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Simulation of Carbon Dioxide Production during Composting of Agro-Wastes

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ABSTRACT

Carbon dioxide production during composting of agro-waste can be taken as the indicator of rate, progress and termination of compost phenomenon and stabilization of organic matter, leading to a balanced compromise between complexity of mathematical model and extensive experimentation. Modeling and simulation of composting of agro-wastes based on experimentally measured carbon dioxide production would reduce the experimental effort, time, and other physical resources in design of optimized compost process for disposal of agro-waste. In this study modeling and simulation of composting of a mixture of agro-wastes like sugarcane bagasse, soya husk, wood straw, mixed with food waste is presented. This approach requires estimates of initial values of different carbon fractions. The effect of such estimates on prediction of carbon dioxide production is also studied in this work.

Key words: *composting; agro-waste; modeling; carbon dioxide evolution*

LIST OF SYMBOLS

x_1	easily biodegradable carbon fraction in substrate,
x_2	moderately biodegradable carbon fraction in substrate,
x_3	difficult biodegradable carbon fraction in substrate,
x_4	carbon fraction in aqueous media,
x_5	carbon in the form of carbon dioxide produced from aqueous media,
K_1	reaction rate for hydrolysis of easily biodegradable carbon fraction
K_2:	reaction rate for hydrolysis of moderately biodegradable carbon fraction
K_3	reaction rate for hydrolysis of difficult biodegradable carbon fraction
K_4	reaction rate for mineralization of aqueous carbon fraction

1. INTRODUCTION

Composting of agro-waste being a complex process, while developing mathematical models to describe this process, adequate emphasis should be given to both model complexity as well as accuracy of experimental data. Therefore, the focus should be to model the process with key parameters requiring simpler experimentation, capable of giving accurate data. Many mathematical models have been proposed for composting of agro-waste in published literature. Higgins and Walker (2001) proposed a model for aerobic organic solid decomposition, with simulations with substrate specific kinetics. The deviations of predicted results from experimentally determined values were attributed to existence of heterogeneous composition of substrate, as against homogenous composition assumed in the model. Briski et al. (2003 a) and Briski et al. (2003 b) reported aerobic composting of tobacco solid waste with the objective of stabilizing this waste. The mathematical model was developed with the assumptions that oxygen concentration was practically equal at all the points inside the experimental bioreactor, the compost process was adiabatic, air flow rate was constant, humidity was constant, composting rate was expressed as degradation of the dry substrate, and biodegradation rate was uniform all over the substrate bed. Hamelers (2004) has presented a review of approaches for modeling of composting kinetics. It is stated in this work that compost modeling is in general characterized as inductive, data is starting point which determines the type of model used. It is argued that such inductive approach has reached its potential in design and development of optimized compost facilities as per the stringent demands of the latest regulations. Limitations of measurement techniques and magnitude of resources required for collection of experimental data are also major drawbacks of such approaches. Kulcu and Yaldiz (2004) reported determination of aeration rate and kinetics of composting of agro-wastes. This study was aimed to determine aeration rate and its kinetics in aerobic composting of mixture of grass trimmings, tomato, pepper and eggplant wastes. Carbon dioxide rate and temperature changes were recorded along with moisture content, pH, and organic matter each day. Komilis (2006) carried out kinetic

analysis of aerobic solid waste composting of food waste, mixed paper, yard waste, leaves, branches, and grass clippings under optimal conditions. Mineralizable solid carbon was assumed to comprise readily, moderately, and slowly hydrolysable carbon fractions. Progress of composing process was evaluated by measuring carbon dioxide production. Nakayama et al. (2007) presented a numerical model of composting process with aeration. Bueno et al. (2008) reported that a second order polynomial mode consisting of four independent process variables (time, moisture, aeration, and particle size) was found to accurately describe the composting process. Baptista et al. (2010) discussed composting kinetics in full-scale mechanical-biological treatment plants. The salient characteristics of the model were first-order kinetics, use of correction factor for temperature, use of correction factor for oxygen, correction factor for moisture content, correction factor for free air space, and initial biodegradable volatile solids content.

Carbon dioxide production during composting of agro-waste can be taken as the indicator of rate, progress and termination of compost phenomenon and stabilization of organic matter, leading to a balanced compromise between complexity of mathematical model and extensive experimentation. Modeling and simulation of composting of agro-wastes based on experimentally measured carbon dioxide production would reduce the experimental effort, time, and other physical resources in design of optimized compost process for disposal of agro-waste. In this study modeling and simulation of composting of a mixture of agro-wastes like sugarcane bagasse, soya husk, wood straw, mixed with food waste is presented. This approach requires estimates of initial values of different carbon fractions. The effect of such estimates on prediction of carbon dioxide production is also studied in this work.

2. MODELING AND SIMULATION

In the mechanism of aerobic decomposition of agricultural solid waste hydrolysis forms the first stage as a result of which the biodegradable components of solid waste eventually enter into aqueous media. The hydrolysis rate of a particular component depends upon its micro structure defined by binding of cellulose by compounds like hemicelluloses and lignin. The degradation of cellulose by microbes takes place after breaking of the protective layers. Cellulose decomposes to glucose and hemicelluloses to arabinose, mannose, xylose, glucose different types of sugars, alcohols, organic acids like amino acids etc. These products of decomposition of cellulose and hemicelluloses are water soluble and therefore enter the aqueous media during decomposition. A part of carbon delivered to aqueous media after hydrolysis is then converted into carbon dioxide. Remaining carbon is retained by the humus substance, which is the final stabilized produce of bio-degradation of organic agro-waste. A schematic presentation of the phenomenon described above is shown in Figures 1 and 2 (Tripathi and Srivastava).

