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TESI DI LAUREA

Compost heat recovery systems (CHRS): a sustainable solution for heat production

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Ai miei genitori, che mi hanno sostenuto durante questi lunghi anni, sia emotivamente che economicamente;
ai miei compagni di corso diventati amici stretti;
ai miei amici di sempre.

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First part: Generalities

1. COMPOSTING

Composting can be defined as the biological aerobic degradation of biodegradable organic matter and transformation into organic compounds by aerobic microorganisms.

The treated material consists of putrescible solid/semi-solid organic substances which is transformed into carbon dioxide (CO2), water vapor (H2O) and complex humic-like compounds.

The whole aerobic degradation mechanism is an exothermic process and energy, in terms of heat, is released and it can be extracted for further uses (Bajko et al., 2018).

The main product of this process is compost, which is used for agronomical purposes.

This material containing N, P, K nutrients is in fact an organic soil improver and it allows a lower use of chemical fertilizers in open field agriculture and a lower use of peat for the preparation of growing substrates in floriculture.

Other benefits of composting include the reduction in wastes volume along with the destruction of weed seeds and pathogenic bacteria.

1.1. Biomass aerobic composting

Biomass aerobic biodegradation is an exothermic natural process in which different microorganisms degrade the organic substrate into stabilized organic matter; remove pathogens and release CO_2, water and heat, as seen in figure 1.

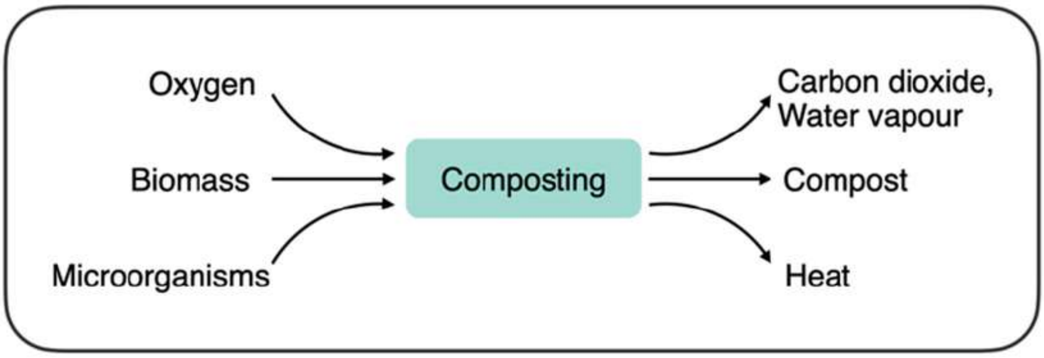


Figure 1: General representation of composting process

Composting starts once the organic wastes are mixed but only if the overall optimal conditions of the system are met in terms of moisture content, oxygen availability, nutrient balance, and presence of microorganisms.

These composting organisms require the presence of four precise compounds to work properly:

- Carbon, which is the major reactant for the oxidation reaction.
- Nitrogen, essential for the growth and reproduction of organisms that oxidize the carbon sources.
- Oxygen, necessary for the survival of aerobic microorganisms, which use it in the decomposition process to oxidize carbon.
- Water, to maintain microbial activity without causing anaerobic conditions and to assure a thin layer of water located on the surfaces of the solid matter.

The key parameter for composting is temperature. Since microorganisms produce heat by degrading organic compounds, it's possible to monitor the progress of the process through this parameter.

Therefore, a correct evaluation of the degradation rate, degradation of the materials, required treatment time and physical conditions (water content, oxygen availability) can be obtained by analyzing the temperature of the pile.

1.2. Process phases

It is possible to notice that, considering the temperature as the primary analyzed parameter, composting usually follows an established pattern.

Under optimal conditions, composting proceeds through four main phases that have been identified based on temperature variations, as shown in figure 2, besides an initial period of maturation due to microorganism acclimatization:

➢ Mesophilic phase: temperatures in the range of 20 to 45 °C, it can last for a few days.

➢ Thermophilic phase: temperatures in the range of 45 to 70 °C, it can last from a few days to several weeks/months.

➢ cooling phase and maturation or curing phase: where within a few months the temperature of the pile slowly decreases up to ambient temperature.

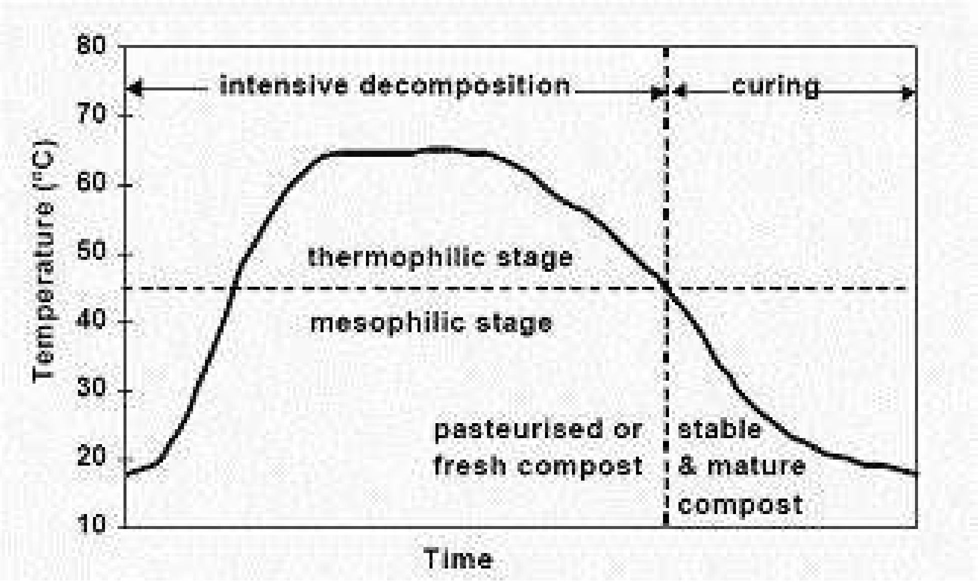


Figure 2: *representation of the four different stages of aerobic process along time*

1.1.1 Mesophilic phase

Mesophilic phase is the phase of composting that occurs between 20 °C and 45 °C.

At the beginning of composting, mesophilic bacteria like fungi, actinobacteria and bacteria generally referred to as *primary decomposers*, degrade soluble and easily degradable compounds of organic matter, such as sugars, proteins, and lipids.

Temperature starts to rise spontaneously as heat is released from exothermic degradation reactions. As the temperature rises above 40° C the mesophilic microorganisms become less competitive and they are replaced by others that are thermophilic (heat-loving). At temperatures of 55° C and above, many microorganisms, are destroyed or inhibited. This phase lasts from a few hours to a few days.

1.1.2 Thermophilic phase

The thermophilic stage (performing between 45-65 °C) consists of a quick decomposition of the organic matter with high oxygen consumption.

The decomposition involves a great quantity of easy molecules as sugars and lipids (ready to be metabolized and transformed into intermediate composite as volatile fatty acids) and a high equivalent consumption of oxygen.

The result of the high oxygen availability, kept via aeration or turning, and the presence of a high fermentability composting substrate, lead to a great heat production and so temperature increase consequently.

The thermophilic phase can last from a few days to several months.

The final product of this stage is fresh compost, a sanitized (with absence of pathogens) material sufficiently stabilized by the bacteria activity.

1.1.3 Cooling and maturation phase

It is a mesophilic stage*; as opposed to the previous phase, this one* presents a slower decomposition and lower oxygen consumption. In fact, most easily biodegradable compounds have yet disappeared, and the remaining complex organic molecules usually involves slower processes for the decomposition.

Also, the death of a large part of the microbial population due to the lack of nutriment, interfere with the decomposition time and the oxygen consumption.

In the maturation phase, the metabolic processes decrease in intensity and fungi and actinomycetes appears next to bacteria. These new microbial groups degrade starch, cellulose and lignine, essential compounds of humus. In this phase the temperatures are lowered to values of 40-45 ° C and then gradually go down, stabilizing around the environmental temperature.

Generally, this phase lasts from a few weeks to several months.

The final product is the mature compost, a stable dark material, with a structure like soil, rich in humic compounds.

1.2. Organisms in a composting pile

Composting heap is characterized by different of aerobic microorganisms during the various composting phases, as seen in figure 3.

Microorganisms such as bacteria, fungi, and actinomycetes account for most of the decomposition that takes place in a composting pile and are considered chemical decomposers, while macroorganisms such as mites, ants, flies, millipedes and worms are considered physical decomposers because they grind, suck, bite and chew materials into smaller pieces.

1.2.1. Aerobic Bacteria

Bacteria are single-celled and structured as either rod-shaped bacilli, sphere-shaped cocci or spiral-shaped spirilla and they are predominant, in terms of numeric presence compared to other microorganisms, inside the composting pile.

As they are able to chemically break down a high variety of organic compounds, they are considered the most important decomposer of the process and, also, the primary responsible for most of the decomposition and heat generation within the composting mass.

Bacteria oxidize organic material, especially the carbon fraction to obtain energy, and nitrogen to build protein in their bodies so they can grow and reproduce.

As said, aerobic bacteria are the preferred organisms since they provide the most rapid and effective composting but, as downside, they have difficulty escaping unfavorable environmental conditions due to their small size and lack of complexity. Moreover, they are susceptible to changes in oxygen, moisture content, temperature and acidity which can make bacteria die or become inhibited.

There are different types of aerobic bacteria that work in composting piles, and they vary according to the pile temperature. Psychrophilic bacteria work in the lowest temperature range, between 10 and 25° C.

