城市污泥堆肥温度动态变化过程及层次效应

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摘要:对城市污泥强制通风静态垛堆肥的温度变化规律进行了研究。结果表明,当调理剂比例较低时,堆体升温速率和降温速率都较为缓慢,堆肥处理时间长,堆体温度较低。当调理剂比例较高时,堆体升温速率较快,堆肥温度将在较短时间内达到灭菌稳定化所要求的高温。堆体温度在高温阶段持续的时间与调理剂比例有着密切的联系,当调理剂比例太高时,高温持续时间短,如加入适当比例的回流污泥,堆温可以在 50℃ 以上高温阶段持续足够的时间。当堆肥原料的起始温度高于 15℃,堆体一般要经历升温阶段、高温持续阶段和降温阶段,但是当堆肥原料的起始温度很低时,堆体温度还要经历一个起爆阶段。堆体内不同层次的温度有着不同的变化趋势,堆肥初始阶段,堆体下层温度高于上层温度,随后上层温度逐渐高于下层温度。

关键词:城市污泥;堆肥;温度;位置效应

Temperature Dynamic During the Sewage Sludge Composting Process

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Abstract: It was well recognized that many factors influenced the composting process and the resulting product. Temperature was the most important ecological determinant within composing material. Temperature increase was a function of starting points, metabolic heat evolution and heat conservation, with the achievement of minimum temperature levels being essential to an effective composting process and contributing substantially to the high rates of decomposition achieved during processing.

Few studies had been undertaken to understand the processes of microbes, heat losses from the mass, and the ecological nature, including microbial succession.

The temperature of a composting mass depended largely on airflow. The temperature between the center and the surface of the composting mass varied greatly in static piles largely because of airflow. Turning of stacks or forced aeration, as in environmentally controlled composting, could control temperature effectively. Termination of such practices resulted in the temperature soon returning to the range of 70℃ to 80℃.

The forced aerating influenced the temperatures at different positions, so the temperature changes were different. To know the difference was important to control the composting process, improve the quality of the composting product.

The study was carried out to investigate the temperature dynamic during the sewage sludge aerobic static composting.

All experimented composting piles were placed in a building in 1.6 m × 1.0 m bays with cement floors and walls. Aeration boards were laid on the bottom of the bays. The piles contained sewage sludge (moisture content

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=83%～85%，Volatile Solid = 49%～58%)，recycled compost and bulking agent with five proportions. A bulking agent layer on the aeration boards dispersed air through the 1.0 m high mix layer. All piles were covered with a 20-cm insulating layer of recycled compost. Each bay had an aerator to supply ambient air. Sensors were inserted into the middle layer and upper layer of the piles' geometrical centers to detect the temperatures, and the detected values were fed back to the computerized control system. In order to study the difference among the different layers, six sensors were inserted into the piles in the treatment II from the bottom to the top. A three-stage control algorithm controlled the damper duty cycle of aerators. The control software logged temperatures every 15 minutes and generated reports.

The temperature increasing and decreasing speed was slow, less than 4.7℃/d and 2.9℃/d respectively, and the composting duration was long and the composting temperature was lower when the proportion of bulking agent was lower. On the contrary, when the proportion of bulking agent was high, the temperature decreasing was faster, about 12～17.6℃/d, and the composting temperature was high enough to destroy the pathogenic microorganisms. The duration in high temperature period related to the proportion of bulking agent: the duration was shorter when the latter was higher, but long enough to destroy the pathogenic microorganisms when the recycled compost was added.

The composting process suggested by earlier reports could be divided into three stages: temperature increasing stage, high temperature stage and temperature decreasing stage. However our experiment indicated that the composting process should be divided into four periods: besides the three periods previously stated, the period from the low temperature to the 15℃ should be noticed because it was important for the microorganisms to proliferate and the composting process to start.

The temperature changing trends at the different places in the composting piles were different. The temperature of the upper-layer was lower than that of the under-layer in the early stage, and then the former was higher with the development of composting process.

he temeprature of under-layer was higher at starting stage and it should be studied in future.

