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Composting of Tobacco Dust in Different Types of Reactors

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A pilot-scale reactor composting of tobacco dust was conducted to determine the feasibility of composting, nicotine removal and effect of intermittent stirring on the composting performance. Two experiments were carried out in a 240 dm^3 packed bed reactor at airflow rate of 0.65 dm^{3}min^{-1}kg$_{VSinitial}$$^{-1}$; without stirring (PBR$_{NS}$); with periodical stirring (PBR$_S$). The third experiment was conducted in a 200 dm^3 horizontal reactor with stirrers (HR$_S$) at air flow-rate of 0.38 dm^{3}min^{-1} kg$_{VSinitial}$$^{-1}$. Substrate was automatically agitated every 24 hours for 1 minute at 6.3 rpm.

Nicotine was not detected in composting products and nicotine degrading bacteria *Pseudomonas fluorescens/putida* was isolated during the process. At the end of the processes in PBR$_{NS}$, PBR$_S$ and HR$_S$ conversions of the volatile matter were 50.6 % (at day 38), 53.0 % (at day 28) and 51.1 % (at day 29), respectively, suggesting that stirring increases the degradation rate of the selected substrate.

Key words:
Composting, tobacco dust, horizontal reactor, packed bed reactor, stirring

Introduction

Composting has become increasingly popular in the past decade as a biological treatment process of organic solid wastes, and it is an acceptable solution for reducing the volume of bulky solid waste and stabilizing waste material in the form of compost. Solid wastes originating from the food processing and agricultural industries are suitable substrates for composting.[2,3,4] Successful composting requires meticulous attention to key parameters, e.g. moisture content (*MC*), air supply, temperature, *pH* and carbon to nitrogen ratio (*C/N*) of the composting material.[1,3,5,6] Among other factors, *MC* has been referred to as the critical design and operating factor for the optimization of compost systems, because decomposition of organic matter depends on the presence of moisture to support microbial activity.[7] Optimum moisture requirements for successful composting of a wide variety of organic wastes range from 25 to 80 %, and the range should be determined for each specific waste material.[8]

Organic fraction of solid waste can be composted either in nonreactor system or reactor system.[6,9] Windrow and pile (nonreactor) systems usually include periodic turning/mixing in order to assure oxygen supply to all parts of the heaps. Besides negative environmental impact of those systems there are significant nutrient loses during the process which affect the final product quality.[10,11] The advantages of in-vessel composting or reactor systems are in the more controllable composting performance[12,13] as well as prevention of air pollutants and odor emissions.[14,15] There are many types of composting reactors with regard to geometry of the reactor, aeration mode, and agitation.[9,16] Agitation or stirring of the composting bed provides enhanced oxygen supply to the microbial community and the homogeneity of the composting mass.[13,16] Stirring also prevents the substrate particles from

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agglomerating which hampers channeling in the composting bed and increases the disposable area of the substrate for the microbial activity.[6,16] Such phenomena have a significant impact on the composting performance when composting powdery substrates consisting of small particles, which is the case in this work.

In recent researches on tobacco solid and liquid waste biodegradation and/or nicotine removal, waste from cigarette production was used as a substrate.[17,18,19] In this work tobacco dust originating from primary tobacco production was used as the composting substrate. The material is specific because it consisting of very fine particles of tobacco, mixed with soil particles. Nicotine content as well as microbiological population depends of climatology, soil properties, sort of tobacco and production itself.[20] The aim of this work was to investigate composting with and without stirring of tobacco dust. For that purpose two types of pilot-scale reactors were used. The study objectives were: (a) to define presence of nicotine degrading microorganisms and possible nicotine removal, (b) to determine the degradation rate of substrate volatile solids (*VS*) and (c) to propose reactor type and define process parameters for the effective composting

Materials and methods

Composting material

Tobacco solid waste generated in the tobacco primary production facility in Virovitica, Croatia, was used as a composting substrate for the composting tests. The tobacco waste was composed of very fine, powdery particles and average initial moisture content (*MC*) was about 8 %. Particle size distribution in tobacco waste was determined in 100 g of a dry sample using vibrating sieves (Analysete 3, Fritsch, Deutschland).