Then mesophilic bacteria, working in the temperature range 20-45 ° C, rapidly decompose organic matter, producing acids, carbon dioxide and heat. When the pile temperature rises above 45° C, they begin to die, and they are replaced by thermophilic bacteria which find their best range at 50-55 °C but decreases dramatically at 60 °C or above.

When conditions become unfavorable, bacilli survive by forming endospores, thick-walled spores that are highly resistant to heat, cold, dryness, or lack of food. They are ubiquitous in nature and become active whenever environmental conditions are favorable.

The decomposition process is continued by these thermophilic microorganisms, raising the pile temperature up to 55-70 ° C, where it usually stabilizes.

Unless a pile is constantly fed new materials and turned at strategic times, the high range temperatures typically last no more than several weeks. This is because thermophilic bacteria use up too much of the degradable materials to sustain their population for any length of time.

When the readily biodegradable matter exhausts, the thermophilic bacteria decline and the temperature of the pile gradually cools off, leading the mesophilic bacteria to become dominant and to consume the remaining organic material with the help of other organisms.

1.2.2. Acetinomycetes

Beyond various types of bacteria, other microorganisms contribute to the degradation process. Actinomycetes are higher-form bacteria, without nuclei, sensitive to pH changes and they grow multicellular filaments like fungi.

They act in the moderate heat zones of a compost pile, playing an important role in degrading complex organics such as cellulose, lignin proteins and chitin due to specific enzymes that enable them to chemically break down these resistant compounds. As they reduce materials, they liberate carbon, nitrogen, and ammonia, making nutrients available for higher plants or organisms.

1.2.3. Fungi

Like bacteria and actinomycetes, fungi, which includes molds and yeasts, are responsible for organic matter decay in a compost pile, especially complex plants polymers.

They are primitive plants that can be either single-celled or many-celled and filamentous.

They can attack organic residues that are too dry, acidic, or low in nitrogen for bacterial decomposition.

Most fungi are classified as saprophytes because they live on dead or dying material and obtain energy by breaking down organic matter in dead plants and animals.

Fungi prefer medium-low temperatures, 20-25° C and this is why they are active during the final stages of composting, digesting compostable materials.

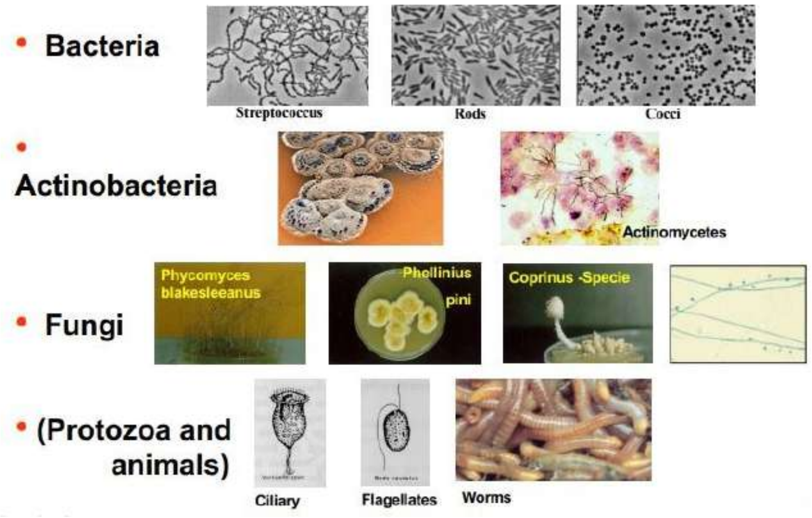


Figure 3: Actors of the decomposition in composting. In order from top to bottom: Bacteria, Actinobacteria, Fungi, Protozoa and animals

1.3. Parameters affecting composting

Aerobic stabilization process can be monitored through several factors that can influence the whole process and the quality of the obtained material.

1.3.1. Aeration and Oxygen content

Most of the microorganisms present in the composting process need oxygen as electron acceptor for their metabolism and to produce energy.

CO_2, heat and stable organic material are produced during the degradation reactions.

So, O_2 and CO_2 concentrations are parameters used in an aerobic process for the evaluation of the degradation rates, i.e., the amount of degraded organic carbon.

Oxygen demand depends on temperature, composition, and water content of the material.

Initially, when easily biodegradable compounds are abundant and the microbial activity is at its maximum, oxygen demand reach a peak, with a consequent minimum in oxygen content and a maximum CO_2 production.

During this initial phase, an optimal oxygen concentration is in the range of 10 – 15 % in volume within the pore space of the compost (from literature)

For easily degradable substances aerobic microorganisms approximately need 1.2 – 1.7 l O_2/(kg TS*h) resp. 5.9–7.9 l air/(kg TS*h) (M.C. Lavagnolo, CSWM course slides, 2021).

As the readily biodegradable organic substance are oxidized, the microbial activity and so the degradation rates slow down.

This entails a decrease in the CO_2 concentration and an increase in the O_2 concentration.

For this step, the oxygen concentration can be adjusted to values between 5 and 10 % in

volume and, in terms of mass to be treated, the required oxygen can be established as 0.55 l O_2/(kg TS*h) respectively 2.6 l air/(kg TS*h) (M.C. Lavagnolo, CSWM course slides, 2021).

O_2 concentration should be carefully monitored because the process aims not to the complete demolition of the organic substance yet to a stabilization and humification phase, which requires lower levels of oxygenation.

If the average O_2concentration decreases below 5%, anaerobic conditions can develop, with the death of aerobes microorganism and a slower decomposition rate.

Moreover, the final products of anaerobic microorganisms' metabolism are organic acids, amines and hydrogen sulphide (H_2S), which are smelly and, in some cases, are toxic to plants.

Said this, it is clear that it's necessary to maintain an adequate level of oxygen also to keep the anaerobic activity to a minimum.

Doing so, the compost pile acts as a bio-filter to trap and degrade the odorous compounds produced by the anaerobic decomposition.

Oxygenation within the windrows or pile may be refilled by turning the materials over with a front-end loader or by means of mechanical agitation with a special compost turner.

Other techniques to maintain the correct O_2 concentration in the compost, that are considered better with respect to manipulations or turnings, can be forced air fans, implementing a suction effect with vacuum pumps, or creating holes in the aeration pipe.

These are not the only interventions useful to maintain the correct O2 concentration in the compost: natural aeration method occurs when air warmed by the composting process rises through the pile, bringing in fresh air from the surroundings, resulting in a convective motion generated by the delta temperature between these two environments.

From literature we know the process of turning compost only increases oxygen level for a very short time until oxygen levels return to their pre-turned levels.

The use of passive aeration with perforated pipes in the compost pile achieves the goal of aeration without having significant water and heat loss associated with turning.

A common equation, is used to calculate aeration hole size (Smith and Aber, 2017):

$$DH = \sqrt{\frac{(d^2 * s)}{(L * 12)}}$$

Where:

- DH is the hole diameter;
- d is the pipe diameter in inches (inch);
- L is the pipe length in feet (ft);
- S represents the hole spacing (inch).

Before investigating the main aeration techniques, it is important to understand the oxygen transport mechanisms.

Oxygen can move from the open air to the composting material through two mechanisms: convection and diffusion.

Convection can be categorized as either "forced", driven by mechanical means, or "natural", caused by the buoyancy of hot air.

In a system with mechanical aeration, blowers move air through the larger pores at relatively high velocities.

In a passive system, hot air can often be seen slowly rising out of the tops of piles, and natural convection pulls cool oxygen-rich air in to replace it.

Water filled pores create a major impediment to uniform convective air movements, by creating zones of high resistance. As air short-circuits through unsaturated zones, the aerobic regions generate more heat and become even drier, while the wetter regions become anaerobic.

One of the principal functions of mixing and turning compost is to redistribute moisture, to minimize this preferential airflow and the nonuniform decomposition that results.

Furthermore, oxygen diffusion through the smaller pores and into the aqueous film surrounding compost particles is essential to maintaining aerobic conditions for the active microorganisms.

Figure 4 below represents the main aeration techniques for composting.