Key words: sewage sludge; composting; temperature; position effect

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在有机废弃物高温堆肥过程中，湿度、温度、pH、C/N 等许多因素均影响堆肥进程和最终产品的质量[1～5]。在诸多因素中，温度是堆肥过程的核心参数[6,7]，堆体一般要经历升温过程、高温持续过程和降温过程[8]。国内外学者对于堆肥温度的研究主要集中于以下几个方面：堆肥升温过程的特点及堆肥所能达到的最高温度；堆体热量散失过程与温度的关系；控制过程与温度的关系；温度与微生物的生长繁殖及种群演替的关系[9～16]。

由于高温分解较中温分解速度快，并且高温堆肥又可将虫卵、病原菌、寄生虫、孢子等杀灭，故有机废弃物资源化处理中一般多采用高温堆肥[17]。

通常需要采用通气调整堆肥温度和有机物分解速率之间的平衡。堆肥初期 3～7d，通气的主要目的是满足供氧，使生化反应顺利进行，以达到提高堆层温度的目的。当堆肥温度升到峰值以后，通气的目的以控制温度为主[18]。Wiley 和 Spillane 认为，如果缺少温度调节措施，堆体温度会很快升至 70～80℃[19]，这将严重影响微生物的生长繁殖，因此，必须通过加大通气，通过蒸发水分带走热量，使堆温下降[20,21]。Finstein 等的研究结果表明，在强制通风静态垛堆肥系统中，鼓风使得堆体中心和表面的温度差异极大[1,2]。

前期的试验结果表明，鼓风对堆体不同部位的温度变化影响不同[22]，因此堆体不同层次的温度变化也会表现出不同的特点，了解这种差异对于调控堆肥过程，提高堆肥效率和堆肥产品质量具有重要意义。

1　材料与方法

1.1 试验材料

城市污泥为北京方庄污水处理厂脱水污泥，含水率 83%～85%，挥发性有机物含量为 49%～58%。堆肥中所采用 CTB 调理剂的含水率和饱和含水率分别为 2.70%、65.7%。回流污泥的含水率和挥发性有机物比例分别为 39.1%、38.3%。

1.2 试验装置

堆肥池大小为 $1.6\times1.0\times1.1m^3$（图 1）。堆肥池底部铺放布气板。

1.3 试验方法

将堆料按设定比例（表 1）充分混匀后上堆。在堆体几何中心的中层和上层放置 2 个温度传感器，测定堆体中层和上层的温度。处理 II 的几何中心从下向上平均放置 6 个温度传感器，以便测定堆体各层次间温度的差异。

试验采用中国科学院地理科学与资源研究所环境修复研究室研制的温度变送器以及堆肥自动测控软件（Compsoft）集成系统（CTB 堆肥自动测控系统），对堆温进行连续监测和控制（图 1）。

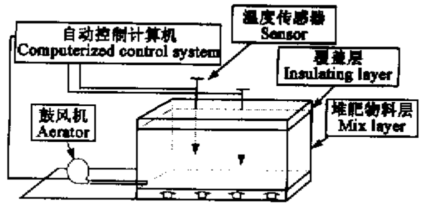

图 1 污泥堆肥试验装置示意图

Fig.1 Schematic of the composting system

2 结果与讨论

2.1 不同混料比例的堆温动态变化

图 2 是 1999 年秋季试验中各处理上层温度的变化曲线。

表 1 堆肥试验时间及处理

Table 1 Date and treatments of composting

试验时间(年-月) Date (Year-Month)	1999-11			2001-03	
处理 Treatments	I	II	III	IV	V
混料比例 Mixing ratio (污泥∶回流污泥∶CTB 调理剂) (Sewage sludge∶recycled compost∶bulking agent)	3∶0∶2	2∶1∶1	1∶0∶1	2∶0∶3	1∶0∶1

