since the values of 2.5 g kg^{-1}, 11.0 g kg^{-1}, and 5.0 mg g^{-1} respectively for phosphorus, potassium and nitrogen are maintained for only 37 days of composting (Table 6). This is considered as a results optimisation because the drop in relative masses of nutrient components is not very pronounced, and the number of composting days is relatively low. This time is already sufficient for the formation of potting soil.

4.2 Predicted Values of Composting Days with Particular Relative Masses of Plants Nutrients

Another analysis can be done, it is to see how composting days varies in relation to only one of the 3 factors in the model, while leaving the 2 other factors unchanged at the maximal, mean and minimal values.

Table 7. The 3 used parameters values for analysis of composting days

	Min value	Mean value	Max value
K	8.7	11.5	13.6
N	1.7	3.45	5.2
P	1.9	2.2	2.5

Table 7 shows the three used particular values for the 3 minerals (factors) (K, N, and P) which affect the days number of composting, i.e. the minimal, the mean and the maximal.

4.2.1 Composting Days with the K-variation

Firstly, the black curves in Figure 3 indicate the true change of the number of composting days described by the polynomial expression; the blue and red ones take into account the ±5% confidence interval. When one introduces in the mathematical model (4) the mean values (table 7) of K=11.5 g kg^{-1}, N=3.45 mg g^{-1} and P= 2.2 g kg^{-1} (figure 3-b) expressed in coded values, one notices that the days number of composting is negative. This is not real and remains purely theoretical values; this case is to be rejected. Figures 3-a (for minimal values of N and P) and 3-c (for maximal values of N and P) show that the relative mass of K remains high and equal to 13.6 g kg^{-1} at the beginning of the process. This is around 33 days of composting for the maximum values (Figure 3-c), and 99 days for the minimum values (Figure 3-a). It is clear that the case in Figure 3-c optimises the process with a high relative mass of potassium and a minimum days number of composting.

4.2.2 Composting Days with the N-variation

The same approach is done when one analyses the days number of wastes composting with the nitrogen change when introducing in the model the values of the 3 elements. Figure 4-a-b-c show how the composting days vary with increasing nitrogen.

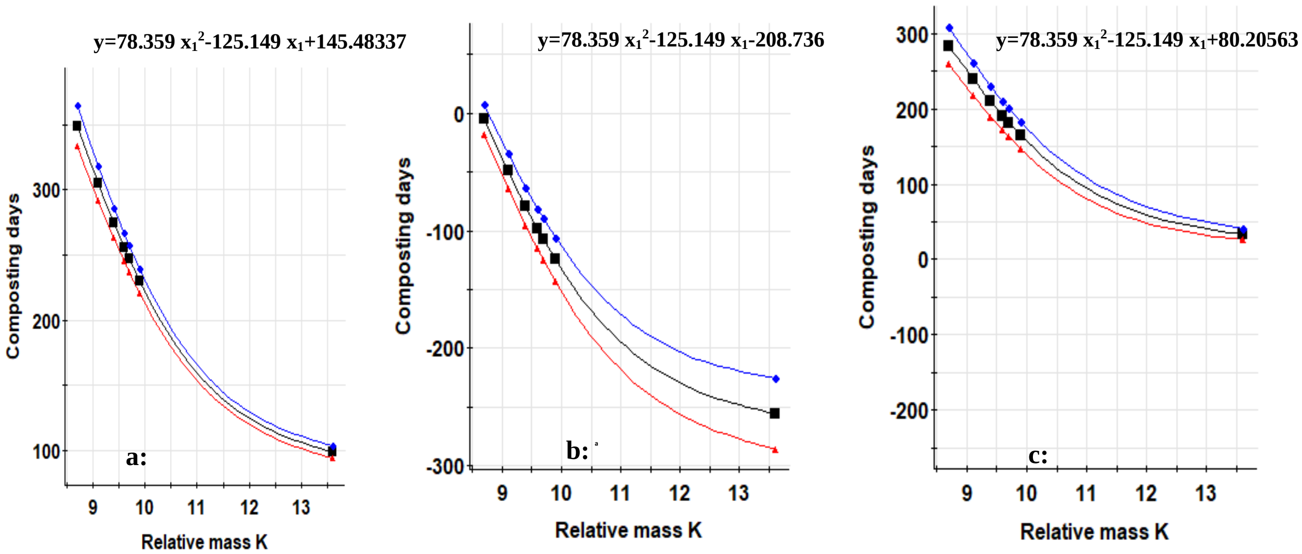
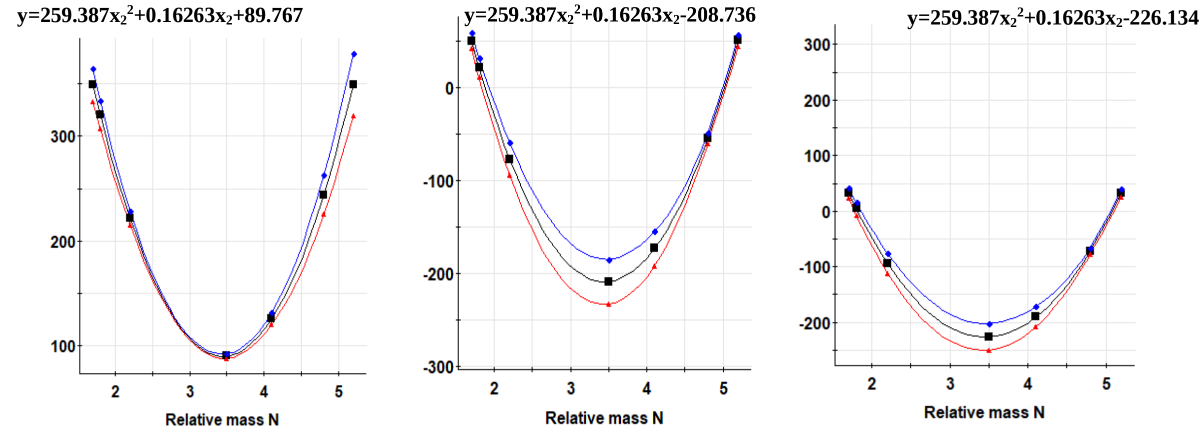