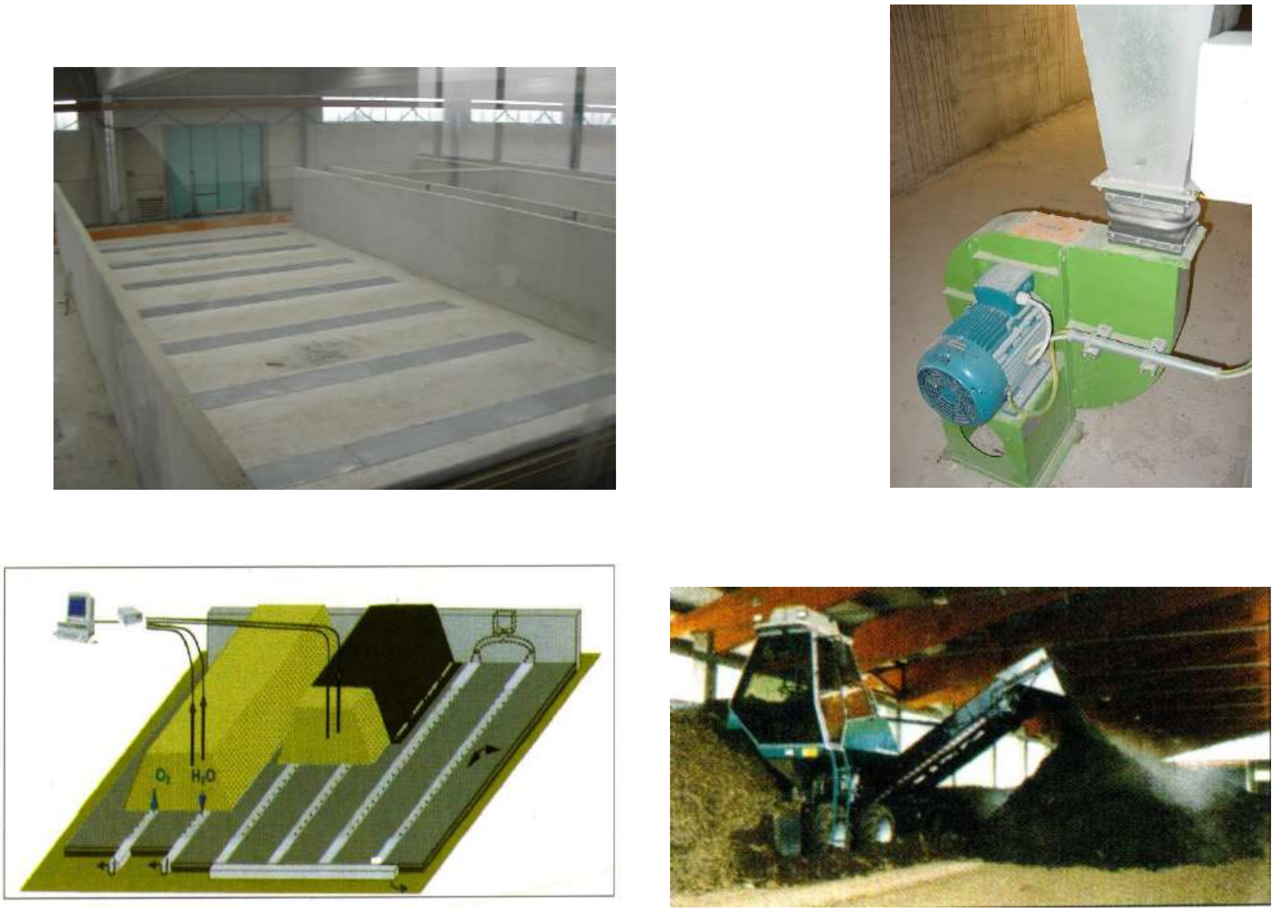


Figure 4: Aeration techniques for indoor and outdoor composting

1.3.2. Carbon -Nitrogen ratio (C/N)

Carbon (C), nitrogen (N), phosphorous (P), and potassium (K) are the primary nutrients required by the microorganisms involved in composting.

Carbon is used by microorganisms for both energy and growth, while nitrogen is essential for proteins, and it is fundamental for cell growth and reproduction.

Even if phosphorus and potassium are usually largely present within the organic materials, carbon and nitrogen play a major role during the process and so their amounts must be initially assessed and then adjusted in case of need, to reach an optimal balance of substrates.

The ratio of carbon to nitrogen is referred to as the C:N ratio and it can be considered a fundamental quality parameter utilized to describe the amount of carbon available, in relation to nitrogen, for the microorganisms.

For C:N ratios below 20:1 (excess in nitrogen), nitrogen is removed from the soil, while if C/N <<15 we can face a rapid microbial growth, accelerated decomposition and this can lead to the conversion of ammonium of ammonia, creating a toxic environment for plant growth, and unpleasant odors as oxygen is used up and anaerobic conditions ensue.

For C:N ratios above 40:1 (excess carbon), not enough N is available for the growth of microorganisms and the process slows dramatically.

The optimum ratio for composting is generally considered to be around 25:1 to 35:1 parts carbon for each part nitrogen by weight.

To theoretically assess the initial amounts of these two elements for the entire composting mass, it can be used the C/N ratio for each one of the compost ingredients according to the formula:

$$C/N_M = \frac{\Sigma(\mathrm{C}/N_{1\ldots n}\ x\ t_{1\ldots n})}{\Sigma t_{1\ldots n}}$$

Where C/N_M is the C/N ratio of the resulting mixture, $\mathrm{C}/N_{1\ldots n}$ is the ratio of the individual components of the mixture (from 1 to n) and $t_{1\ldots n}$ is the mass of the individual components of the mixture in tons (from 1 to n).

The values for each material to be composted can be obtained by associating the carbon content values to the TOC (Total Organic Carbon) and the nitrogen content ones to the TKN (Total Kjeldahl Nitrogen).

TOC can be measured in laboratory or estimated by using the formula: $TOC(\%) = \frac{VS(\%)}{1.8} = \frac{100-Ash(\%)}{1.8}$

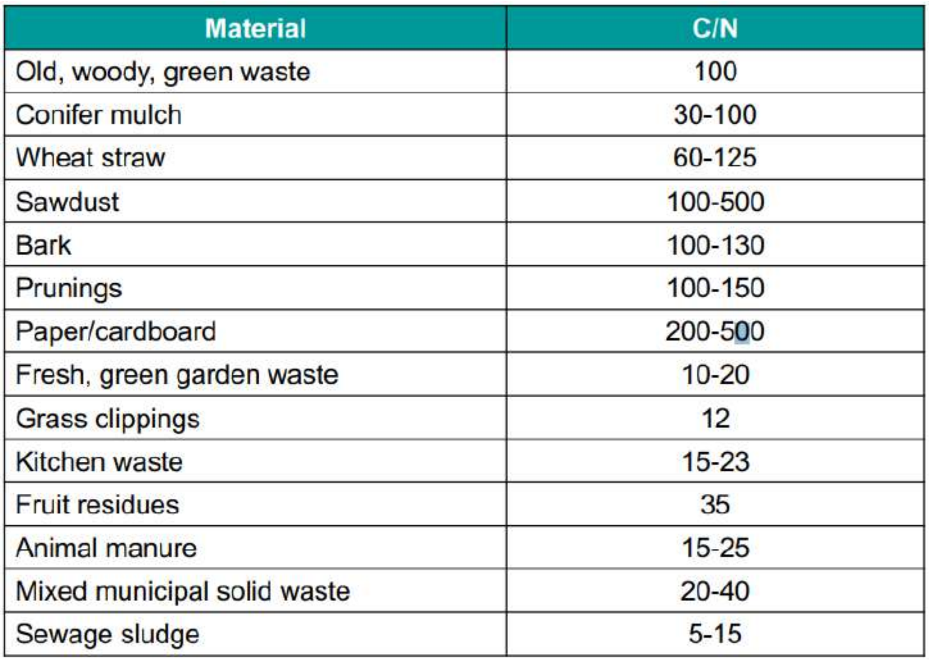
Where TOC (%) is the percentage of total organic carbon, VS (%) is percentage of volatile solids, Ash (%) is percentage of ash content expressed as percentage of residues after muffle furnace ignition at 550 °C for 6h.

Then the expression of the C/N ratio becomes calculable analytically for each material or for the entire composting mixture in the form of:

$$\frac{C}{N} = \frac{Carbon\ content\ (\%)}{Nitrogen\ content\ (\%)} = \frac{TOC\ (\%)}{TKN\ (\%)}$$

Having a look at figure 5, it’s easy to notice that compost materials that are green and moist like grass, plant cuttings, and vegetables scraps, tend to be high in nitrogen.

Brown or woody materials such as autumn leaves, wood chips, sawdust, and shredded paper are high in carbon.



Material	C/N
Old, woody, green waste	100
Conifer mulch	30-100
Wheat straw	60-125
Sawdust	100-500
Bark	100-130
Prunings	100-150
Paper/cardboard	200-500
Fresh, green garden waste	10-20
Grass clippings	12
Kitchen waste	15-23
Fruit residues	35
Animal manure	15-25
Mixed municipal solid waste	20-40
Sewage sludge	5-15

Figure 5: Typical C:N ratio of common compost ingredients.

1.3.3. Nutrient balance: the Carbon/Phosphorus relationship

Carbon and Nitrogen are not the only main nutrients that influence the composting process and the quality of compost.

Phosphorus, potassium, and trace elements (calcium, iron, boron, copper, etc.) are also essential to microbial metabolism. Normally these nutrients are not limiting because they are present in enough concentration in organic material and farm manure.

The value of the optimal ratio between carbon and phosphorous is estimated in the range of 100:1 to 200:1.

1.3.4. Toxic compounds

Toxic substances are naturally present in the environment, soil, and food so they can be found inside the final produced compost, where concentrations limits are established by the regulations because of their potential for toxicity for humans, animals, and plants.

Toxic compounds usually present in compost are generally heavy metals (Cr, Cu, Ni, Cd, Pb, Zn, Hg).

The term “heavy metal” has no precise chemical definition, but it indicates a variety of toxic elements, most of them metals or metalloids heavier than carbon that are a source of serious environmental concern.

During composting procedure complex pesticide molecules are break down but heavy metals are resistant to the whole process and even if many of these elements are required for the plant growth in small doses, an abundance of the compounds can inhibit the biological process of degradation because of their interference with the bacterial activity.

To contrast the bioaccumulation of these heavy metals it is possible to improve the source collection and separation of the wastes before composting process and in general, to improve the quality of the entering material.

1.3.5. Moisture content (MC)

Water is a fundamental element for the life of most of the microorganisms present in a composting process, because their degradative activity occurs most rapidly in thin water-films on the surface of organic materials, and they can only utilize organic molecules that are dissolved in water.

Since water and air compete against each other to fill the empty spaces (pores) of the material, if too much water is present, it will limit the air distribution and motion through the pile.

From experience we know that the process slows down when the moisture content is below 40% and it becomes completely inhibited when it reaches a percentage equal to 25-30%, with the compost pile that could be subjected to spontaneous combustion.