Determining the optimum moisture content

The concept of free air space (*FAS*), adopted from soil science, was used to establish the relation between moisture content (*MC*) and physical structure of the composting materials. *FAS* (%), porosity (*P*, %) and *MC* (%) are related through the following equation:[6]

$$FAS = P(1 - MC/100) \qquad (1)$$

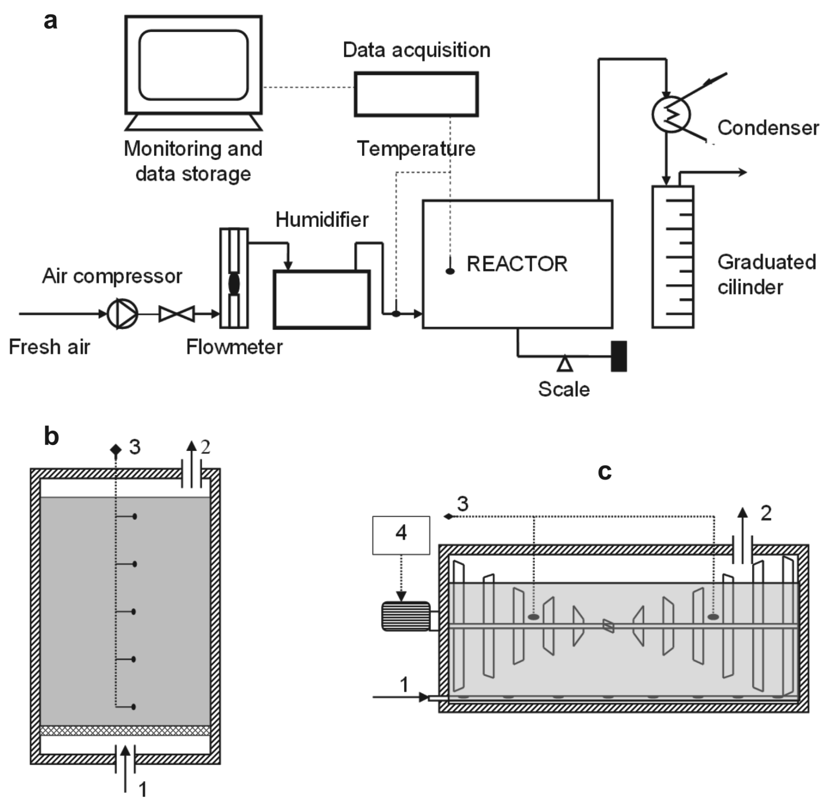
To achieve optimum composting, 20–35 % *FAS* is required.[6] The method used to investigate optimum *MC* of the compostable material is reported in the work of Madejon et al.[8] The measurements were carried out in a glass tube of 0.4 dm^3. The tube was filled with samples of waste mixture with different *MC*; water was slowly added to completely fill the free air space, shaking slightly to avoid the formation of air bubbles. The difference between the final and initial weight was considered as the volume of pores. Values of *P* were calculated for a series of samples with different *MC*. Three measurements were performed for each initial *MC*. The values of *FAS* were calculated applying Eq. (1).

Pilot-scale reactors

Composting was conducted in two specially designed, forcefully aerated reactors. Reactors were thermally insulated with 19.5±1.5mm thick AF/Armaflex® foam (Armacell, Germany). The moisture content of the substrate was set to about 60 % by adding the water and the substrate was put into the reactors from the top, which could be easily opened. Three experiments were carried out: two in the vertical packed bed reactor (without stirring (PBR_{NS}) and with intermittent stirring (PBR_S)), and one in the horizontal reactor with stirrers (HR_S). During composting in all experiments, continuous upward aeration was provided by an air compressor. To ensure permanent air humidity at the reactors inlet, prior to entering the reactor air was saturated with moisture by passing it through a humidification tank. After leaving the reactor, the hot spent air cooled down naturally and the condensate collected into the graduated cylinder (Fig. 1a).

The packed-bed reactor – PBR (Fig. 1b) was made of PVC with a working volume of 240 dm^3 ($L \times W \times H = 540 \times 500 \times 890$ mm). The waste material was placed into the reactor on the perforated plate with holes of 7 mm in diameter. The temperature was periodically measured with a digital temperature indicator (Cole Parmer, USA, –50 to 150 ± 1.0°C) at the reactor inlet and inside the reactor at five heights: 200, 350, 500, 650 and 800 mm, respectively, starting from the bottom. Two experiments were carried out with initial mass of the wet substrate of 120.0 kg at airflow rate of 0.65 $dm^3 min^{-1} kg_{VSinitial}^{-1}$. The first experiment was conducted without stirring (PBR_{NS}); during the second experiment, the reactor was periodically opened and the substrate was manually stirred (PBR_S).

