

The Composting Process from a Waste Management Method to a Remediation Procedure

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Abstract—Composting is a controlled technology to enhance the natural aerobic process of organic wastes degradation. The resulting product is a humified material that is principally recyclable for agricultural purpose. The composting process is one of the most important tools for waste management, by the European Community legislation. In recent years composting has been increasingly used as a remediation technology to remove biodegradable contaminants from soil, and to modulate heavy metals bioavailability in phytoremediation strategies. An optimization in the recovery of resources from wastes through composting could enhance soil fertility and promote its use in the remediation biotechnologies of contaminated soils.

Keywords—Agriculture, biopile, compost, soil clean-up, waste recycling.

I. COMPOST UTILIZATION IN AGRICULTURE PRODUCT-ORIENTED PERSPECTIVE

A. Advantages of Compost Utilization

THE European directives regarding wastes priorities the various options for waste management. These are, in order of importance, prevention (product, no-waste, reduction of waste production and hazard), preparing for re-use, recycling, other recovery and disposal [1]. This hierarchy is based on the effects that each option has on the environment and sustainability is the guiding principle. Moreover, it is considered the total life cycle of the product introducing the prevention concept.

There is a large agreement on the fact that whatever the waste management selected, it must contribute to the recycling of nutrients, conservation of organic matter and reduction of environmental impact. The Landfill Directive [2] establishes to diminish the quantity of biodegradable waste disposed in landfills, such that only 35% of the total amount (by weight) disposed in 1995 will be permitted by 2016. This strategy should include measures of recycling, composting, biogas production or materials/energy recovery [2]. This will be a hard task given that the amount of wastes yearly generated is increasing.

However, the conclusions of report from the Commission to the Council and the European Parliament [3] refer that all strategies adopted by Member States show the promotion of composting, recycling of paper and energy recovery, stressing the importance of using source segregation of organic waste to obtain good quality compost [3].

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Recent estimates indicate that 45% of European soils have low organic matter content, principally in the southern regions of Europe, but also in areas of France, the UK and Germany, and more than 70% of the soils contain less than 4% of organic matter in the topsoil (0-30 cm), a condition that sometimes is defined of pre desertification stage [4].

In this context the amount and quality of the organic matter present in many urban wastes, above all those deriving from some selected uses, justify the choice of a biological treatment, for the production of compost, as a means of exploiting the waste itself.

However the most common destination of the about 220 million tons of municipal solid wastes (MSW) generated in the Community every year are incineration and land filling.

For instance, in the Europe (EU27), 486 kg per person of MSW has been treated in 2010, of which about 37% is disposed in landfills (on average 185 kg/inhabitant per year), approximately 23% has been sent to incineration (109 kg/inhabitant per year), while about 25% (121 kg/inhabitant per year) and about 15% (71 kg/inhabitant per year) are sent, to recycling and composting, respectively, depending on local conditions, and degree of industrialization [5].

The utilization of compost in agriculture with its contribution of humified organic matter is a powerful means to maintain or restore the quality of soil, contrasting the organic matter depletion.

The use of compost greatly improves soil physical conditions, which can promote root growth and penetration into the soil, with an increase of root biomass production [6].

Fertility is enhanced as a result of re-establishing the balance between the withdrawal and restitution of organic matter in the biosphere. Moreover compost also increases soil biodiversity and locks to the soil organic carbon that otherwise would go in the atmosphere.

In addition we have to consider the presence in the compost of essential elements for plant nutrition such as nitrogen, phosphorus, potassium and it should be noted that organic nitrogen is much more slowly released from compost than from mineral fertilizers thus reducing nitrogen losses in the environment, potassium is protected by the organic matter from absorption by clay minerals, and phosphorus is protected from co-precipitation with calcium.

Many studies indicate that utilization of compost can increase the yield and in part the quality of plants depending on the kind of compost and soil.

B. Limitations to the Use of Compost

The main constraints to the use of biomasses in agriculture derive from the presence of inert substances such as plastics,

glasses and textiles or from toxic substances such as heavy metals and synthetic organic substances, whereas a process carried out efficiently can eliminate the lack of stabilization of the organic matter.