处理 I 堆温的上升趋势缓慢，从开始升温到温度峰值的平均升温速率为 4.7℃/d，峰值为 46.3℃，降温阶段温度平均下降速率为 2.9℃/d。处理 III 的堆体，升温和降温过程都很剧烈。温度上升阶段，2.5d 即达堆温峰值，升温速率 17.6℃/d，降温速率为 10.1℃/d。根据我国《粪便无害化卫生标准（GB7959-87）》的规定，要求堆肥温度在 50～55℃ 以上维持 5～7d 作为灭菌的标准。按照这一标准，处理 III 的堆体温度在≥50℃ 高温期维持时间仅为 1.5d，达不到该标准的要求。由于堆体中调理剂所占比例高达 50%，通气性能良好，微生物活动剧烈，堆温上升很快；但是堆体保温性能差，堆体散热较快，导致堆温迅速下降。

处理 II 的堆温经 2d 后可达到 58℃，上升速率 12℃/d，在 50℃ 以上的高温期维持 6d，达到了无害化标准的要求。

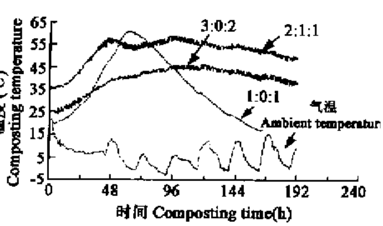

图 2 秋季堆肥温度的动态变化（1999 年 11 月）

Fig.2 Temperature dynamic changing in autumn (1999-11)

不同混料比例的堆温变化特点表明，当调理剂比例较低时，堆体升温速率≤4.7℃/d，降温速率≤2.9℃/d，因此堆肥处理时间长，而且堆体温度较低，达不到污泥高温堆肥所要求的灭菌温度。当调理剂比例较高时，堆体升温速率为 12～17.6℃/d，堆肥温度将在 2.5d 内升高到无害化处理所要求的≥50℃ 高温。堆体温度在高温阶段持续的时间与调理剂比例有着密切的联系，当调理剂比例太高时，高温持续时间短，如加入适当比例的回流污泥，堆温可以在 50℃ 以上阶段维持无害化处理所需的时间。

图 3 是 2001 年 3 月试验各处理上层温度的变化曲线。

Mosher 等研究认为,当堆肥物料的温度低于 20℃,堆肥过程将显著变慢甚至停止[3],但是从本试验结果来看,临界温度应该在 15℃甚至更低。以 15℃作为临界温度,则 2 种处理从开始到 15℃约需 4.5～4.7d 左右,温升速率为 2.7～2.9℃/d,但是处理 IV 的堆温从 15℃到 50℃的时间仅为 1.3d,温升速率高达 26.9℃/d,处理 V 的温升速率为 6.1℃/d。

Miller 认为,堆肥温度的上升过程是堆肥起始温度、微生物新陈代谢产热过程及堆体保温效应综合作用的结果,堆体一般要经历升温过程、高温持续过程和降温过程[16]。李国学等国内学者也有类似看法[17]。从 3 月的试验结果来看,当堆肥原料的起始温度高于 15℃,堆肥温度的动态变化规律符合 3 阶段理论。但是当堆肥原料的起始温度很低时,堆体温度的动态变化明显分成 4 个阶段:除了升温、高温和降温阶段,堆体还要经历一个从低温到 15℃的阶段。这一阶段对于微生物的大量繁殖和堆肥过程的启动具有重要意义,因此称之为起爆阶段。在随后历次的堆肥试验中,都存在这一现象,说明这一规律具有普遍意义,因此,堆肥的温度动态变化可以用以下典型温度动态变化曲线描述。

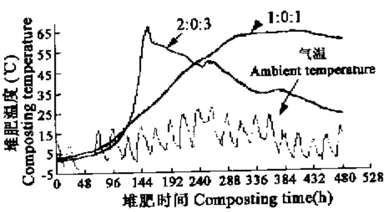

图 3　春季堆肥温度的动态变化(2001 年 3 月)

Fig.3　Temperature dynamic changing in spring (2001-03)

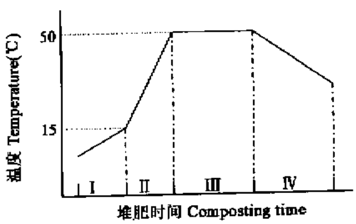

图 4　污泥堆肥温度动态变化的典型曲线

Fig.4　Typical curve of temperature dynamic changing

2.2　不同层次堆温的动态变化

污泥堆体是一个复杂的生物反应系统,虽然都要经历起爆、升温、高温和降温 4 个阶段,但是各个层次的温度升降规律并不一致。图 5 是 1999 年 11 月各处理上、下两层次的温度动态变化。