The horizontal stirred-drum reactor – HR_S (Fig. 1c) was made of stainless steel and it had a total working volume of 200 dm^3 with inner diameter of 494 mm. The stirrer was constructed of 12 paddles symmetrically mounted onto a horizontal central axis, and rotated to the left side one to another for the angle of 45° (beginning with the one next to electromotor). Each side of the paddle was rectangle (200 × 30 mm), rotated for the angle of 45° in opposite direction one to another. The stirrer was powered by an electromotor (W 63 U, Končar



F i g . 1 – *Schematic diagram of composting process* ***(a)*** *and schemes of packed bed reactor-PBR* ***(b)*** *and horizontal reactor with stirrer-HR_S* ***(c)****; 1-air inlet; 2-spent air outlet; 3-temperature probes; 4-electromotor*

MES, Croatia) on the side of the reactor. Electromotor was connected to the computer by 1-chanell analog output SCC-AO10 (National Instruments, USA), via reley Zelio RUN 31A21 (Schneider Electric, Romania). The reactor was filled from the top with 74.0 kg of wet substrate and the experiment was carried out at airflow rate of 0.38 $dm^3\ min^{-1}\ kg_{VSinitial}^{-1}$. RTD compact probes (Cole-Parmer, USA, –50 to 500 ± 0.7 °C) for continuous temperature monitoring were placed at the reactors inlet and inside the reactor next to the central axis of the stirrer. Temperature probes were connected to the computer by the 2-chanell RTD analog input (SCC-RTDO1, National Instruments, USA). The substrate was automatically agitated every 24 hours for 1 minute at the stirring rate of 6.3 rpm. The computer software used for temperature monitoring and for automatic agitation was NI-DAQ 7, LabVIEW Win/PCI-6024/CB_68LP starter Kit, National Instruments, USA.

Physical-chemical and microbiological analyses

Temperatures at different positions were monitored by means of the temperature probes. Airflow rate was regulated by air flow meters with a regulation valve (Cole Parmer, USA, 2–25 $dm^3 min^{-1}$ and 4–50 $dm^3 min^{-1}$, ±3%). At the beginning and end of the process, the mass of the substrate/composting mass was determined and samples were taken in order to analyze the most relevant physical-chemical parameters (*pH*-value, moisture content, and dry matter and volatile solids content). All analyses were carried out in duplicate, and in compliance with to the Austrian standard methods for analysis of compost[21] which are widely used in Europe. Samples were taken at preset times in order to determine number of thermophilic and mesophilic microorganisms (in PBR_{NS} and PBR_S), and a nicotine content (in PBR_S). During the experiment in PBR_{NS} samples were aseptically taken from six different points of the composting mass concerning three different depths and two distances from the reactor wall. Samples were then mixed, and about 5 g of mixed sample was taken for the analysis while the excess was returned into the reactor. During the experiment in PBR_S, about 5 g of the sample was taken after stirring. Viable plate count was determined by the decimal dilution method and the results expressed as colony-forming units (CFU) of mesophilic or thermophilic bacteria and fungi per gram of the composting mass. Petri dishes were kept in the incubator, under 80 % relative humidity, at 28 °C for the growth of mesophilic fungi, at 37 °C for the growth of mesophilic bacteria, and at 50 °C for the growth of thermophilic bacteria and fungi. Incubation times for bacteria and fungi were 24 and 72 hours, respectively. Prevailing microorganisms were recognized by typical colony morphology on agar plates, and cell morphology observed under light microscope (Olympus B201, Japan). The bacteria were Gram stained before microscopic observation. Streptomycetes and actinomycetes were identified by their aerial mycelium with spores. Isolated Gram negative bacteria and yeasts were identified using sets of biochemical tests API 20NE and API 20 C AUX (Biomerieux, France), respectively. Nicotine and total organic carbon concentrations in the samples were determined at the beginning and end of the experiment. During the experiment in PBR_S nicotine was determined in the samples taken at intervals of 3 to 4 days. HPLC method[22] with DAD (diode-array detector) was used to measure the content of nicotine.