Fig. 3: Variation of composting days as a function of K-element under conditions of the 2 others (N and P)

For curves 4-b and 4-c, the theoretical values for the number of negative days, are far from the reality. Therefore, one analyses essentially the case of the variation of the composting days number as a function of nitrogen under the presence of the minimum values of P and K (table 7) (Figure 4-a).



a: b: c:

Fig. 4: Variation of composting days as a function of N-element under conditions of the 2 others (P and K)

When the minimum values of K = 8.7 g kg^{-1} and P = 1.9 g kg^{-1} (Table 7) act on the days number of composting as a function of the variation of nitrogen, the minimal relative mass of 3.48 mg g^{-1} of nitrogen is present when 90 days of composting is reached. On the other hand, the maximum value of 5.18 mg g^{-1} of nitrogen is theoretically reached after 350 days. Relative masses of nitrogen of 5.18 mg g^{-1} at 51 days and 5.18 mg g^{-1} at 34 days are present in the compost in the respective cases of mean (Figure 4-b) and maximal (Figure 4-c) values of potassium and phosphorus.

Under the influence of nitrogen and potassium in their minimum, mean and maximum values, the days number of composting changes according to the prediction of the mathematical model (4) differently. In the case of Figure 5-b, it can be seen again that the number of days is negative along the length of the measurement domain of the potassium quantity present in the compost. No real interpretation can be given; this remains a purely theoretical case. When the quantities of K and N have their minimum value (Figure 5-a), 2.5 g kg^{-1} of phosphorus is retained at 283 days of composting; this is considered as a very high number of days.