Particular attention has been reserved from many years to heavy metals, given that organic micro-pollutants are subjected to biodegradation phenomena in the composting process and therefore end up in the finished products only in extremely low concentrations. In addition, the soil, by itself, is able to biodegrade almost all the organic composts in the wastes, whereas the same cannot be said of the heavy metals, which have the tendency to persist and accumulate.

Heavy metals can be present in compost in various chemical forms [7], such as carbonate salts, sulphites, linked to organic substances, or in an adsorbed or exchangeable form. The predominance of one chemical species with respect to others depends on the type of metal and on the composting process. Cationic species have a different mobility from that of complexed species being often the chelating agents humic-like substances with a considerable variety of molecular weights deriving from the cellular matter. The nature of the metal considerably influences its distribution between the solid and aqueous phases in composts and can in some way also influence the initial availability for plant nutrition after application of the biomasses to the soil.

Although we must take account of the important diversity of the chemical forms of heavy metals in compost, it is above all in the soil that we have the fundamental processes that move these elements into the food chain.

It is essential to recognize that any detrimental effect on soil quality only occur if the metals are present in "bio-available" forms. Also the most recent advances in the procedures for conducting ecological risk assessment (ERA) of heavy metals, stress the need to incorporate bioavailability in the ERA procedures [8].

Because plant uptake of heavy metals occurs only via soil solution, it is necessary to assess the amount of heavy metals in soluble and/or solubilisable forms, which are also the chemical species able to enter nearly all the environmental processes.

The main factors that influence solubility, and therefore environmental mobility, are pH, cationic exchange capacity (C.E.C.), organic matter content and the water and thermal regime of the soil.

The activity of a metal ion in the soil solution depends directly or indirectly on the pH. Most of the ions able to precipitate the metals are weak acids, which become soluble following protonation and shifting of the metal in its solid phase. Besides, an increase in acidity reduces the number of specific adsorption sites available for heavy metals.

The cationic exchange capacity regulates the mobility of metal ions. As this is a measurement of the negative charge on the constituents of the soil, the C.E.C. is an index of the soil's capacity to adsorb and hold metal cations. Both the organic matter and the clay minerals contribute to the C.E.C.: that deriving from the clays is generally little influenced by the pH, unlike the C.E.C. deriving from the organic matter.

The humic substances can interact with the metals forming complexes of varying stability. The complexing ability of the humic substances essentially depends on the content of functional groups containing oxygen and on the amino and imino groups. The complexes of the heavy metals with the organic matter of the soil can have different solubility and therefore a different environmental mobility.

The effect of the chemical and physical properties of the soil distributes heavy metals into different pools of different availability, from simple or complexed ions in the soil solution, to ions in the crystalline lattices of the primary minerals.

The aim of soil chemistry is to use the appropriate tools (chemical, biological and physical) to evaluate bio-available fractions of metals, while models based essentially on assessment of the following parameters could predict the behaviour in the long term of these elements:

- original content of heavy metals in the soil
- amount of metals applied each year with compost
- the plant species that determines the amount of metals removed with the harvest
- the amount lost due to leaching

In the models used to describe the long term behavior of metals the variables should be considered as derivatives of time.

Defining, for example, the amount of metals added to the soil as dq/dt , the amount that accumulates in the arable layer dq_s/dt , the amount removed by the plants dq_p/dt and that lost through leaching dq_l/dt , for a given soil layer the following relation applies [9]:

$$\frac{dq_i}{dt} = \frac{dq_s}{dt} + \frac{dq_p}{dt} + \frac{dq_l}{dt} \quad (1)$$

All these quantities are expressed as amount of metal per area unit per time unit, for example $\text{kg ha}^{-1} \text{ year}^{-1}$. Assuming that the input of heavy metals starts from a time zero, corresponding to the first application of compost, and that the amounts added in successive years remain constant, for $t \geq 0$, the following relation applies:

$$\frac{dq_i}{dt} = K_i \quad (2)$$

where K_i is a constant expressed in $\text{kg ha}^{-1} \text{ year}^{-1}$.