Theory and calculation

The reaction enthalpy ($-\Delta H_r$) was calculated from experimental results by measuring the temperature of the composting mass during the reaction. The value of ($-\Delta H_r$) was calculated using the following equation (Eq. 2):

$$(-\Delta H_r) = \frac{\rho Q_V}{m_{VS0}(1 - w_{VS})} \int_0^t [c_{pa}(T - T_{in}) + h_{w(T)}(H_{S(T)} - H_{S0})] \cdot dt \quad (2)$$

where m_{VS0} is initial mass of volatile solids, T and T_{in} are temperatures of the substrate and the air at reactor's inlet, $h_{w(T)}$ is the heat of vaporization, and $H_{S(T)}$ and H_{S0} are saturated humidities at reactor and ambient temperature.

Eq. (2) was assigned to a mathematical model developed using the kinetic model and mass and energy balances and was reported in previous works.[23,24] Reactors were modeled as a continuous stirred tank reactor (CSTR) and several assumptions were used in developing the model: biodegradation of the substrate was slow compared to oxygen transfer through the boundary gas layer; oxygen concentration in the substrate bed was constant; airflow rate during composting was constant. It was also assumed that the process had been carried out under adiabatic conditions and that the released heat was proportional to the progress of biodegradation.

Results and discussion

Tobacco waste particle size distribution and optimization of initial moisture content

Solid wastes are usually shredded into particle sizes between 10 to 70 mm to obtain, among other, optimal conditions for the composting process.[6,9,12] Granulometric analysis of tobacco waste showed that 26.85 % of particles were smaller than 63 µm, around 40 % were ranged between 63 µm and 630 µm, and 30.23 % were larger than 630µm (Table 1).

Evidently, particle sizes of selected tobacco solid waste were initially smaller than recommended for this kind of process. However, composting was carried out with this type of waste without amendment with bulking agents what is an usual practice when composting material consisting of fine particles.[25]

The obtained moisture content (*MC*) values and free air space (*FAS*) were linearly correlated with high coefficients of determination (R^2 = 0.9976) and linear regression equation was *MC* = –1.2311 · *FAS* + 90.9870. Finally, knowing the optimal *FAS* range, optimal *MC* of the given substrate was calculated between 47.9 and 66.4 %.

Table 1 – *Results of granulometric analysis of tobacco solid waste*

Particle size	Percentage (%) of weight
630 µm ≤ d ≤ 10 mm	30.23
450 µm ≤ d ≤ 630 µm	3.81
250 µm ≤ d ≤ 450 µm	3.92
100 µm ≤ d ≤ 250 µm	15.13
63 µm ≤ d ≤ 100 µm	19.07
Sieve bottom	26.85
Loss	0.99

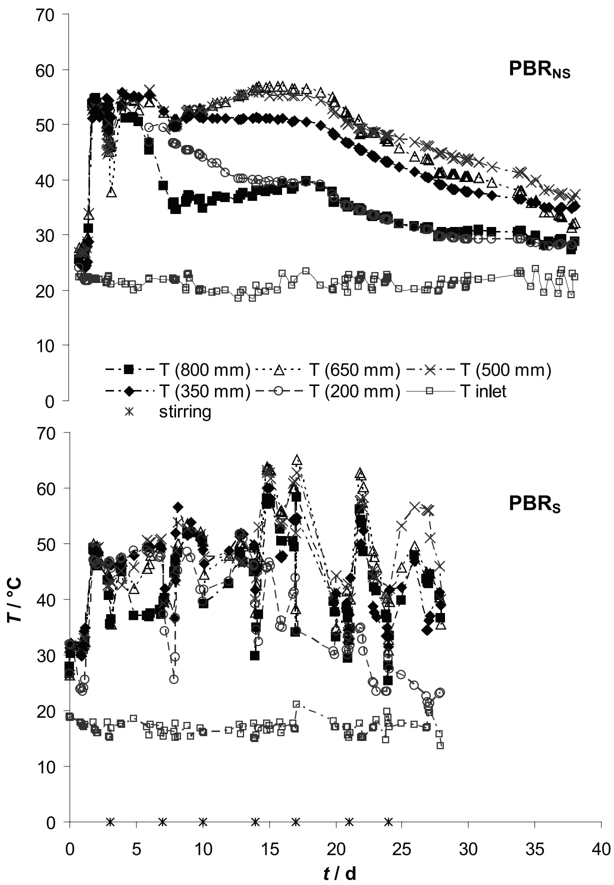
Temperature and reaction enthalpy

Composting of tobacco waste was carried out in a packed bed reactor and in a horizontal reactor with stirrers. The temperature of the composting mass in the reactors was continuously monitored as an indicator of the progress of microbial degradation of the solid waste. Temperature curves obtained in the experiments are shown in Figs. 2 and 3.