Humidity generally decreases over time as composting process goes on due to the evaporation facilitated by the exchange of air in the mass. It is therefore necessary to ensure an optimal range of humidity values of the composting material which are generally set between 40% and 65%: this range is achieved in the initial phase by correctly mixing the materials to be composted, considering that, for example, wood, straw and corn stalks will need more moisture than leaves, while food waste or grass don’t require additional moisture.

Also, a further humidification of the compost pile using different washing systems, may be needed during the process. The water required for compost making may be around 800-1200 litres for each cubic meter of finished compost (Courtney, 2009).

If a level of humidity above 65% arise, water would occupy most of the pore spaces of compost and this could lead to some difficulties in the diffusion of oxygen in the mass. Also, this limited diffusion of oxygen in the mass can lead to the establishment of anoxic conditions resulting in unpleasant odours and slower degradation. (ARPAV, 2002).

It is possible to also compost materials with humidity close to 80% (sludge from treatment plants, grass, zootechnical manure) by mixing these products with dry materials like sawdust, straw, dry leaves, so that the average mass moisture does not exceed 65%.

1.3.6. pH

Aerobic decomposition process rarely requires modifications in the pH of the finished compost as it is a self-regulating process regarding this parameter.

The value of pH varies greatly during the process, but the finished compost should be neutral or slightly alkaline with optimal values between 6.5 and 8.

During the first phase of composting, in which organic acids are released, the pH tends to fall, then immediately rise during the thermophilic phase because the organic acids become neutralized and because of the release of ammonia.

In the final phases it tends to lower again, returning to values around neutrality, thanks to the activity of nitrifying bacteria which transform ammonium into nitrous and nitric acid in sequence.

If anaerobic conditions develop during the process, organic acids may accumulate rather than break down, leading to an excessive acidification of the system that will lead to the generation of an unsuitable environment for most of the microorganisms, especially bacteria.

So, pH is an important parameter to monitor to guarantee a healthier environment for the living organisms that have to carry out the degradation and if needed, it is possible to aerate or mix the system to reduce this acidity.

When measuring the pH, it’s important to keep in mind that, as the materials that compose the mixture are non-homogeneous, pH may vary from location to location.

Samples to be measured should be taken from different spots and then mixed to do a combined pH test or test each one individually.

1.3.7. Temperature and heat loss mechanisms

During composting, heat is produced as a by-product of the microbial degradation of organic material, and it depends mainly on the degradation rates, type of microorganisms at work, size of the system, moisture content, nutrients that compose the material to be treated and the ambient temperature.Composting has various stages and associated optimal temperatures so it’s not feasible to indicate a fixed range of temperatures among which the process finds its best operating way.

Thermophilic temperatures are desirable as a necessary condition for sanitation because high temperature maintained for several days, are able to destroy more pathogens, weed seeds and fly larvae in the composting materials.

What is very important to evaluate is that the compost does not exceed a temperature threshold at which microorganisms being to die. If this over-heating occurs, the composting process will be longer to complete as decomposers could die and harmful bacteria like Salmonella could arise.

If temperature increases too much, it can be lowered by turning or by varying the oxygen supply.

Especially for thermocomposting, where the main goal is to extract and recover the generated heat from the composting mass, as is going to be illustrated in the next chapter, it is important to understand the heat loss mechanisms that occurs in a pile and how to limit them to increase the possible efficiency of the heat recovery system.

For what concerns these heat losses, in a composting pile essentially the temperature at any point during the process depends on how much heat is being produced by the microorganisms, balanced by how much is being lost to the surroundings through conduction, convection and radiation.

Through conduction, energy is transferred from atom to atom by direct contact and this takes place usually at the edges of a compost pile, where conduction causes heat loss to the surrounding air molecules.

Convection instead, refers to the transfer of heat by movement of a fluid such as air or water. When compost gets hot, warm air rises within the system, and the resulting convective currents cause a steady but slow movement of heated air upwards through the compost and out the top. In addition to this natural convection, some composting systems use "forced convection" driven by blowers or fans. This forced air, in some cases triggered by thermostats that indicate when the piles are beginning to get too hot, increases the rates of both conductive and convective heat losses. Much of the energy transfer is in the form of latent heat, i.e., the energy required to evaporate water.

The third mechanism for heat loss, radiation, refers to electromagnetic waves: the warmth generated in a compost pile radiates out into the cooler surrounding air.

The smaller the bioreactor or compost pile, the greater the surface area-to-volume ratio, and therefore the larger the degree of heat loss to conduction and radiation. Insulation helps to reduce these losses in small compost bioreactors.

It is important to notice that drier compost mixtures tend to heat up and cool off more quickly than wetter mixtures.

1.3.8. Substrate physical structure (bulk density, porosity, particle size)

The bulk density of compost is a measurement of the mass of material within a given volume: generally, dry bulk densities are in the range 100 to 400 kg/m^3 whereas wet bulk densities are typically 500 to 900 kg/m^3.

Higher values of bulk density imply an increase in mass and a decrease of porosity in favors of the moisture content (water fill the empties volume) and air volume, which negatively affects the aeration mechanism of the composting pile and leads to slower degradation rate or even anaerobic conditions.

Porosity indicates the pore space in compost that is not occupied by solid particles or water, and it is indicated as a percentage between the volume occupied by the empty spaces inside the biomass and the volume occupied by the biomass itself.

As voids are occupied in part by air and partly by water, the free porosity indicates the percentage of volume occupied by air.

Thus, porosity is strictly correlated to the air flow as it influences the possibility for the compost material to maintain the quantity of oxygen necessary for the aerobic degradation.

Usually, a minimum porosity of 5% is needed for the aerobic degradation, while the anaerobic one, occurs with less 1% of O_2. Under optimal conditions, the total porosity stands at values between 35% and 50%.

Another important parameter which has an influence on the porosity is the size of the particles in the compost pile.

In general, the smaller composting materials, achieve higher composting rates: smaller materials have greater surface areas in comparison to their volumes than large particles, and more particle surface is available for microorganisms' decomposition in the initial stage of the process and this guarantee higher degradation rates.

Moreover, small particle sizes reduce the number of large pores and increase the probability that oxygen will need to diffuse a long way through small pores (which are more likely to be filled with water).

The optimal material size is of the order of 25-75 mm. If the composting materials have smaller dimensions (grass, manure), it will be necessary to use structuring materials (bark, wood chips, etc.).

Particles shouldn't be too small as they may compact too much, not allowing oxygen to flow in the void spaces with a consequent decrease of the degradation rate.

On the contrary, too large material can lead to an excess of aeration, forming remarkable aeration channels, dropping the temperature, and slowing down the degradation process.

It is important to notice that whether the particle size decreases, will also decrease the porosity and will increase the bulk density; vice versa, if it increases, will decrease the bulk density and will increase the porosity.

1.4. Biological stability and maturity

Nowadays the only valuable final product of coming from the composting plants treatment is the stabilized organic material named compost.

However, as it will be seen in the next chapter, some studies are investigating the possibility to recover and reuse the heat generated during the process.

Finished compost has to meet certain requirements: it must be both stable, i.e., resistant to decomposition, and mature, i.e., ready for a defined end-use with a guaranteed sanitization level.

If these conditions are respected the material can safely be packaged and transported and used with the certainty of no adverse effects during its use.

As said, compost stability and compost maturity are the two terms often used to describe the rate of decomposition and transformation of the organic matter in compost, but they are not synonymous.

Compost stability refers to the compost in which the rate of energy release due to microbial degradation of the substrate is equal to the rate of energy loss in the environment. It could be depicted as the resistance of compost organic matter to further rapid degradation, and it is directly associated with the rate of microbial activity.

A material is considered unstable if it contains a high proportion of biodegradable matter that may favor high microbial degradation.

Compost maturity is an important factor to be analyzed to determine if finished compost is already suitable for saleability and for agricultural purposes.

It is therefore a term used to indicate the level of phytotoxic substances in composts and its suitability for plant growth: compost in an immature phase can release compounds harmful to plants, compete with plants for oxygen, and pull nitrogen out of the soil.

Many methods for evaluating stability and maturity are available and, as a there’s no single, and standard approach for both compost stability and maturity, it is better to use a combination of tests whose results are to be analyzed and interpreted, also considering the specific law.

Biological stability is commonly assessed by three methods: calorimetry, respirometric index (RI) and CO2 evolution; while maturity is related to other parameters like humification index (HI), water soluble C/N ratio, optical density, changes in nitrogen species, enzyme activity germination tests (GI), calorimetric methods and many others.

The mainly used parameters used to assess compost stability and maturity are described forward.

1.4.1. Respirometric index (RI)

The respirometric index comes out from laboratory tests that aim to determine the microbial respiration in a closed system, for a certain period (4 to 7 days) and in controlled temperature conditions, based on the estimation of oxygen consumption of an organic substrate through the monitoring of O_2 uptake or CO_2production resulting from the degrading activity of compost microorganisms.

During the composting process, the hourly oxygen consumption and, consequently, the respirometric index tend to decrease as a consequence of the decrease in the concentration of easily degradable organic compounds. This parameter is therefore inversely correlated with the biological stability of the material: the higher the value of the index, the less stable the organic material and vice versa.

Approaches based on oxygen uptake rate are classified into two different classes: statics and dynamics. (Adani *et al.* 2001). They depend on whether oxygen absorption is carried out in the absence (static) or presence (dynamic) of air, i.e., oxygen, supplied by aerating the biomass during the tests.

In the dynamic method (DRI) the O_2 diffusion limitations are minimized, and this is particularly important since it is well known that biological reactions that take place within solid substrates are often limited by the O_2 transfer rate. Static methods (SRI) do not include a continuous O_2 supply during the assay.