4.2.3 Composting Days with the P-variation

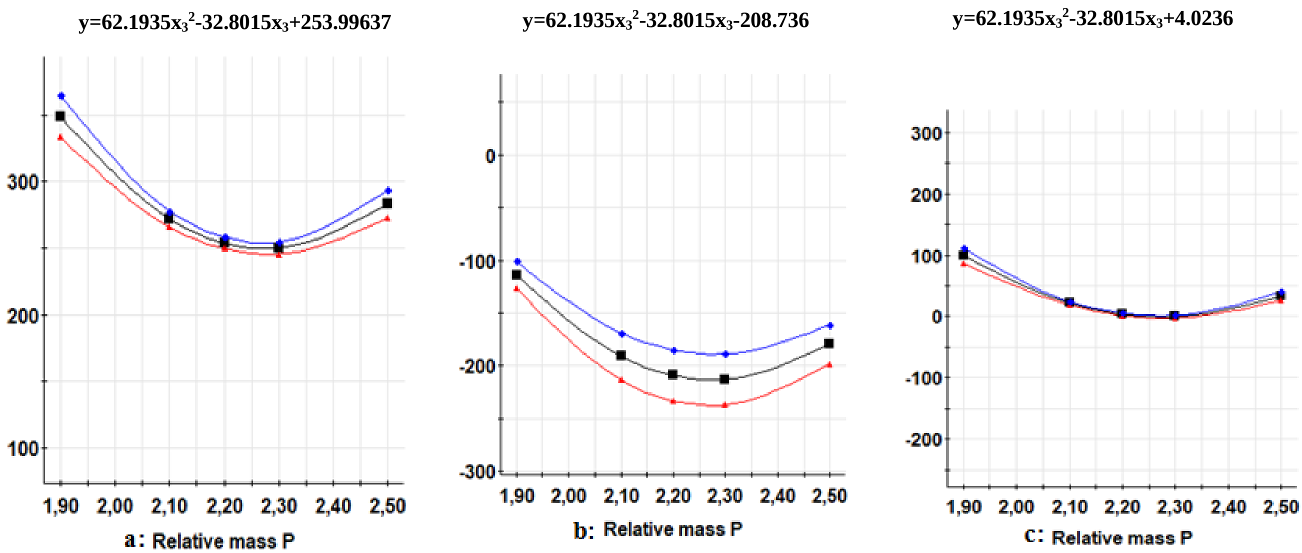


Fig. 5: Variation of composting days as a function of P-element under conditions of the 2 others (N and K)

However, when they reach their maximum value K=13.6 g kg^{-1}, N=5.2 mg g^{-1} (Figure 5-c), the quantity of phosphorus remains at 2.50 g kg^{-1} at only 34 days of composting; this is considered as a good result. Depending on the number of days of composting of the household waste, which degrades and then turns into a natural fertilizer only after 30 days of fertilisation, and depending on the action of each level of values of the elements K, N and P, the graphs predicted by the model in Figures 3, 4 and 5 are resumed in table 8 below:

Table 8. Summary of the predicted compost elements values according to 3 categories

Values of components	Value of K and composting days	Value of N and composting days	Value of P and Composting days
K_{min} – N_{min} - P_{min}	13.6 g kg^{-1} - 99 days	5.18 mg g^{-1} - 350 days	2.5 g kg^{-1} - 283 days
K_{moy} – N_{moy} - P_{moy}	-	5.18 mg g^{-1} - 51 days	-
K_{max} – N_{max} - P_{max}	13.6 g kg^{-1} - 33 days	5.18 mg g^{-1} - 34 days	2.5 g kg^{-1} - 34 days

Table 8 can be expanded and replenished indefinitely with values of K, N and P taken from the experimental design domain in a haphazard and disordered manner because the software is user-friendly and can predict an infinite number of composting days based on the mathematical model (4) . However, our choice is made on simultaneous minimum, average and maximum values taken for the 3 elements K, N and P to show how the number of predicted days varies when the experiment has not been done with these values.

4.2.4 Comparative Study

Comparing the 3 cases in Figure 2, where a change in phosphorus mass from 1.9 g Kg^{-1} to 2.5 g Kg^{-1}, it can be seen that case (a) where P-relative mass=1.9 g Kg^{-1} is more descriptive than the other 2 and is close to the actual values for 2 essential reasons: The first is that the area of positive composting days between 0 and 240 days is larger than the other two cases, which improves the prediction of the values not obtained by experimentation. The second is that the extreme values of negative composting days that are rejected as not reflecting reality is only -160 days in case (a) while the other two are respectively -240 days and - 220 days, which enlarges the theoretical zone that does not describe composting.

5 Conclusion

The study carried out through the different analyses illustrated by graphs and tables has sought to keep the relative masses of the compost nutrients initially existing before decomposition and fertilisation of the wastes in their maximum values. In addition to the interaction between the formations of these elements, they tend to decrease with the days number in the process. However, it is also necessary to allow the formation of potting soil after the waste has decomposed without rotting by controlling humidity and temperature. These 2 parameters are inversely proportional, the number of days activates the formation of fertilizer, but decreases the relative masses of these minerals. There is therefore a choice to do and a consensus to reach on the values to chosen according to the importance of each element in the plant nutrition. There remains the composting time, the duration of which must take into account. It is obvious that it is greater, the risk that the components values decrease. Then the compost availability takes

a longer time. However, modern methods can achieve retention of K, N and P losses and eliminate the odours of NH_3 and N_2O by introducing physical, chemical and microbial additives. This is a separate study to be carried out. This study using non-conventional experimental design modelling is used for the first time in this field of composting and gives very satisfactory results; the fact of predicting a composting time without any additional costly and time-consuming experiments makes this work different from the results of other works and differentiates it from other models.

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