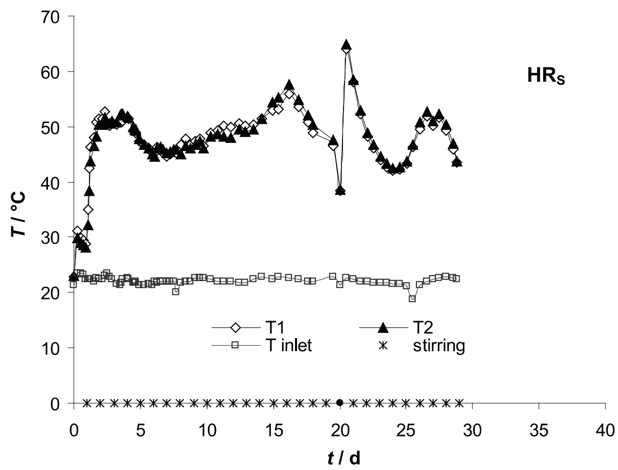
During the process conducted in the packed bed reactor without stirring (PBR_{NS}), the temperature maximum was reached at day 2, and the thermophilic phase in the middle of the reactor lasted until day 28 (Fig. 2).

After day 5, there was a significant temperature distribution over the bed height. The temperature measured at the top and at the bottom of the reactor (200 and 800 mm from the bottom) was 40 °C and lower, and between 50 and 57 °C in the middle of reactor. Due to compaction of the substrate and settlement of different layers, the temperature probe at the top (800 mm) was left in the void and the measured temperature became the temperature of the spent air. Settlement of different layers is very important phenomena in packed bed reactors. It affects the efficiency of oxygen supply, water evaporation and heat ventilation rates, and the impact of settlement on bed temperature increases with the bed height.[16] On the other hand, the lower temperature of the bottom layer was a consequence of the direct impact of the inlet air at ambient temperature.[26] Temperature distribution indicated that the reaction rate was not the same in all segments of the reactor.[12]

In the second experiment, composting was carried out in a packed bed reactor where the solid waste was manually stirred (PBR_S) at time intervals of 2–5 days, i.e. when temperature drop was ob-



F i g . 2 – *Temperatures at different heights of the reactor during composting in packed bed reactor without stirring (PBR_{NS}) and in packed bed reactor with stirring (PBR_S)*



F i g . 3 – *Temperature at reactor mid-height during composting in horizontal reactor with stirrer (HR_S); (●) marks overall mixing during 10 minutes at 6.3 rpm*

served. The obtained temperature values were similar to those obtained in PBR_{NS} but the temperature distribution was less distinctive (Fig. 2). Nevertheless, the temperatures measured at the lowest point were considerably lower than other values. This was due to the inability of complete manual stirring of the substrate bottom layer. The temperature profiles in Fig. 2 also show a rapid increase in temperature after the stirring period. In fact, stirring provided a breakdown of the agglomerates and increased the available area of the substrate particles for further degradation.[16,27] The rapid temperature decrease at the moment of stirring was a consequence of the stirring of the composting mass while the reactor was opened.

During the experiment in the horizontal reactor (HR_S) stirring was conducted automatically once a day for 1 minute. The stirring intervals were selected according to the published works.[13,28] The airflow rate was set to 0.38 $dm^3 min^{-1} kg_{VSinitial}^{-1}$ and it was purposely lowered after preliminary experiment (results not presented). Namely, when composting was conducted in a horizontal reactor at airflow rate of 0.65 $dm^3 min^{-1} kg_{VSinitial}^{-1}$, after a short period of temperature rise at the beginning of the experiment, there was a rapid temperature decrease and thermophilic phase was not observed. That indicated that airflow rate of 0.65 was too high for composting in that type of the reactor which is in agreement with the literature.[29] Unlike in PBR_S, the horizontal reactor was closed during the process (except when opened for sampling) and rapid increase in temperature after stirring was not observed (Fig. 3).

The exception was the overall mechanical and manual stirring for the 10 minutes at the day 19. Namely, that action was done to remove the thin layer of composting material captured between the paddles and the reactor wall, as well as to explore substrate "potential" for further degradation. After overall mixing, the temperature in the composting bed increased to 64°C. This effect indicated that the stirrer should be somewhat modified and that the stirring intervals should be precisely investigated in further work.[28]

The reaction enthalpy ($-\Delta H_r$) was calculated by Eq. (2) using experimentally obtained temperature values of the composting mass. The calculated values ($-\Delta H_r$) and necessary data for the calculation are given in Table 2.