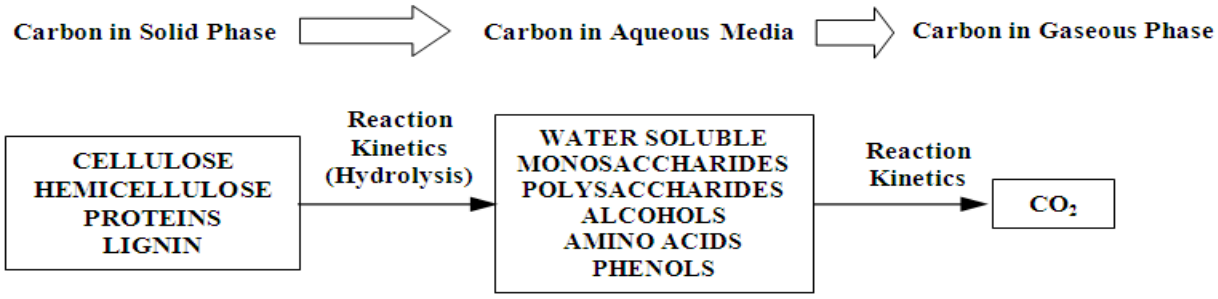

Figure 1. Pathway of Carbon during Composting of Agro-Waste

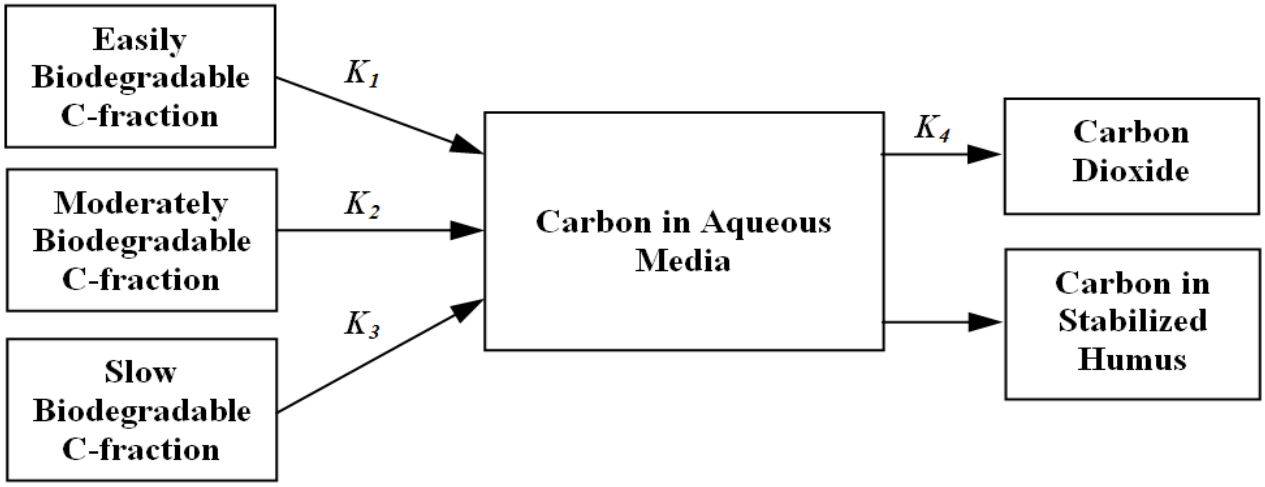

Figure 2. Compost Model for Agro-Waste

According to the rate at which a particular biodegradable component hydrolyses into aqueous carbon, it can be categorized as easily hydrolysable, moderately hydrolysable, or difficult to hydrolyze. Agro-wastes like sugarcane bagasse, soya husk, and wood stock contain all such components in different proportions. Food waste was used in this work to initiate and support the decomposition during the initial stages, to support sufficient growth of micro-organisms takes place to continue decomposition of agro-waste components of substrate.

The reaction kinetics of the process is defined by the system of simultaneous differential equations (1) to (5)

$$\frac{dx_1}{dt} = -K_1.x_1 \quad (1)$$

$$\frac{dx_2}{dt} = -K_2.x_2 \quad (2)$$

$$\frac{dx_3}{dt} = -K_3.x_3 \quad (3)$$

$$\frac{dx_4}{dt} = -K_1.x_1 + K_2.x_2 + K_3.x_3 - K_4.x_4 \quad (4)$$

$$\frac{dx_5}{dt} = K_4.x_4 \quad (5)$$

The analytical solution of simultaneous differential equations (1) to (5) gives the following set of equations:

$$x_1 = x_1(0)\, e^{-k_1 t} \quad (6)$$

$$x_2 = x_2(0)\, e^{-k_2 t} \quad (7)$$

$$x_3 = x_3(0)\, e^{-k_3 t} \quad (8)$$

$$x_4 = x_4(0).e^{-k_4 t} + x_1(0)K_1 \frac{e^{-k_1 t} - e^{-k_4 t}}{K_4 - K_1} + x_2(0)K_2 \frac{e^{-k_2 t} - e^{-k_4 t}}{K_4 - K_2} + x_3(0)K_3 \frac{e^{-k_3 t} - e^{-k_4 t}}{K_4 - K_3} \quad (9)$$

$$\begin{aligned} x_5(t) = {} & x_1(0)\left[1 + \frac{K_4}{K_1 - K_4}\, e^{-k_1 t} - \frac{K_1}{K_1 - K_4}\, e^{-k_4 t}\right] \\ & + x_2(0)\left[1 + \frac{K_4}{K_2 - K_4}\, e^{-k_2 t} - \frac{K_2}{K_2 - K_4}\, e^{-k_4 t}\right] \\ & + x_3(0)\left[1 + \frac{K_4}{K_3 - K_4}\, e^{-k_3 t} - \frac{K_3}{K_3 - K_4}\, e^{-k_4 t}\right] \\ & + x_4(0) - x_4(0)\, e^{-k_4 t} + x_5(0) \end{aligned} \quad (10)$$

The model uses many parameters for prediction of carbon dioxide production, which are as follows:

- Initial easily biodegradable carbon fraction,
- Initial moderately biodegradable carbon fraction,
- Initial difficult biodegradable carbon fraction,
- Initial carbon fraction in aqueous media,
- Reaction rate of easily biodegradable carbon fraction
- Reaction rate of moderately biodegradable carbon fraction
- Reaction rate of difficult biodegradable carbon fraction
- Reaction rate of mineralization of aqueous carbon fraction

3. RESULTS AND DISCUSSIONS

In this section a preliminary simulation of carbon dioxide production is presented, using arbitrarily selected values of the various parameters, to get the simulation results close to the experimentally determined carbon dioxide production. The conversion rate for aqueous carbon to carbon dioxide is assumed to be very large compared to the rates of hydrolysis of easily and moderately hydrolysable carbon fractions. Also, the hydrolysis rate of difficult to hydrolyze carbon fraction is considered to be very small compared to these rates. These assumptions are made to simplify the model by reducing the number of initially unknown parameters. The values of parameters for different trials are given in Table 1.