Both can be performed either with solid or liquid samples. However, it is found DRI, and SRI values have almost the same magnitude, with the latter usually a little smaller since it lacks a continuous airflow that supports the transfer of oxygen to biomass. In both cases, the quantity of oxygen consumed per kg of volatile substance is measured in the time unit of one hour.

In the first 10 days during composting, it is shown that the DRI and SRI increase initially but then decrease with increasing composting time, so when it became more stable. It is known that the DRI tend to be higher than the SRI because the continuous air flow in a dynamic system supports the transport of oxygen to biomass.

One of the most common laboratory devices able to determine respiration activity, both for dynamic and static configuration, is called SAPROMAT®.

It is an electrolytic respirometer designed as a closed system composed of several test vessels with electrolytic cells that act as manometers (pressure control gauge) and oxygen generators/suppliers.

The organic material to be tested is put inside the vessels, is degraded by microorganisms, with a resulting consumption of oxygen and CO_2 production by microorganisms during the respiration activity and is absorbed by a base, like sodium hydroxide (NaOH) or potassium hydroxide (KOH).

This induces the formation of a negative pressure within the samples that gives a signal to a sensitive pressure sensor connected to an electrolytic oxygen production cell.

The secondary cell, once the input of the detected pressure drop is received, starts releasing oxygen from a sulphuric acid solution and it continues until the initial pressure is re-established.

In Figure 6 (a,b) are shown the static and dynamic respirometer while in figure 6 (c) all the elements needed for the measurement are represented.

In particular, the adaptation for dynamic conditions is obtained by including a system to circulate air through the organic sample and a new reactor vessel design. The new dynamic respirometer design contained an air inlet, an air outlet, and a metal grid to support the solid biowaste or compost sample. The air circulation system included a rotameter, a valve, and an external compressor, allowing different airflow rates through the solid sample to be used.

The O2 concentration data acquisition system is adjusted to detect a value every 6 hours. The total duration of the test could be 4 or 7 days. With this device is possible to trace the quantity of O_2 consumed during the oxidative process; the appliance is set so that one click is equal to 0,25 mg of O_2.

The formula for calculating the amount of O_2 consumed after 4 days, expressed in O_2 mg/g ST, could be presented as follow:

$$IR_4 = \frac{n^\circ\ of\ clicks\ after\ 4\ days * 0{,}25\ O_2}{mg\ introduced\ material * ST(\%)}$$

Where IR4 represents the exchange activity after 4 days, while ST is the percentage value of total solids obtained by loss to incineration at 105 °C.

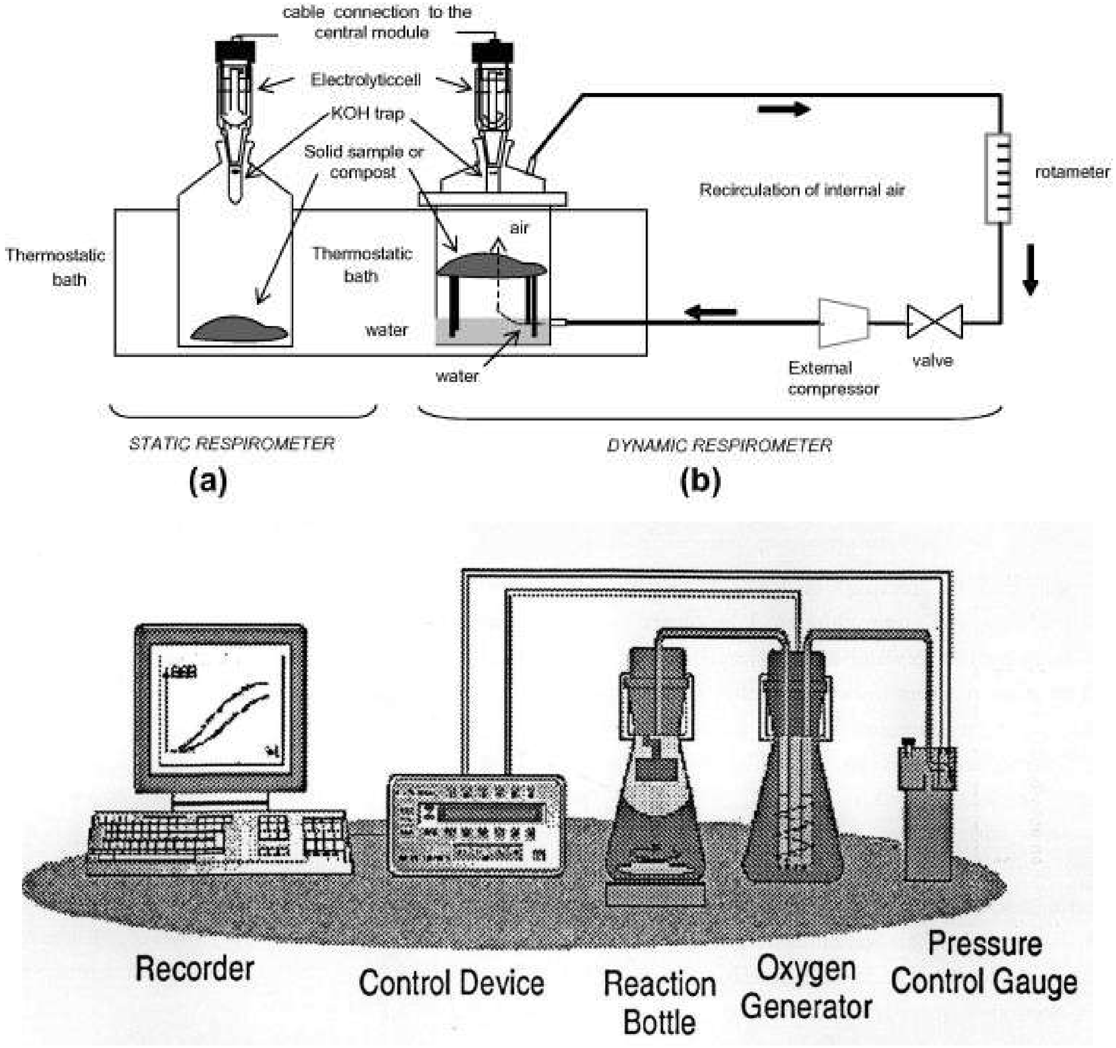


Figure 6: *Sapromat devices with an example of the dynamic and static configuration*

1.4.2. Germination Index (GI)

This index can estimate the maturity of compost through the germinating power and root growth of seeds in watery extracted samples of compost under analysis.

It allows to find the presence of phytotoxic substances which are not sign of maturity in the compost. These substances are mainly represented by compounds derived from intermediate transformations (acetic acid, volatile fatty acids, phenols, etc.); with compost maturing, these intermediate compounds undergo mineralization and complexation processes, becoming more stable and less phytotoxic.

The test begins by mixing water with compost samples until an 80-85 % moisture content and with a contact time of a couple of hours.

Then, a centrifuge and a membrane filter are used to separate the solid phase from the aqueous one.

The final step is the preparation of several liquid samples where the aqueous extracts are diluted with water at a concentration of 30 %, 50 %, 75%.

At this point, selected seeds for a rapid germination, are placed inside Petri dishes above a filter paper moistened with the previous diluted samples of compost' eluate. It is now required a period of incubation of several hours and at its end, the number of seeds germinated is counted and the radical length of the roots is measured.

A compost with a germination index higher than 60%, at the 30% dilution, is considered non-phytotoxic.

The index is obtained from the average of the germinated seeds, for the radical length in percent compared to a witness in the water, as in the formula:

$$GI(\%) = \frac{G_C * L_C * 100}{G_B * L_B * 33}$$

G_C and G_B represent the average of the number of seeds germinated respectively in the sample and in the witness in the water; while L_C and L_B describe the average of the lengths of the seeds' rootlets germinated respectively in the sample and in the witness in water (expressed in millimeters).

1.4.3. Humification index (HI)

The humification index is used to evaluate the degree of compost maturity and it assumes that during the humification process non-phenolic materials are decomposed to produce polyphenolic substances.

During the composting process, wood wastes, non-humic substances (non-HSs), such as polysaccharides and lignins are degraded and then polymerized to produce humic substances (HSs), organic matter that has reached maturity.

During this transformation, from non-humic to humic substances, there's a progressive enrichment in the phenolic functional groups of the organic matter.

Moreover, during the process the material is gradually consumed by the contemporary proceeding of mineralization and so there's a subsequent decrease of the extractable fraction of the labile organic substance.

The index is calculated chemically as the ratio of non-humified (non-phenolic) to humified (phenolic) organic carbon after extraction with alkaline sodium pyrophosphate.

The separation is done on small polyvinylpyrrolidone columns; phenolic substances are adsorbed on the resin at low pH and eluted by 0.5 M sodium hydroxide.

The humification index assumes values that are much smaller the greater the quantity of humic substances presents in the extract and generally assumes values lower than 0.5 for humified substrates (soil extracts, humid peat, mature compost) while it assumes values greater than 1 for non-humified materials, such as compost and/or non-mature sludge and organic fertilizers.

For the determination of the humification index it is normally used the method Sequi et al.

$$HI = \frac{NH}{HA + FA}$$

Where: HI is the humification index, NH is the not humidified fraction, HA are humic Acids, FA are fulvic acids and the sum (HA+FA) is the humidified fraction.

2. THERMOCOMPOSTING

2.1. Description of the plant

Thermocompost, also called Composting Heating Recovery System (CHRS), is a biorefinery plant able to generate thermal energy from the recycling and composting of residual biomasses from forestry, agriculture, and residues from households.