The reaction enthalpy ($-\Delta H_r$) values obtained for the selected substrate were 3 to 4 times lower than those found in the literature.[6,29] This could be explained by heat losses through the reactors walls and temperature probes sockets as well as the losses caused by opening the reactors in order to take a sample (in PBR_{NS} and PBR_S). Another reason for heat losses during composting in HR_S were thermally non-isolated parts of the reactor, e.g. electromotor. As the time of composting was relatively long, the losses were significant. The lowest value

Table 2 – *Dimensions and characteristics of process and calculated reaction enthalpy (–ΔH$_r$)*

Parameter	PBR_{NS}	PBR_S	HR_S
m_{VS0} (kg)	41.5	41.5	23.5
Q_V (dm^3 min^{-1} kg$_{VS}$$^{-1)}$	0.65	0.65	0.38
c_{pa} (kJ kg^{-1}K^{-1})	1.01	1.01	1.01
ρ_a (kg m^{-3})	1.30	1.30	1.30
T_{in} (°C)	21.0±2.0	19.5±2.0	21.5±1.5
(–ΔH$_r$) (kJ kg$_{VSinitial}$$^{-1}$)	5538	4675	5179

of reaction enthalpy was calculated for the PBR_S, which showed that there was a significant heat loss caused by periodic stirring of the composting mass while the reactor was opened. It should also be noted that the reaction enthalpy in the packed bed reactors was calculated using the temperature measured at mid-height of the reactor. Higher temperatures at the middle of the reactor in PBR_{NS} and longer composting period (38 days) were the reason for the highest (–ΔH_r) value.

Extent of solid waste biodegradation

The tobacco solid waste at the beginning and the product at the end of composting were weighed and samples were analyzed to determine: moisture content (*MC*), *pH*-value, volatile solids content (*VS*) and nicotine content. At the end of the processes in PBR_{NS}, PBR_S and HR_S conversions of the volatile matter were 50.6 % (at day 38), 53.0 % (at day 28) and 51.1 % (at day 29), respectively (Table 3).

The conversion values obtained as well as the duration of the composting process showed that stirring increased the degradation rate. Final moisture content was the lowest in PBR_S. That confirms the loss of heat and water by evaporation due to opening the reactor, which is not the case in HR_S. Stirring of the bed in HR_S while the reactor was closed maintained the *MC* during the process at satisfactory level.

Table 3 – *Physical-chemical properties of the substrate and the product of the composting*

Property	PBR_{NS}		PBR_S		HR_S	
	initial	final	initial	final	initial	final
m (kg)	120.0	77.0	120.0	53.9	74.0	49.1
MC (%)	59.7	65.5	59.6	52.4	60.4	59.4
pH-value	5.6	7.2	5.3	8.9	6.1	9.4
VS (%)	85.8	77.1	85.2	75.9	80.0	63.0
X_{VS} (%)		50.6		53.0		51.1

At the end of the composting in all three experiments nicotine was not detected what indicated that nicotine-degrading microorganisms were present in the tobacco dust. Figure 4 presents the growth of mesophilic and thermophilic microorganisms and the changes in their number in the substrate during composting in the packed bed reactor without stirring (PBR_{NS}) and with stirring (PBR_S).

In both experiments at the start, the numbers of microorganisms were similar (mesophilic bacteria and fungi 3.6 × 10^6 and 5.3 × 10^4, thermophilic bacteria and fungi 1.5 × 10^6 and 2.1 × 10^4 CFU g$^{-1}_{substrate}$, respectively). Changes of the microbial groups and changes of their number followed the temperature curve during 38 and 28 days of composting in PBR_{NS} and in PBR_S, respectively. At the end the number of all bacterial species was around 10^9 and the number of mesophilic fungi was around 10^5 in both experiments. In contrast, in the experiment PBR_S the number of thermophilic fungi was lower by three orders of magnitude than in PBR_{NS} (Fig. 4). As the temperature in the reactor decreases, the number of mesophiles increases and the number of thermophiles decreases, and vice versa. Elevated temperatures in the reactor over an ex-