Table 1. Data Sets for Different Trials

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11	Trial 12
Initial Aqueous Carbon Fraction	0	0	0	0	0	0	0	0	0	0	0	0
Initial Easily Hydrolysable Carbon Fraction	100	100	150	150	200	200	100	100	125	125	125	125
Initial Moderately Hydrolysable Carbon Fraction	100	100	150	150	200	200	200	200	250	250	225	225
Initial Difficult to Hydrolyze Carbon Fraction	410	410	310	310	210	210	310	310	235	235	260	260
Reaction Rate of Easily Hydrolysable Carbon Fraction	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Ratio of Reaction Rates	20	10	20	10	20	10	20	10	20	10	20	10
Reaction Rate of Moderately Hydrolysable Carbon Fraction	0.045	0.09	0.045	0.09	0.045	0.09	0.045	0.09	0.045	0.09	0.045	0.09
Total Carbon	610	610	610	610	610	610	610	610	610	610	610	610

The value of initial aqueous carbon is taken as zero because carbon enters the aqueous media only after hydrolysis of the different carbon fraction begins. Total carbon content is 610 gC/kg substrate in all the trials, as measured experimentally. In Trial 1 the ratio of reaction rates of easily hydrolysable carbon fraction to reaction rate of moderately hydrolysable carbon fraction is taken as 20 based on data available in published literature. The values of initial easily hydrolysable carbon fraction and moderately hydrolysable carbon fraction are taken as 100 gC/kg substrate each. The results of simulation are shown in Figure 3. The total carbon dioxide production is much lower than experimentally determined values. In Trial 2 the ratio of reaction rates is reduced to 10. Figure 4 shows the results of simulation and in this case also the total carbon dioxide production is much below the experimental values. In Trial 3 the values of initial easily hydrolysable carbon fraction and moderately hydrolysable carbon fraction are increased to 150 gC/kg substrate each. The ration of reaction rates is taken as 20. Figure 5 shows the results of simulation. The total carbon dioxide production has come closer to the experimental values. In Trial 4 the ratio of reaction rates is reduced to 10. Figure 6 shows the results of simulation. The total carbon dioxide production was found to increase faster than the experimental values but becomes constant at about 35 days and remains lower than the experimental values. In Trial 5 the values of initial easily hydrolysable carbon fraction and moderately hydrolysable carbon fraction are taken as 200 gC/kg substrate each and ratio of reaction rates is taken as 20.