This heat recovery technique from composting can be subdivided into three phases: heat production, heat capture and heat utilization.

One of the main characteristics of these plants is the necessity to involve very large volumes of residual biomasses and, as a consequence, wide spaces are required to implement a CHRS. For this reason, CHRSs are plants that, in their most traditional configuration, are ideal to be implemented in decentralized environments by farmers, farmhouse owners or private households with large outdoor spaces around the building and, potentially, huge amounts of residual biomasses coming from gardening maintenance or agricultural activities that need to be managed.

According to literature data and direct experiences, average CHRS dimension is between 25 and 55 m^3, but even larger plants can be implemented if enough space and biomass are present.

CHRS are usually installed in decentralized areas where large spaces are available (from 10 to 50 square meters) and high quantities of biomasses are present or produced but they can also be installed at domestic- or farm-scale.

This aspect represents the first and main limitation to the implementation of full-scale CHRS as domestic heating system to replace most traditional heating systems: the volumetric thermal power generated per unit of volume of organic substance is quite low, when compared with the efficiencies of other heating systems.

Diffusion at industrial/commercial scale is low due to the difficulties related to the contraposition of CHRS heat output and industries' energy needs.

These systems can present different designs according to the thermal needs to be fulfilled, the feedstock composition, installation location, climate and other several factors.

One of the most used set-ups consists of a pile of the selected organic materials which are stacked in heaps that can range from 1 meter to 10 meters in diameter. (Malesani et al. 2021).

The heaps may have a natural truncated conical shape following the natural one given by the material, with an angle of about 70 degrees, or they can also be contained with structures (such as iron or straw bales).

Polyethylene pipes, containing an exchange fluid are placed inside the pile, to recover the heat produced during the degradation process. Generally, the exchanging fluid is water, but it could also be glycol or other fluids.

The pipes can range from 16mm to 40mm, depending on the size of the system and are laid in concentric spirals or overlapped spirals and placed to different strata.

The exchanging fluid is warmed because of the high temperatures, even above 65°, provoked by the degradation process of the aerobic compost.

A simple hydraulic system made of polyethylene pipes for irrigation and a small electric pump allow the circulation of the fluid and the extraction of hot water.

The pump can be controlled with a timer, or with thermostats with temperature probes.

The heat produced and can be taken to a different possible configuration: an exchanger collected to a split, directly into the heating system, to one or more puffer containing an exchanger.

Figure 7 represent a scheme of a CHRS connected with a puffer distributing warm water between the domestic hot water (Sanitary Hot Water System) and the heating system (Underfloor Heating System).

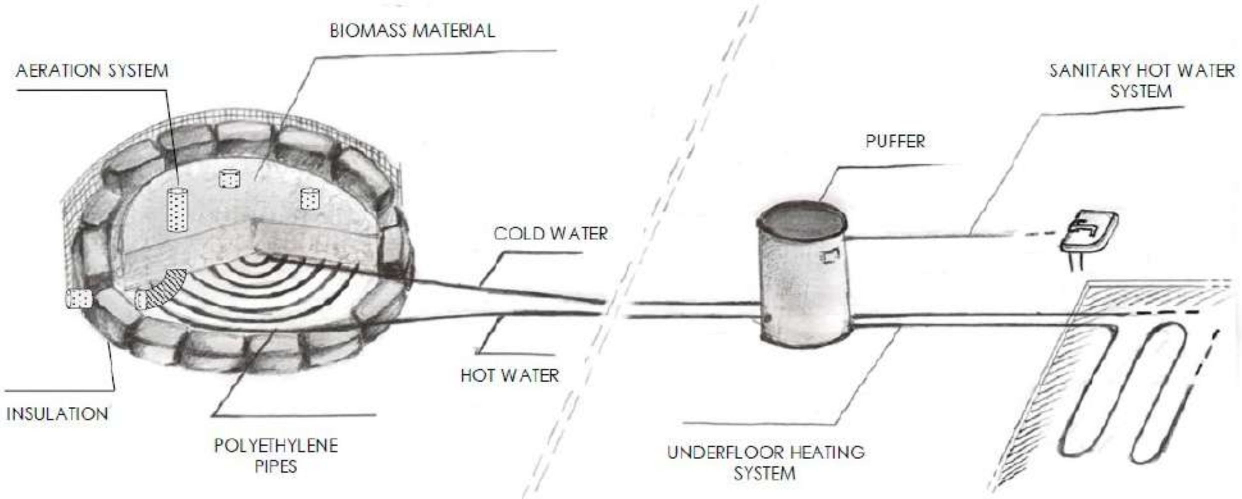


Figure 7: schematic representation of a *CHRS connected with a puffer*

Current uses of thermocomposting includes:

- Space heating
- Greenhouses heating
- Maintain temperature of anaerobic digester tanks
- Heat water for sanitary use
- Dry biosolids to reduce landfill costs

Figure 8 and figure 9 show the model of a traditional CHRS.

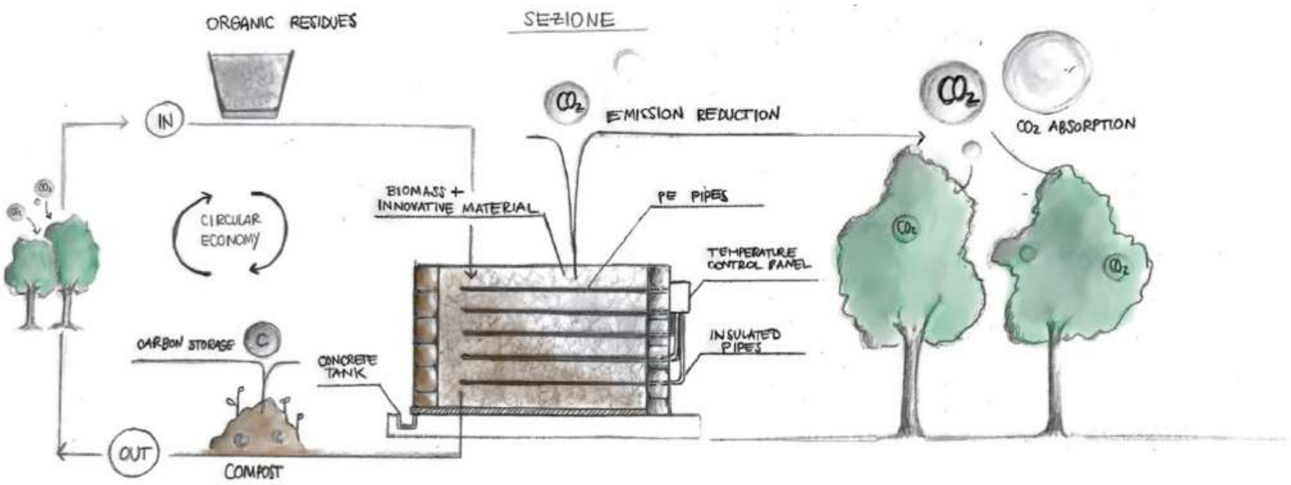


Figure 8: Conceptual model of CHRS (Malesani, 2021)

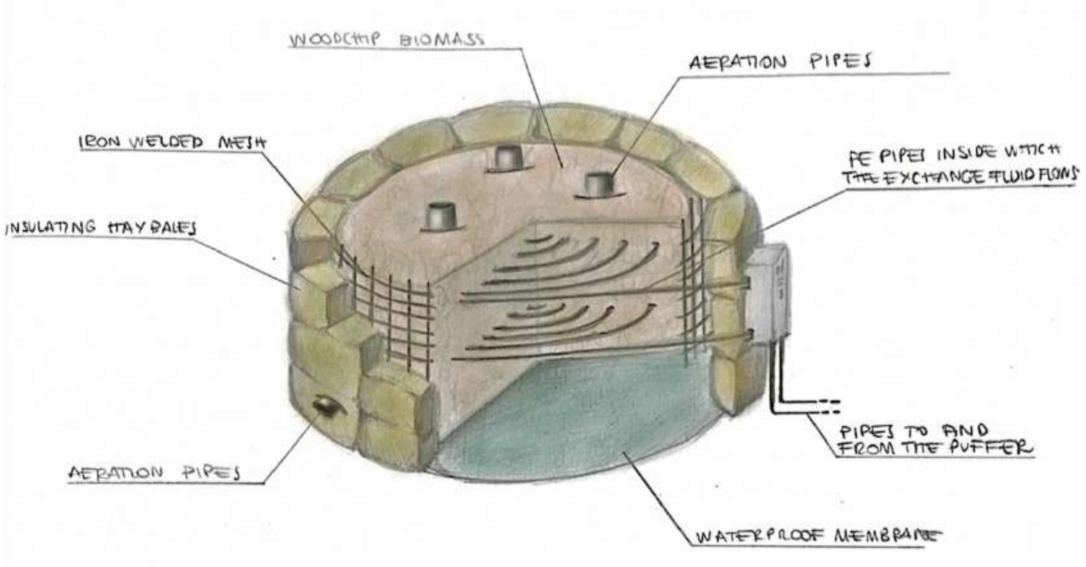


Figure 9: Illustration of a traditional CHRS (Malesani, 2021)

It has been determined that the average thermal power output provided by a CHRS plant is usually between 0.05 and 0.1 KW/m^3, depending on various factors.

Among these, as said in the previous chapters, we must consider degradability and energy content of the substrate used (mostly lignocellulosic), moisture and oxygen availability, C/N ratio and pH but also the plant dimensions, the operative lifetime (12-18 months) and the external climatic conditions.

It should be assessed how difficult it can be for these systems to satisfy the thermal demand of common homes and therefore CHRS systems should currently be seen as a complementary source of energy, to the more traditional heating systems.