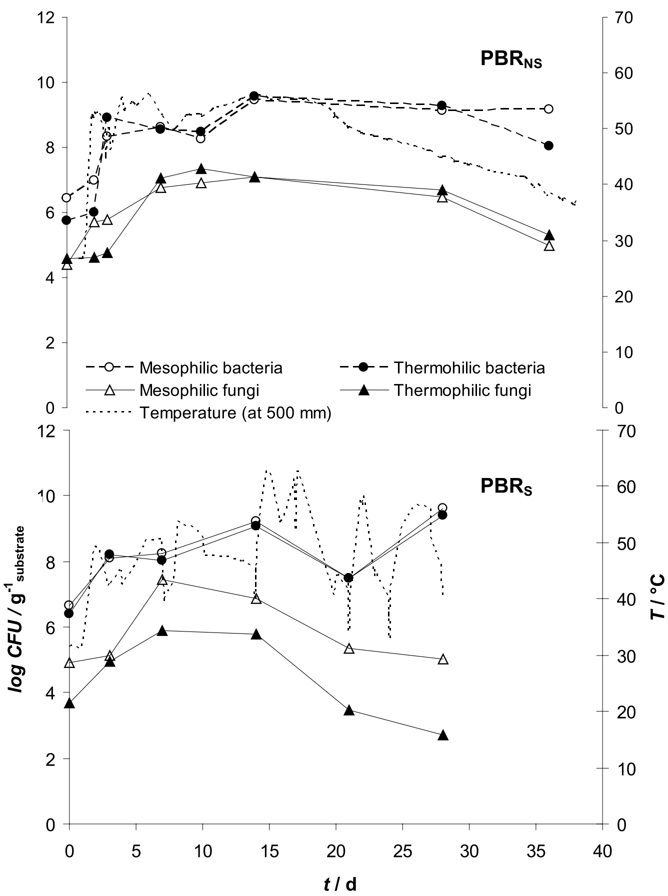


Fig. 4 – *Growth of total viable-cultivable mesophilic and thermophilic bacteria and fungi over time in composting mass in packed bed reactor without stirring (PBR_{NS}) and in packed bed reactor with stirring (PBR_S)*

tended period of time affect the proper process of composting. Under these conditions there is a further degradation of complex organic fraction in the substrate, and die-offs of pathogenic microorganisms.[6,9]

Detailed examination of colonies of mixed cultures grown on nutrient media reveals the presence of different types of bacteria (*Pseudomonas fluorescens / putida*, *Streptomyces* sp. and *Actinomyces* sp.) and molds (*Aspergillus fumigatus*, *Mucor* sp., *Rhizopus* sp. and *Trichoderma viride*). Yeasts (*Candida krusei* and *Candida rugosa*) were also present at the beginning in the composting mass, but at the end of composting they could not be detected. This was confirmed in an experiment where the kinetics of degradation of nicotine was studied. Nicotine concentration and the number of nicotine degrading microorganisms were determined in the experiment PBR_S at certain intervals to find out the course of nicotine biodegradation (Table 4).

Table 4 – *Nicotine biodegradation during composting*

Sampling day	Nicotine (%)	Microorganisms	
		Pseudomonas fluorescens/putida	*Candida rugosa* and *Candida krusei*
0	0.95	4.0×10^5	n.d.
3	0.93	8.5×10^5	1.1×10^5
7	0.93	5.3×10^6	2.7×10^7
10	0.98	n.d.	n.d.
14	0.96	4.4×10^8	7.6×10^6
17	0.76	n.d.	n.d.
21	0.46	3.1×10^7	2.2×10^5
24	0.01	n.d.	n.d.
28	0.00	4.8×10^8	0

A detailed microbiological analysis of the compost mass, at the time intervals of measured concentrations of nicotine, showed that in mixed cultures of microorganisms prevailed bacteria *Pseudomonas fluorescens/putida* and yeasts *Candida rugosa* and *Candida crusei*. When nicotine was completely degraded, the cells of *P. fluorescens/putida* still remained in large numbers in the raw compost.[18,30] At the same time, the cells of yeasts were not detected.