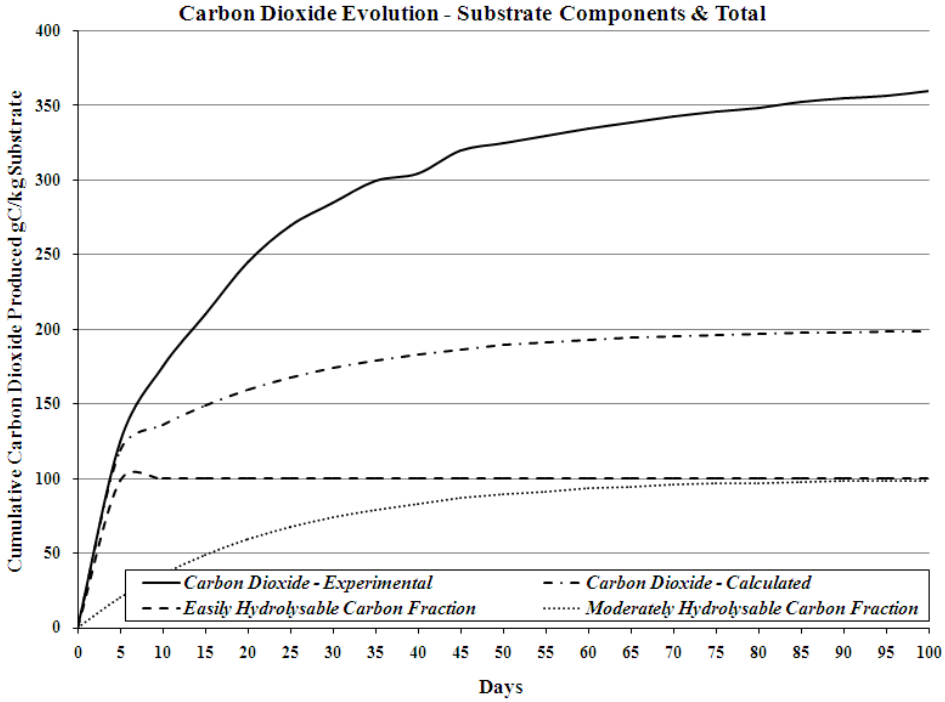

Figure 3. Results of Simulation of Carbon Dioxide Production – Trial 1

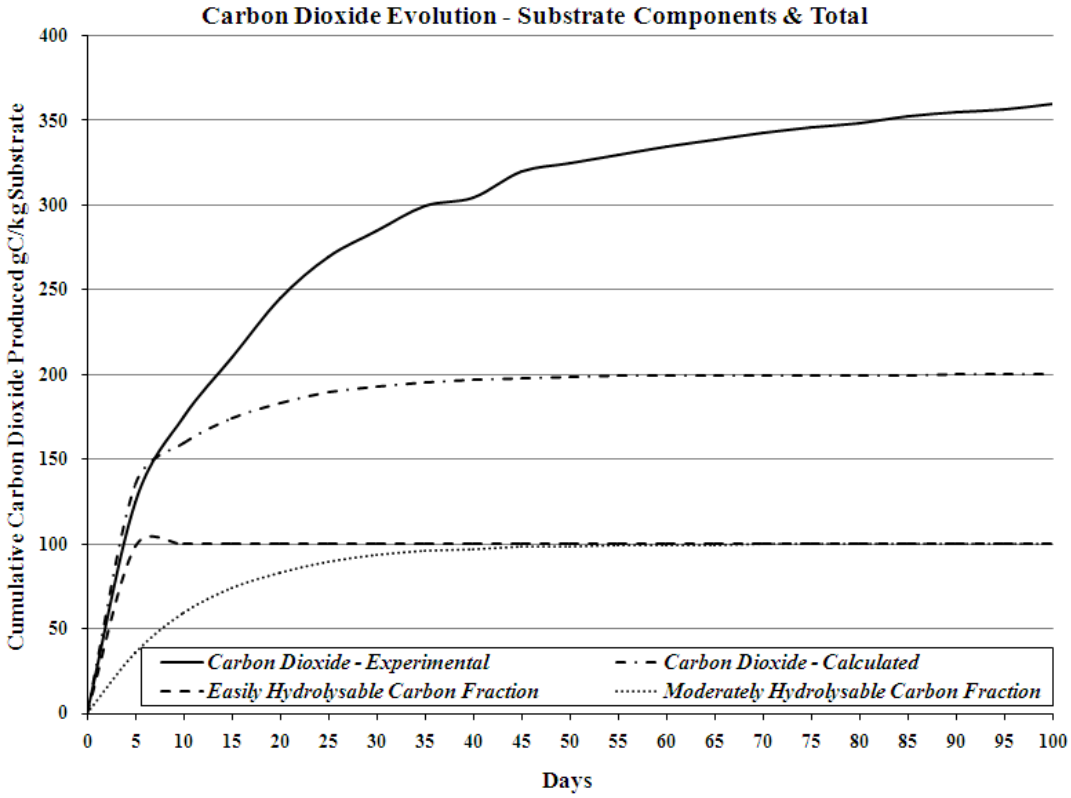

Figure 4. Results of Simulation of Carbon Dioxide Production – Trial 2

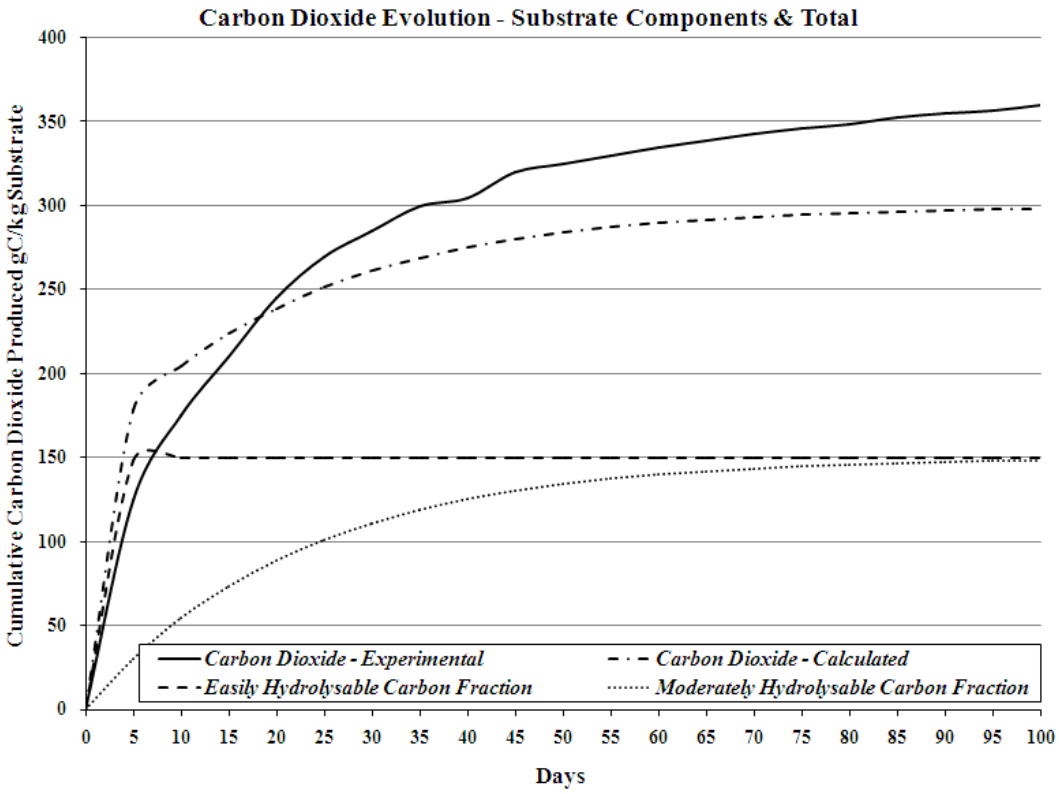

Figure 5. Results of Simulation of Carbon Dioxide Production – Trial 3

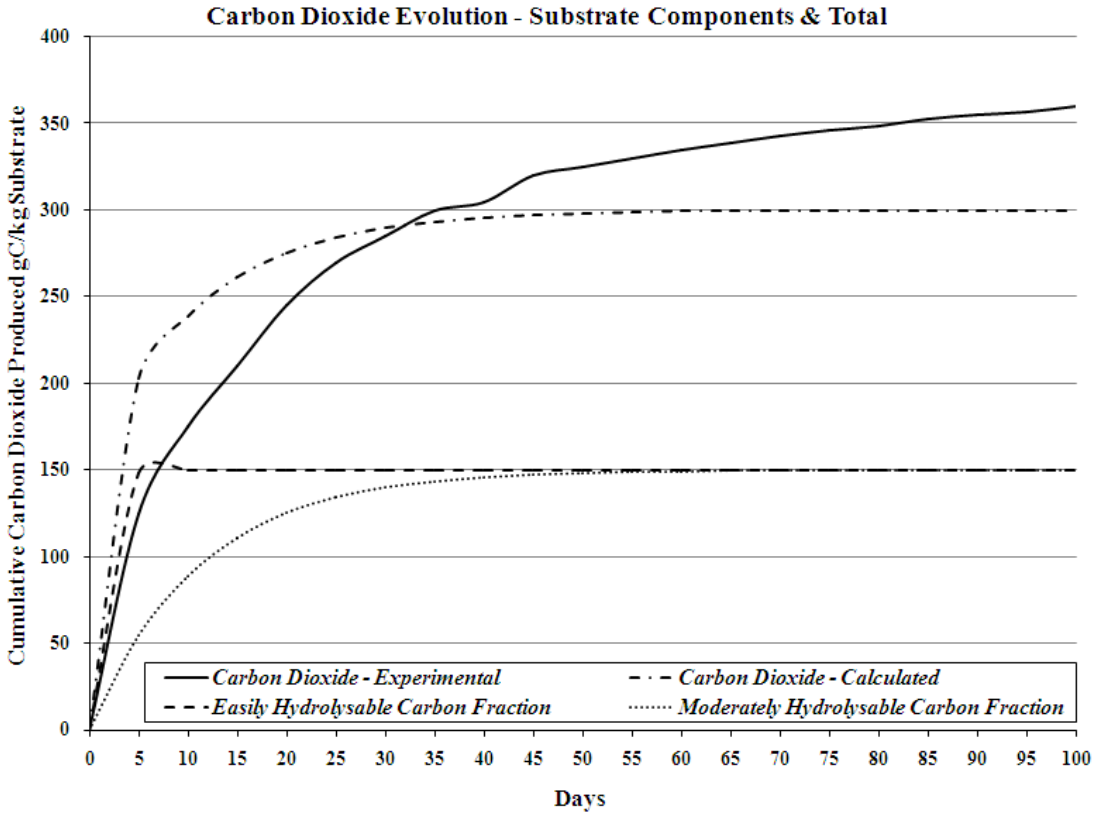

Figure 6. Results of Simulation of Carbon Dioxide Production – Trial 4

Figure 7 shows the results of simulation. The results of simulation are much higher than the experimental values. In Trial 6 the ratio of reaction rates was reduced to 10. Figure 8 shows the results of simulation. The results of simulation were found to be even higher than those in Trial 5. Also, the rate of production of carbon dioxide was found to be high in the initial period but the total carbon dioxide production became constant after about 30 days. In both Trial 5 and Trial 6 the results of simulation were higher than experimental values for the entire duration of compost period. In Trial 7 the value of initial easily hydrolysable carbon fraction was taken as 100 gC/kg substrate and initial value of moderately hydrolysable carbon fraction was taken as 200 gC/kg substrate. The ratio of reaction rate was taken as 20.