处理 I 的堆体温度上升缓慢,0～43h 下层温度高于上层温度,43～192h 上层温度较高(图 5A)。两个层次的最大温差出现在堆肥进行到 115h 左右,此时为上层堆温的峰值前后。

处理 II 与处理 III 的堆体温度上升较快,不同层次的温度变化规律基本相似(图 5B、图 5C)。初期下层堆温比上层高,但随着堆肥过程的进行,上层堆温逐渐比下层高。两个层次的最大温差为上层堆温的峰值前后。2001 年 3 月的试验结果也有类似现象。

出现这种现象的主要原因可能是:在堆肥初期,堆体上层对下层的压实作用不明显,而下层与空气直接接触,好氧生物活动过程快速充分,因此温度较高。随着下层逐渐被压实,自由孔隙减少,通气性比上层差,上层的好氧发酵过程比下层活跃,故上层温度又逐渐高于下层。

Russell 等研究认为,对于自然通风的条垛式堆肥系统,堆体上层温度较下层高[24]。本研究的结果表明,对于强制通风静态垛,Russell 等的研究结论不适用于整个堆肥过程。Smith 等观察到,在污泥条垛式堆肥化中,堆体温度呈梯度分布,图 6 中 A 是条垛式堆肥高温阶段温度与堆体深度关系的典型曲线[25],堆体几何中心温度最高,底部温度高于上部温度。

处理Ⅱ的测定结果表明,通风静态垛堆肥系统中心进入高温阶段时,其温度梯度曲线符合图 6-A 所示的梯度模式。但是在堆肥起始阶段,因为其下层的温度较高,其典型温度梯度模式为图 6-B 所示。

3　结论

堆体温度在高温阶段持续的时间、升温和降温速率都与调理剂比例有着密切的关系。当堆体混料比例中调理剂比例较低时,堆体升温速率和降温速率都较为缓慢,而且堆体温度较低,达不到污泥高温堆肥

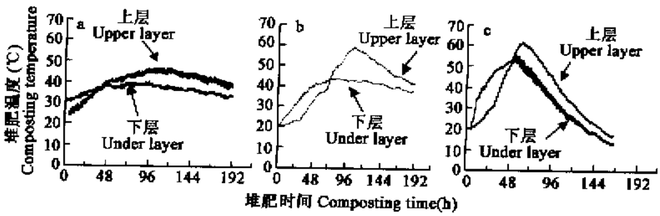

图5 堆体上层和下层温度的动态变化

Fig.5 Temperature dynamic changing of upper and under layers

a.处理Ⅰ TreatmentⅠ,b.处理Ⅱ TreatmentⅡ,c.处理Ⅲ TreatmentⅢ

所要求的灭菌温度。当调理剂比例较高时,堆体升温速率较快,降温也快,高温持续时间短。但如加入适当比例的回流污泥,堆温可以在50℃以上高温阶段持续灭菌所需的时间。

当堆肥原料的起始温度高于15℃,堆体一般要经历升温过程、持续高温过程和降温过程。但是当堆肥原料的起始温度较低时,堆体温度的变化还必须经过一个从开始升温到堆体温度到达15℃的起爆阶段。

堆体内不同层次的温度有着不同的变化趋势。堆肥初始阶段,各个混料比例的处理中堆体下层温度均高于上层温度。此后,上层温度则高于下层温度。

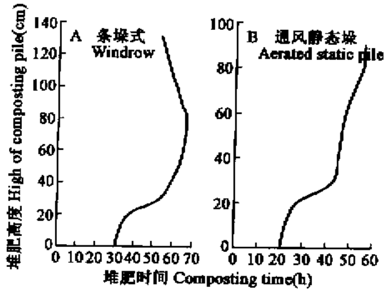

图6 堆体内的温度分布曲线

Fig.6 Temperature changing curve following to the depth of pile

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