At the end of the process in the PBR_{NS}, the top of the composting mass was good in appearance (Fig. 5a); structurally adequate and overgrown with actinobacteria which indicated the proper moisture and good oxygen supply[9] in the higher regions of the reactor. However, after removing the composting product from the reactor, dry and non-degraded

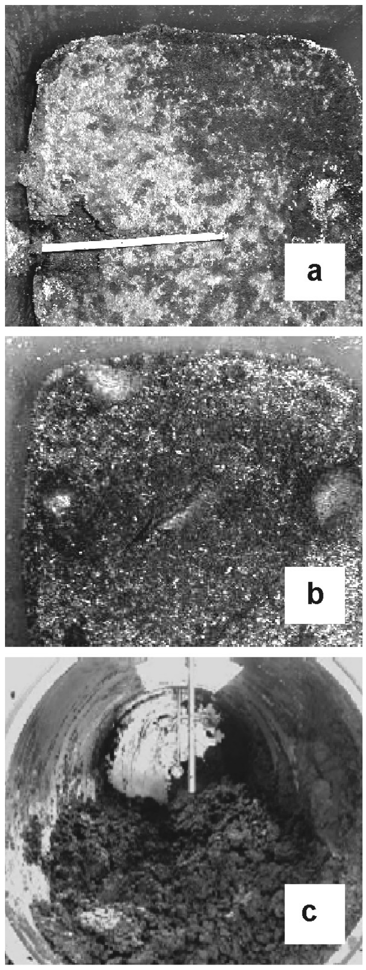


Fig. 5 – *Photographs of a composting mass at the end of the process:* ***(a)*** *in packed bed reactor without stirring (PBR_{NS}, photography taken from the top);* ***(b)*** *in packed bed reactor with stirring (PBR_S, photography taken from the top)* ***(c)*** *in horizontal reactor (photography taken from the side, after removing the stirrer)*

as well as moist and smelly zones were observed in the rest of the material. In addition, shrinkage of the material in PBR_{NS} was observed what probably facilitated pass of air between edges of the material and the reactor wall (Fig. 5a), and limited oxygen supply to the composting bulk. In order to avoid such phenomena and temperature distribution in packed bed reactors, the critical bed height should be investigated.[31]

Physical and organoleptic characteristics of the end-product in HR_S (Fig. 5b) gave it a typical compost appearance[6] (black color with white spots, humid earth odor, among other).

Conclusions

The tobacco dust was consisting of very small particles where 69.77 % of the particles were smaller then 630 μm. The moisture content (MC) for efficient composting of the tobacco dust was estimated by a simple method and calculated to be between 47.9 and 66.4 %.

Composting of tobacco dust, was efficiently conducted with (PBR_S and HR_S) and without stirring (PBR_{NS}). In all three experiments thermophilic phase was observed and over 50 % of volatile solids were degraded. Furthermore, nicotine was not detected in composting products and nicotine degrading bacteria *Pseudomonas fluorescens/putida* was isolated during the process.

The higher degradation rate was observed in the experiments with stirring. At the end of the processes conducted in PBR_S (at day 28) and in HR_S (at day 29), 53.0 % and 51.1% of volatile solids were degraded, respectively. The obtained temperature profiles and calculated reaction enthalpies showed that a significant heat loss occurred in the PBR_S due to the periodic stirring of the composting mass while the reactor was opened. In contrast, horizontal reactor (HR_S) was easier to handle, but heat losses also occurred, presumably through thermally non-insulated parts (electromotor). Both reactors (PBR_S and HR_S) could be recommended for composting process but further investigations should be done with the scope on the heat transfer through the all parts of the reactors and on the optimization of process parameters.

List of symbols

c_{pa} – specific heat capacity of air, kJ kg^{-1} K^{-1}
FAS – free air space of material, vol.. %
$h_{w(\mathrm{T})}$ – heat of vaporization of water at reactor temperature, kJ kg^{-1}
$H_{\mathrm{S(T)}}$ – saturated humidity at reactor temp., kg kg^{-1}
H_{S0} – saturated humidity at ambient temp., kg kg^{-1}
m – mass of the substrate, kg
m_{VS0} – initial mass of volatile solids, kg
MC – moisture content of material, %
P – porosity of the material, vol.. %
Q_{v} – airflow volume, m^3 h^{-1}
t – time, day
T – temperature in reactor, °C
T_{in} – temperature of air at reactor inlet, °C
VS – volatile solids content, %
w_{VS} – mass fraction of volatile solids, kg$_{\mathrm{VS}}$ kg$_{\mathrm{VSinitial}}^{-1}$
ΔHr – reaction enthalpy, kJ kg$_{\mathrm{VSinitial}}^{-1}$
ρ_{a} – air density, kg m^{-3}

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