In order to distinguish between the original content of the soil, $qs(0)$, and that at time t , $qs(t)$, we define the amount:

$$\Delta q_s = qs(t) - qs(0) \quad (3)$$

which represents the amount of metals that has accumulated in the soil.

Equation (1) thus becomes:

$$\frac{d\Delta q_s}{dt} = K_i - \frac{dq_p}{dt} - \frac{dq_l}{dt} \quad (4)$$

from this general equation it is possible to predict the behaviour, in the long term, of the heavy metals added with

compost in relation to the values of dq_p and dq_l , which will depend on the solubility of the metals in different conditions.

Phenomena of accumulation in the soil occur only if:

$$\frac{dq_p}{dt} + \frac{dq_l}{dt} < \frac{dq_i}{dt} \quad (5)$$

The solubility of the metals can be defined, in general terms, according to different possible cases:

- I) The solubility depends on the reactions of precipitation and solubilization. Therefore it is not related to the amount of metals present in the solid phase of the soil.

In this case we should not worry excessively about their potential increase in agricultural soils, because their bioavailability will not increase with time, and the amounts removed by the plants and by leaching will be constant, that is: $dq_p/dt = kp$ and $dq_l/dt = kl$

Equation (3) becomes:

$$\frac{d\Delta q_s}{dt} = k_i - k_p - k_l \quad (6)$$

- II) The solubility is regulated by reversible and irreversible adsorption processes.

This is the commonest case and with the highest number of experimental verifications, in which part of the metals added to the soil is irreversibly adsorbed. It is well known, in fact, that most of the processes of adsorption in the soil are not reversible and that the metals tend to bond with the reactive groups of the soil surfaces in an irreversible manner.

The following relation applies:

$$\Delta q_s = \Delta q_{rev} + \Delta q_{irr} \quad (7)$$

and the solubility of the metal is regulated only by Δq_{rev} .

Assuming that the rate of transformation of the chemical forms is of the first order according to the equation:

$$\frac{\Delta q_{irr}}{dt} = k_t \Delta q_{rev} \quad (8)$$

where k_t is a constant of velocity (years^{-1}). From (7) and (8) we have general equation as follows:

$$\frac{\Delta q_{rev}}{dt} = k_i - \frac{dq_p}{dt} - \frac{dq_l}{dt} - k_t \Delta q_{rev} \quad (9)$$

In this case the amount in solution, and therefore available for plant nutrition and influenced by leaching and percolation processes towards the water table, depends exclusively on the chemical forms adsorbed reversibly and not by the total amount in the soil.

We must, however, take into account that the validity of these models is always limited. This is because the relation between biological availability and the solubility of heavy metals is extremely complex. It depends, moreover, on the competitive and synergetic effects existing between the various metals, on the plant species cultivated, on the distribution and density of the root system, on the structural properties of the soil, on the processes of release of chelating

agents that occur in the rhizosphere and also on the varying humidity and temperature during the growing season. It is clear that modeling cannot take into account all these specific parameters. However, choosing the right plants to use and the best type of compost to apply, models enable us to plan applications of quality products over several years and assess, with a certain approximation, the accumulation of a metal with time, in a specific soil, so that any possible pollution can be avoided.

II. COMPOSTING AS A REMEDIATION TECHNOLOGY PROCESS-ORIENTED PERSPECTIVE

The composting process is currently viewed primarily as a waste management method aimed at organic waste recycling. In the latest years, many researches indicate that the composting process and the use of compost be also utilized as remediation technologies for soils contaminated with toxic organic compounds. Among the possible technologies composting and biopile are the most frequently used.

Composting is a technology that use controlled biological process to convert organic contaminants by microorganisms under aerobic conditions to innocuous, stabilized by-products. For instance the composting process promotes the degradation of a large number of hydrocarbons included PAH. Soil is excavated and mixed with bulking agents and organic amendments, and submitted to a composting process maintaining adequate levels of oxygen and humidity. The technology can be applied by the use of aerobic static pile in which compost is aerated with blowers or by windrow composting when soil and compost are periodically mechanically mixed and aerated with mobile equipments.