One of the main limitations is represented by the necessity to replace the biomass used as feeding material inside the plant which has to be replaced, depending on the biomass used, the operative conditions, the weather and so on.

After this period, the temperature decreases too much, meaning that the degradation process is over, and the material is mature.

After that time the plant has to be dismantled, the compost has to be extracted, and the plant must be rebuilt with new substrate material.

The phase of demolition and re-construction requires time and money, becoming a limiting factor when implementing CHRS as full-scale domestic heating system.

Usually, the average operative lifetime of this kind of plant is 12-18 months.

However, it is important to also evaluate the positive aspects that the thermocompost can offer:

- CHRS can lower the energy demand required from the traditional heating systems, which most of the time comes from non-renewable sources, and therefore participate in reducing greenhouse gases emissions and air pollution.
- It can enhance the creation of small circular economies, by replacing fossil fuels with organic wastes coming from forestry, agriculture, and households with the consequent reduction of economic savings and reduction of vehicular traffic and therefore of air pollution with a decrease in the displacement of biodegradable waste.
- CHRSs allows to recover and use energy from biomass without involving any kind of combustion. It is true that during the aerobic degradation of biomass, CO2 is emitted as a result of the microbial metabolism, but there is no net increase in CO2 since biomass capture the same amount of CO2 from the atmosphere during growth as is released during aerobic biodegradation.

- CHRS not just reduces the CO2 emissions into the atmosphere but rather decreases the CO2 already present in atmosphere, capturing it and storing it as carbon in soil. (Malesani et.al, 2021)
- One of the outputs of the thermocomposting process is the compost, which is a soil improver that can increase land quality replacing synthetic fertilizers leading to less pollution and higher food quality.

2.2. Heat Potential

As said in the previous chapters, composting consists of three stages according to its temperature regimes: mesophilic stage, thermophilic stage, cooling and maturation stage.

Figure 10 shows the changes in the temperature and heat production rate during these phases.

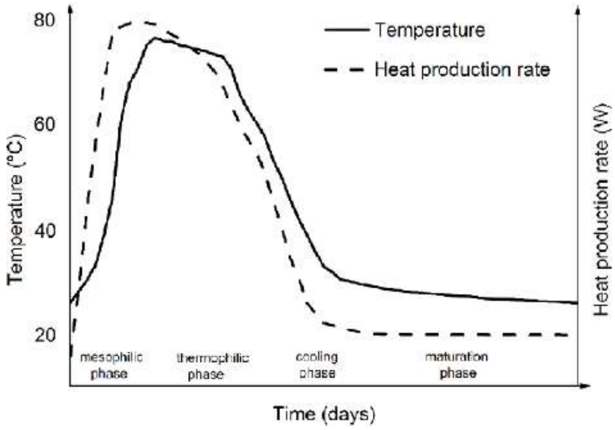


Figure 10: *Heat production rate and temperature trend during composting*

In the mesophilic and thermophilic ones, the heat production rate is high and maintains elevated values for a long period, because the involved microbes quickly degrade the energy-rich and easily degradable compounds (starches, sugar and fats), and some more resistant substances (proteins, hemicellulose and cellulose).

In the cooling stage the heat production rate decreases, and the temperature of the compost pile declines. The cooling and maturation stage may last for several weeks to several months. Therefore, the composting process can release a large amount of heat in the first two stages. It is usually during this interval that the maximum available thermal output is obtained and recovered.

2.3. Heat recovery

Heat recovery from composting can be considered in three highly interdependent stages: heat production, heat capture, and heat utilization.

It is well known that heat accumulation in composting could greatly interfere with the degradation process: the temperature could rapidly rise to thermophilic conditions and even higher, reaching values greater than 70 °C, where most likely the entirety of the microbial activity stops.

Another problem related to heat accumulation is that the pile could dry out during the process with a consequent decrease of the degradation rate.

Thus, the excess heat must be removed to keep the compost at a proper temperature range in order to achieve high biological activity and maximal heat generation.

2.3.1. Heat production

Data on the amount of heat produced during the composting process is scarce, and the results are as diverse as the composition of composted biomass.

The heat production depends on many factors such as feedstock energy content and its degradability, duration of composting, ambient temperature and all the parameters mentioned in the previous chapters (moisture content, temperature, oxygen, C/N ratio, porosity, particle size etc.).

It is important to model and quantify the generated heat as it significantly affects the temperature, pathogen removal, degradation rate during the process and, most importantly for the CHRS, the types of heat recovery and heat utilization systems that can be installed.

Compost heat is a by-product, together with water, carbon dioxide and ammonia, of the bio-oxidation of organic material described by an exothermic reaction, which can be represented by the following equation:

$$Organic\ Matter + H_2O + O_2 \rightarrow Compost + CO_2 + H_2O + NH_3 + Heat$$

As decomposition liberates heat, the surrounding composting substrate and its air and water increase in temperature. In addition, part of the liquid water evaporates, creating water vapor.

Therefore, the heat liberated during composting essentially assumes two forms: sensible heat (energy associated with an increase in temperature) and latent heat (the energy associated with an increase in water vapor).

The total energy of a substance is characterized by its enthalpy (h) in units of joules per gram (J/g) or kilojoules per kilogram (kJ/kg).

Heat production can be also expressed on the organic carbon loss (Qc) base.

Knowing the organic carbon loss, the quantity of heat produced by the organic compound oxidation, can be determined.

The percent organic carbon loss can be determined using the following equation:

$$\Delta C_{org} = \frac{C_{org\ start} - C_{org\ end}}{C_{org\ start}} * 100$$

where $C_{org\ start}$ and $C_{org\ end}$ are respectively the content of organic carbon at composting process start and end (% dry mass).

Heat production can be calculated from C_{org} loss using the following equation (Klejment and Rosinski, 2008):

$$Q_c = 17{,}6 * 10^3 * \frac{C_{org\ start} - C_{org\ end}}{100} * \frac{100-W}{100}$$

Where Qc is the heat determined from the loss of C_{org} (kJ/kg), $17{,}6 * 10^3$ is the quantity of heat produced during carbohydrate oxidation (kJ/kg), $(C_{org\ start} - C_{org\ end})$ is the loss of C_{org} during composting process (% of dry matter of compost), (100 - W) is the dry matter content of compost (%) and W is the total moisture content of compost (%).

Calculated heat based on organic carbon loss represents only a part (32.03– 48.70% of the total) of the heat released during composting (Klejment and Rosinski, 2008).

In order to best harness the heat energy from the composting process it is important to align the mesophilic, thermophilic and curing phases with the coolest months of the year when heat demand is at its peak.

We have to pay attention to ensure that the compost is not cooled by winter temperatures: an uninsulated compost heap could potentially lose 80% of its heat to the surrounding environment.

2.3.2. Heat capture

Heat produced by the compost mass can either remain inside the heap, resulting in an increased temperature, or exit the compost.

There are three approaches used to extract heat from composting.

1. The simplest method is direct heat utilization of compost vapor (Aquatias 1913; Fulford 1986). This system is widely use in greenhouses as they can exploit both the heat and carbon dioxide (CO2) available in the composting exhaust air.

2. The second approach is hydronic heating through conduction of within-pile heat exchangers (Brown 2014; Pain and Pain 1972).

These systems can move the heated water into a hydronic space heating system or use the heated water for a consumptive water use like equipment cleaning. Often, a storage tank is included to buffer temperatures and energy demand.

3. The third and more recent approach is to capture the latent heat using compost vapor and a condenser-type heat exchanger (Brown 2015; Smith and Aber 2014; Tucker 2006). This approach captures the greatest quantity of thermal energy and is most commonly used by commercial composting sites.

In particular, reasons provided for using compost vapor heat exchangers (approach n.1) over within-pile exchangers (approach n.2) were as follows (Smith et al. 2016):

- Within pile heat exchange tubing can be easily damaged, due to compression from compost settling, loading, or unloading (Pain and Pain 1972; Schuchardt 1984).
- Recirculating the within-pile heat exchange liquid too early or too fast can inhibit the composting process, reducing temperatures and future heat exchange (Allain 2007; Seki 1989; Viel et al. 1987; Verougstraete et al. 1985).
- Compost cannot be mixed once the heat exchanger is placed within the pile (Thostrup 1985).
- Energy recovery is limited due to poor heat conduction characteristics of composting feedstocks (Verougstraete et al. 1985).
- Unlike the within-pile approach, vapor heat exchangers can potentially capture the abundant latent heat energy produced during composting (Jaccard et al. 1993; Verougstraete et al. 1985)

The efficiency of the various compost heat recovery systems depends on the flow rate and temperature of the heat extracting fluid: greater flow rates and lower entering fluid temperatures capture more heat, but exiting fluid temperatures tend to decrease.

In CHRS water flow rate, circulating in pipes within the compost mass, is usually projected to reach a target exiting water temperature.

It is possible to remove too much heat from the pile, and consequently lower the composting temperature by circulating too much cold water, inhibiting microbial growth (Brown 2014; Viel et al. 1987).

Hence, the performance of the system depends on how heat is recovered downstream and its influence on the return water.

Through the investigation of the increase in water temperature between the inlet and the outlet of polyethylene pipes embedded in composting windrows it has been reported that 73% of the theoretical value of heat energy is transferred to the water (S. Lekic 2005).

A closed loop system, with a pump can be used with a radiator to provide space heating. The addition of a radiator will not overly adversely affect ability to make hot tap water. The radiator should be regulated by a thermostat so as not to leech excess energy from the pile.