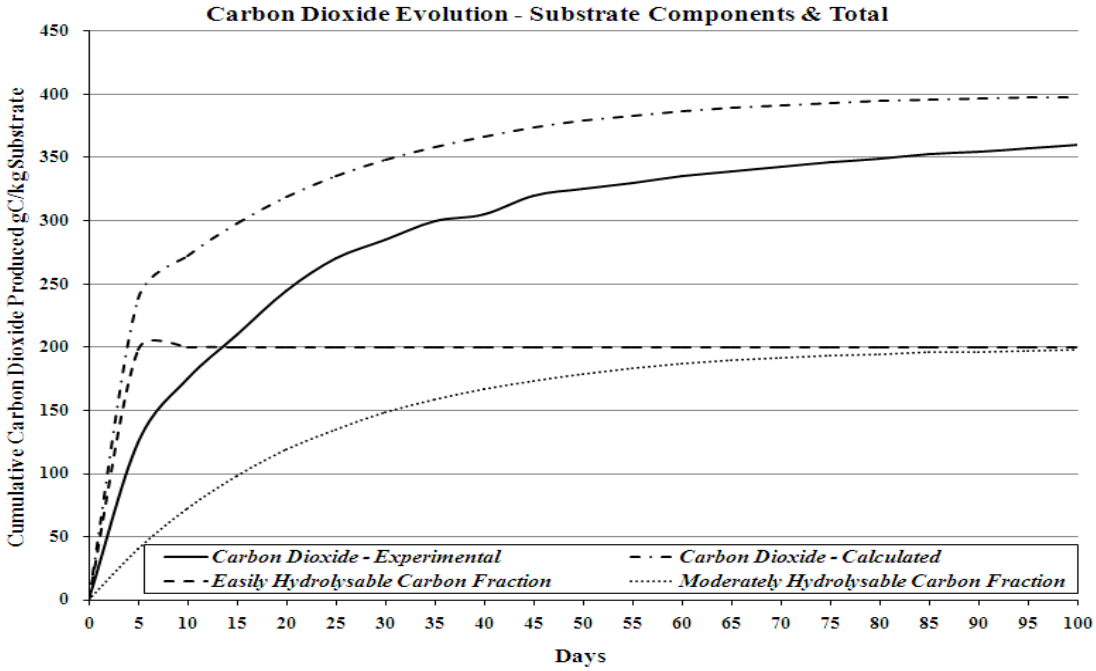

Figure 7. Results of Simulation of Carbon Dioxide Production – Trial 5

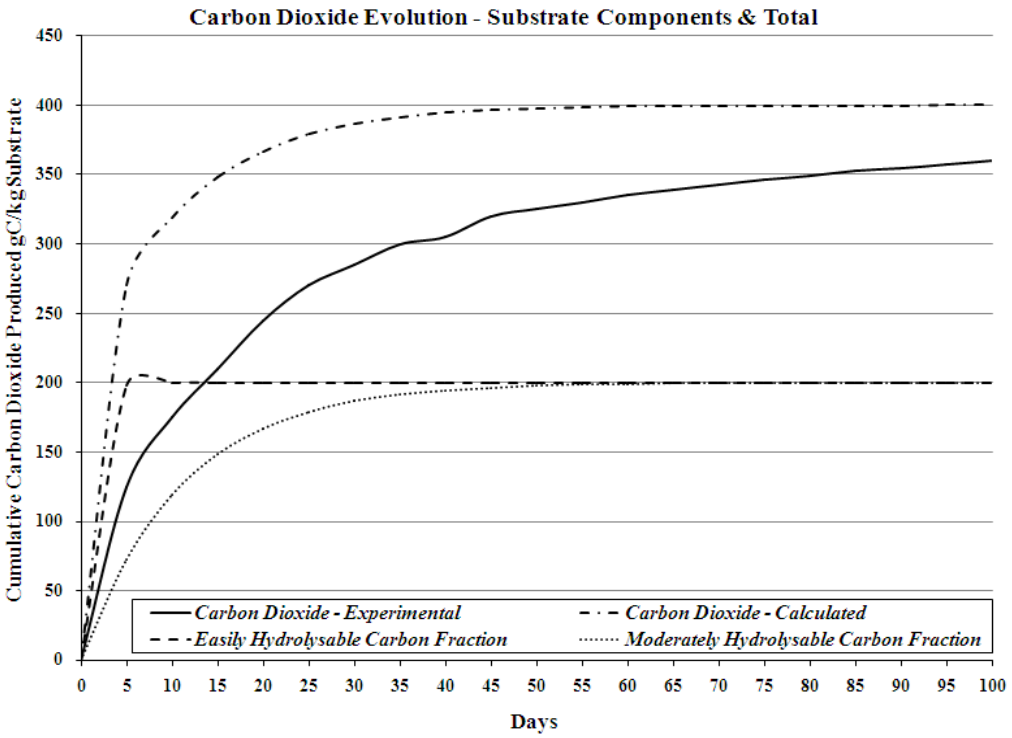

Figure 8. Results of Simulation of Carbon Dioxide Production – Trial 6

Figure 9 shows the results of simulation. Here the predicted carbon dioxide production remained lower than the experimental values for the entire duration of composting but kept rising almost up to the end of compost period. In Trial 8 the ratio of reaction rates was reduced to 10. Figure 10 shows the results of simulation. The predicted cumulative total carbon dioxide production was found to increase rapidly in the initial phase but became constant after about 35 days. In the initial phase the predicted values were higher than experimental values but were lower than experimental values in the later part of compost process. In Trial 9 the value of initial easily hydrolysable carbon fraction was taken as 125 gC/kg substrate and initial value of moderately hydrolysable carbon fraction was taken as 250 gC/kg substrate. The ratio of reaction rates was taken as 20.

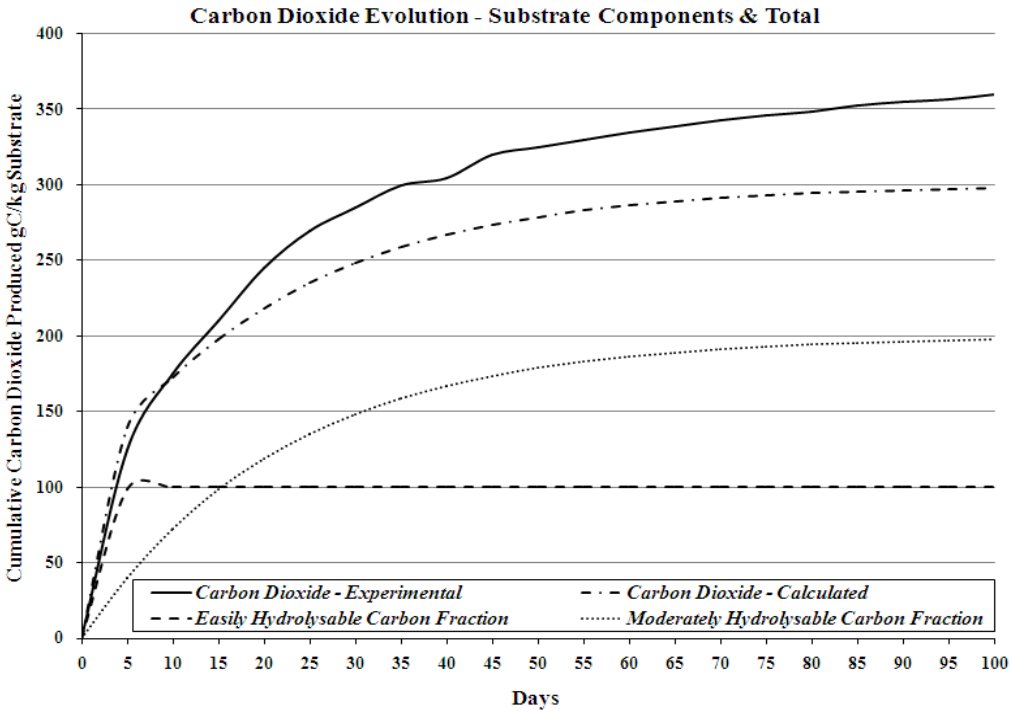

Figure 9. Results of Simulation of Carbon Dioxide Production – Trial 7

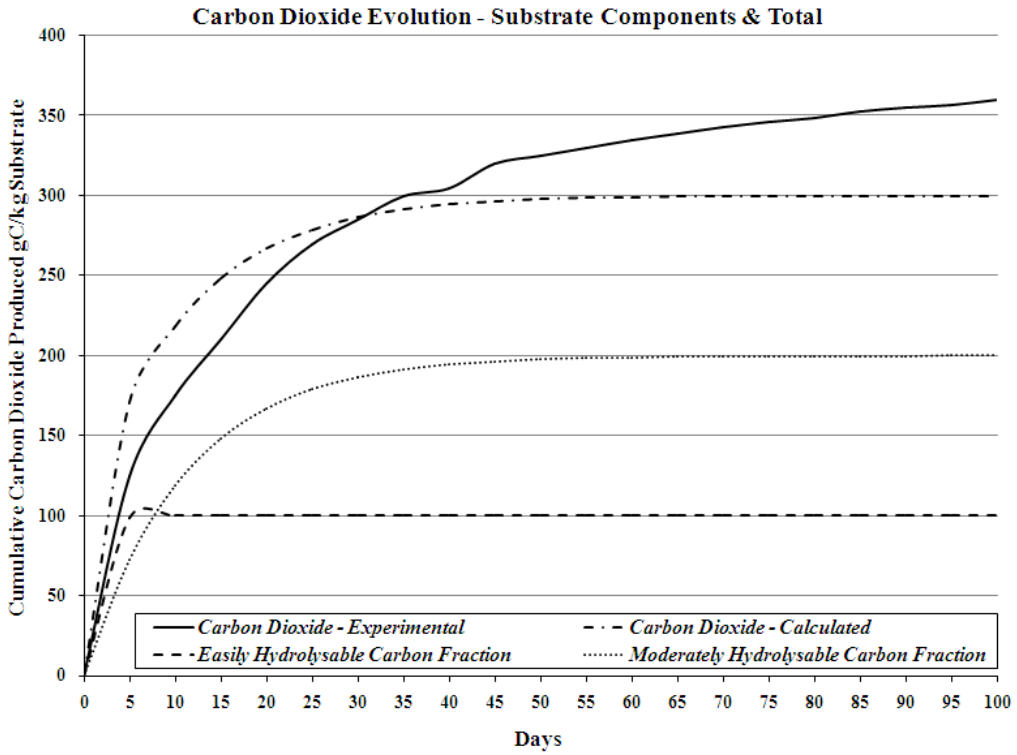

Figure 10. Results of Simulation of Carbon Dioxide Production – Trial 8

Figure 11 shows the results of simulation. The predicted cumulative carbon dioxide production was higher than experimental values for the entire duration of compost process, but was closer to it compared to previous trials. Also the predicted curve kept increasing continuously almost till the end of compost process. In Trial 10 the ratio of reaction rates was reduced to 10. Figure 12 shows the results of simulation. Here the predicted carbon dioxide increased rapidly in the initial phase of compost process and became constant after about 30 days. The predicted results were higher than those in Trial 9. In Trial 11 the value of initial easily hydrolysable carbon fraction was taken as 125 gC/kg substrate and initial value of moderately hydrolysable carbon fraction was taken as 225 gC/kg substrate. The ratio of reaction rates was taken as 20. Figure 13 shows the results of simulation. It was observed that the predicted cumulative carbon dioxide was slightly higher than experimental results in the initial period but thereafter the two were very close. In Trial 12 the ratio of reaction rates was reduced to 10.