In presence of volatile contaminants off-gas control is necessary.

Biopile is a technology in which soil is excavated, mixed with amendments (also mature compost) and placed on a treatment area that is equipped with systems of leachate collection [10]. The pile is aerated and moisture, nutrients, oxygen, and temperature are maintained under control to promote the biodegradation process of organic contaminants (fuel hydrocarbons, pesticides, etc...).

A wide range of common environmental contaminants (TNT, PAH, TPH) degrades rapidly in the composting process. Many results, ranging from bench scale to field studies indicate that up to 30% of polluted soil by volume could be mixed with compostable materials to produce relevant degradation of several contaminants. Positive results have been reported about the effects of compost on petroleum hydrocarbon, and pesticides degradation in soil-compost mixtures, by using both soil composting and biopile treatments [11]-[15].

A common disadvantage of bioremediation methods is that they are very slow. The addition of compost can, significantly, reduce the remediation time required to degrade organic contaminants, from 20% to 40%.

A noteworthy decrease of degradation time was achieved also by addition of compost to the processes of landfarming in soil contaminated with petroleum hydrocarbons.

This technology is based on the deposition of a layer of excavated contaminated soil on the ground surface. The soil mass is stimulated by periodically turn over or till to aerate the mixture which is irrigated with water to stimulate the aerobic microbial activity. The leachates are collected and recirculated directly or after being purified.

Based on the data reported [16] many organic contaminants could be remediated, using compost, in only 2 weeks to 2 months, in contrast to the 6 months or more required for typical landfarming operations.

Some problems need to be taken into account in the utilization of these technologies. The degradation rate of specific contaminants is greatly influenced by the materials being composted. Incomplete mineralization of aromatic compounds can occur in composting or biopile systems, with the possible formation of potentially toxic intermediates. In all cases, biological reactions that characterize composting must be managed carefully to allow the degradation of organic pollutants (aliphatic and aromatic hydrocarbons, halogenated solvents, etc...) to proceed to the highest extent with formation of innocuous end products.

The process of soil composting has been demonstrated useful also in heavy metal contaminated soil. Co-composting of mine spoil with mature compost reduced metal bioavailability and Cu, Pb and As plant accumulation and promoted plant growing in mine soils [17]. Further application of compost in soil remediation, are those related to its use in combination with phytostabilization. Compost can promote plant establishment and growth in soil contaminated also by toxic metals, by improving soil physical properties also in mining environments [18]. Compost was successfully applied also in the remediation of an agricultural soil highly contaminated by Cu (1140 mg kg⁻¹), Zn (235 mg kg⁻¹) and Ni (141 mg kg⁻¹). Due to the very acidic pH (4.8), an excess of metal bioavailability promoted a very high uptake of heavy metals thus inducing phytotoxicity in plants, leading to a strong reduction in growth and biomass production. In these conditions phytoextraction was not practicable. The addition of compost produced more favourable conditions for the growth of plants, probably also due to the increase in fertility of elements such as carbon, nitrogen and phosphorous in the contaminated soil.

Moreover humus-like substances in compost were able to complex or adsorb heavy metals, thus reducing their bioavailability. By manipulating heavy metal bioavailability, with compost addition, allowed the use of phytoextraction technology also, in this highly contaminated site. This solution led to a cost reduction and improved the soil quality [19].

In conclusion of the potential use of composting ranges from programs aimed at organic waste recycling to application as remediation technology at contaminated sites.

The main driving forces for encouraging composting and compost production are related to the fact that composting can be considered as an important strategy to reduce the amount of MSW that is landfilled, and a sustainable source of stable organic carbon and slow-release nutrients. Moreover it is worth noting that, composting and biopile as bioremediation

technologies, are among the lowest cost methods for detoxification of soils contaminated with organic compounds with high efficiency and low environmental impact.

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