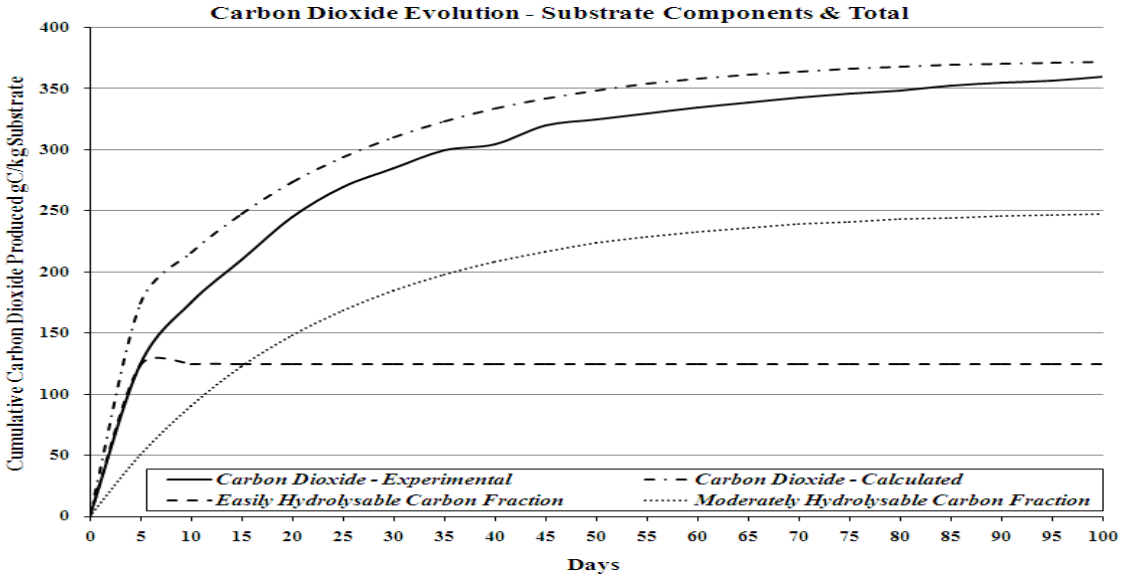

Figure 11. Results of Simulation of Carbon Dioxide Production – Trial 9

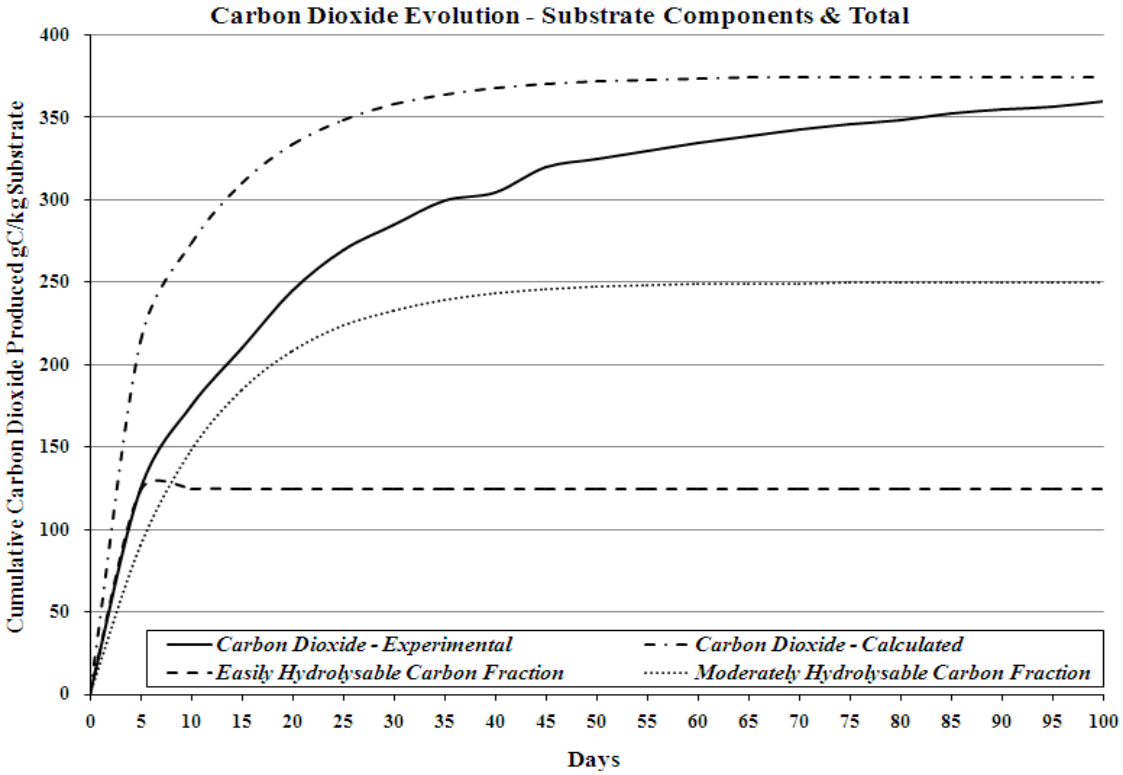

Figure 12. Results of Simulation of Carbon Dioxide Production – Trial 10

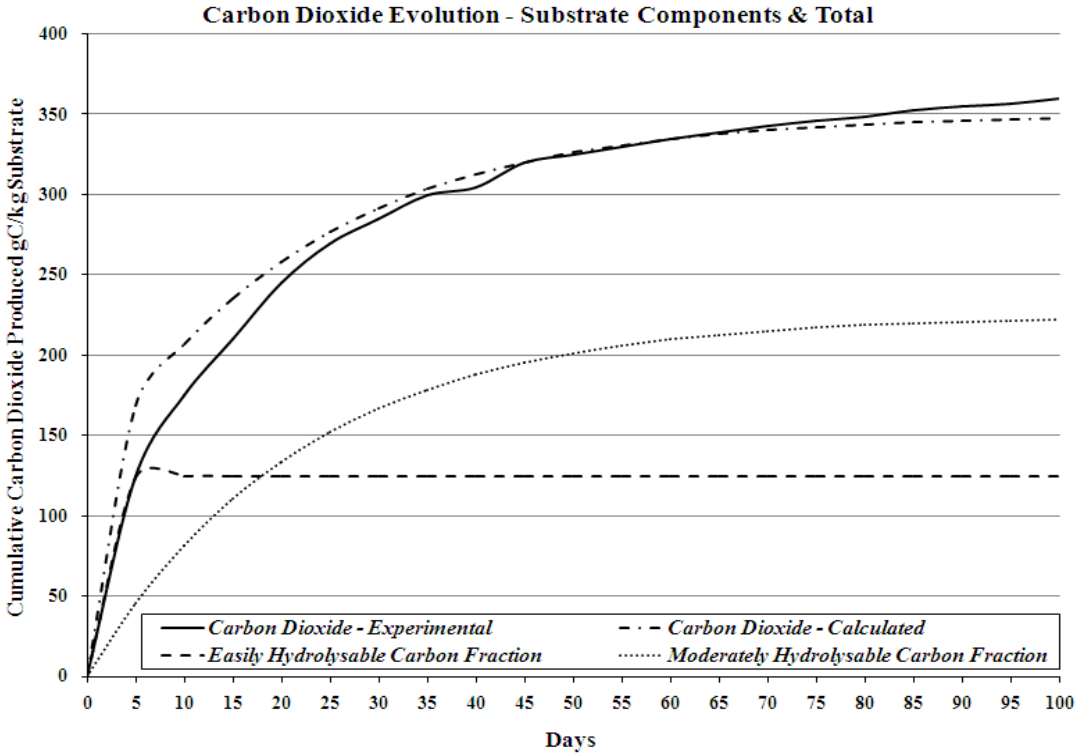

Figure 13. Results of Simulation of Carbon Dioxide Production – Trial 11

Figure 14 shows the results of simulation. The predicted cumulative carbon dioxide was found to increase rapidly in the initial phase and became constant at about 30 days. The results were not close to experimental values. Thus, it was observed that the best matching results were obtained in Trial 11, but these results were not very satisfactory. It is however observed that the ratio of reaction rates of 20 gives a smoothly increasing prediction of cumulative carbon dioxide production, similar to the experimental

results. Therefore this finding may be used in further modeling and simulation of the compost process.

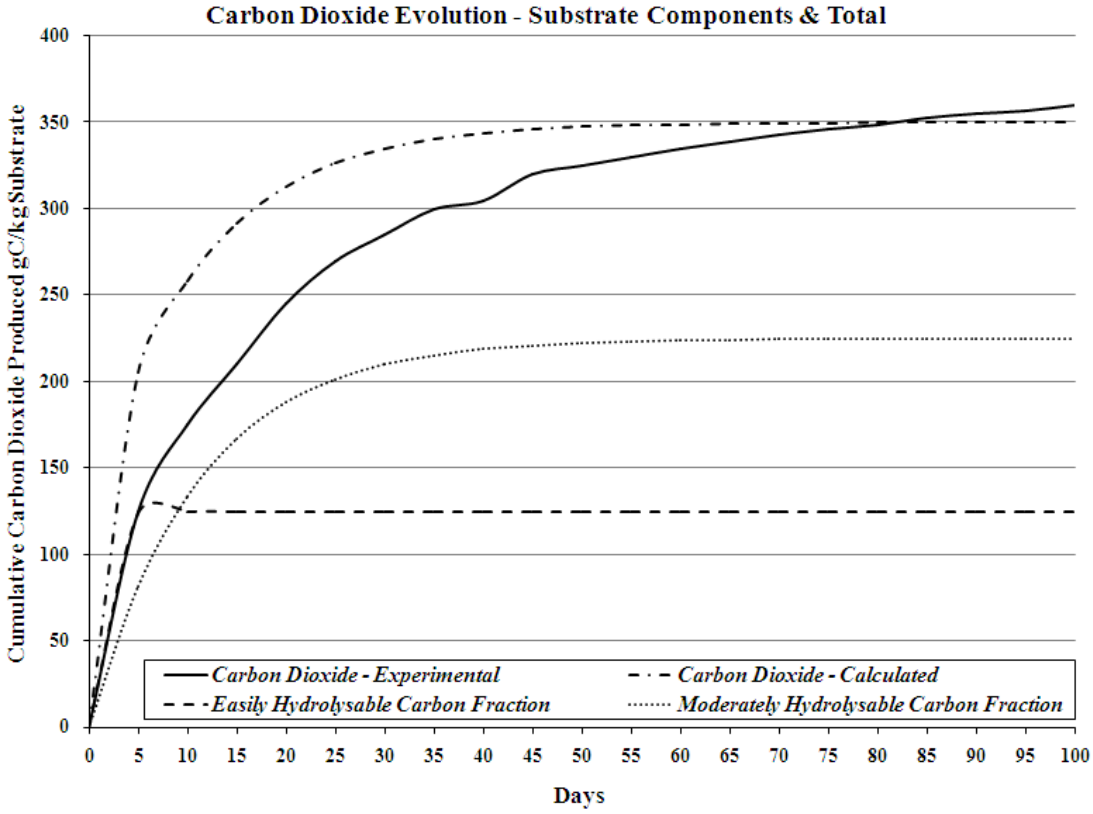

Figure 14. Results of Simulation of Carbon Dioxide Production – Trial 12

4. CONCLUSION

In this study modeling and simulation of composting of a mixture of agro-wastes like sugarcane bagasse, soya husk, wood straw, mixed with food waste is presented. This approach requires estimates of initial values of different carbon fractions. The effect of such estimates on prediction of carbon dioxide production is also studied in this work. Thus, it was observed that the best matching results were obtained in Trial 11. It is also observed that the ratio of reaction rates of 20 gives a smoothly increasing prediction of cumulative carbon dioxide production, similar to the experimental results. Therefore this finding may be used in further modeling and simulation of the compost process. Other techniques like neural networks may provide better predictions of carbon dioxide.

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