Jean Pain’s experiments show no variance in production in any of the arrangements horizontal, vertical, or spiral. The set up and take down of them is different:

- The horizontal placement tends to settle unevenly, making the removal of the finish product more difficult.

- The vertical placement does not suffer from settling issues but is more tedious to set up initially.

- The spiral configuration, figure 11, seems to be the easiest to set up and take down. First build a pillar of compost material, then wind the poly pipe around it.

Bury the pillar inside larger and larger piles of compost material, stopping to wind more poly pipe as you go. Even when this settles, the pipe can be easily collected by digging out and unwinding: the exact reverse of the set-up process.

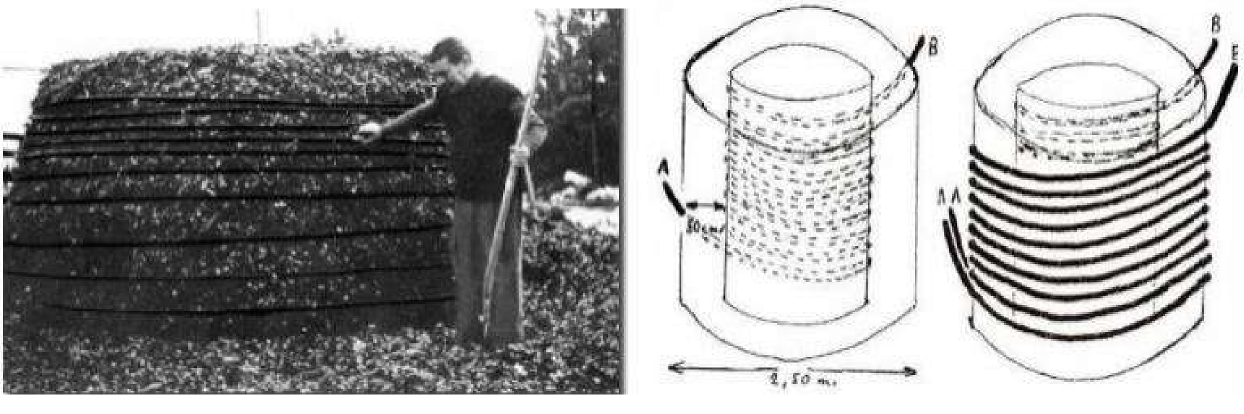


Figure 11: spiral configuration of pipes, adopted by Pain

2.3.3. Heat Utilization

After recovery, the heat is ready for utilization.

Based on different composting processes and heat recovery systems, the outlet temperature of heat generated usually ranges from 20 to 80 °C.

This temperature range fits well for building applications such as air heating, floor heating, and domestic hot water service, in particular for households located in decentralized or rural areas but also for swimming pools. Heat from composting can also serve for agricultural, horticultural and greenhouses applications, extending the crop production season in cold regions.

Regarding the commercial levels of application of the technology, the generated heat can be also used to heat anaerobic reactors and it would be quite convenient since these two processes can be implemented within the same plant.

However, there are some aspects that limit the application of CHRS.

First, the heat production rate is usually dynamic during the composting due to the high heterogeneity of the organic substrates and so, the controlling of heat extraction becomes difficult.

Moreover, although the heat production rate is high in the mesophilic phase and thermophilic phase, there is still a lot of heat generated in the cooling phase and maturation phase.

3. HISTORY OF CHRS

Numerous Compost Heat Recovery Systems (CHRSs) have been tested over the years, and are described in detail in Smith and Aber (2017).

Compost heat recovery systems have ancient origins and, even if it is unknown when humans first began to utilize the heat generated from decomposing organic matter, it has been discovered that farmers in China were capturing this renewable energy source over 2000 years ago by using hotbeds (Brown 2014).

These ancient CHRS systems consisted of a one-meter trench filled with manure and covered with a layer of topsoil for crop production; plants placed above the decomposing manure, benefited from the heat being generated by microorganisms.

With this method, the thermal energy was recovered passively via convection of heat to the root zone of crops.

According to Grazia Cacciola, in his book "The Natural Vegetable Garden for Dummies", the first references to composting must be searched in the Latin historian and writer Lucio Giunio Moderato Columella's treatise *De re rustica*: he explained some techniques to produce "artificial manure", to be used for fertilizing the field using plant residues in the absence of manure.

Upgrades and innovative designs have been implemented over the years, in particular during the 1600s, in France, with the creation of glass-enclosed hotbeds (figure 12) utilized for winter cultivation (Fulford 1983).

Then, in the 1900s, with the diffusion of vehicles, horses were replaced and so, manure production and availability was reduced; thus, the implementation of French hotbeds came to an end because of the lack of available biomasses.

Oil crises of 1973 and 1979 caused a great increment of energy prices and led to a conversion of many CHRS designs. They evolved from conduction-based recovery systems to those using compost vapor stream to capture the latent heat. Authors of compost heat recovery work described the need to move away from volatile energy inputs and switch to more renewable forms.

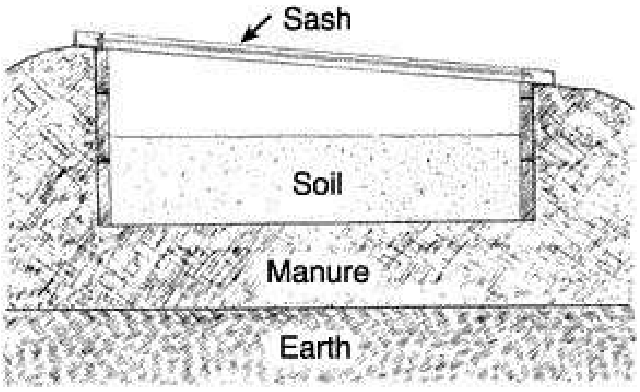


Figure 12: Example of hotbed

3.1. Jean Pain method

It was only in the late 1900s that CHRS made a significant improvement thanks to the works and publication of Jean Pain. His book "*Another kind of Garden*", released in 1972 in France, described a new approach of a combined heat and power extraction from composting systems.

"The Jean Pain Method" involves the sustainable harvesting of forest underbrush and small branches:heaps of chipped brushwood, used as organic feedstock for the aerobic degradation reaction, with hundreds of meters of water-filled tubing imbedded in the compost were utilized for heat exchange and the fluid in the tubes' system was warmed by the decomposing material via conduction.

The ability to warm water significantly increased the utility of the CHRS, as it could be used for more than just agricultural purposes.

The biomass material was recommended to be no larger than 8 mm in diameter and prior to heaping the compost materials, everything was soaked for one to three days until all the material was saturated. A volume of 4 m^3 material was imposed as a minimum recommended batch size.

Pain reported that 50 tons of brushwood warmed well water from 10°C to 60°C at a rate of 4 liters per minute for 6 months, without interfering with the composting process and the heat was able to supply domestic hot water and heating to a 100 m^2 farmhouse for 6 months.

The system could extract 50115 kJ/h or 4330 kJ/kg DM over a 6-month period.

No difference in the PE pipes arrangements to extract hot water were observed: horizontal, vertical or spiral layout gave the same results regarding the heat production.

Instead, the set up and take down of them was different and the spiral configuration was considered the easier one to adopt.

In figure 13 a schematic representation of the Jean Pain system is shown.

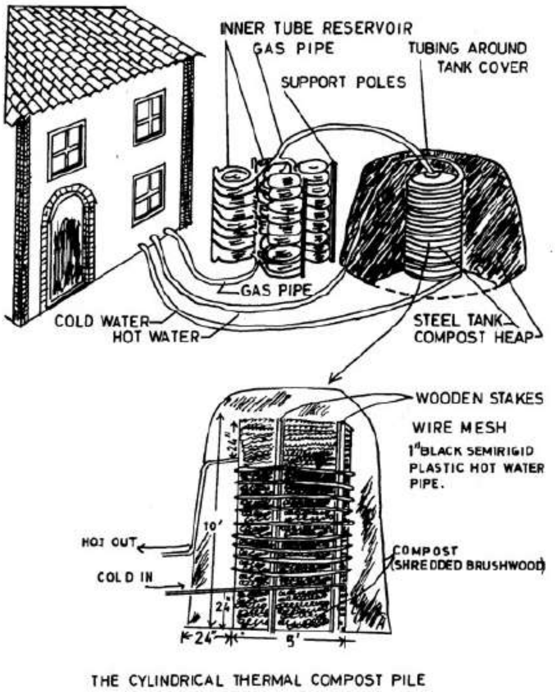


Figure 13: Diagram of the Jean Pain system

3.2. Other methods

A second type of CHRS was discovered by Knapp in 1978. The system was very similar to that of the French hotbeds: it used a 7,6 m^3 pile within a greenhouse for winter heating.

Another process was described by Vemmelund and Berthelsen in 1979.

Agricultural manures were stocked in a double-walled 1 m^3bin. Heat exchange occurred by filling the inner void between the bin walls with water, which was warmed by via conduction from manures being aerated within the bin.

3.2.1. 1981-1990

In 1986, the Biothermal Energy Center (BTEC) formed in USA and the New Alchemy Institute developed small-scale composting greenhouses.

The system used a polyethylene-covered greenhouse with a 19 m^3 composting chamber attached to the north of the structure. The chamber contained 10 separate bins, which were aerated by electric blowers that pushed air through the compost. The heated exhaust was blown through a perforated pipe below growing beds, which served as biofilters, and the heat was transferred to the media through stored latent heat.

To ensure a constant supply of hot air, fresh compost was loaded into the bins every 4 to 5 days.

This method turned out to be ideal for supplying heat to growing crops, but Fulford reported also additional benefits of the compost vapor, which included irrigation, supplemental CO_2 and nitrogen fertilizer from ammonia that was converted to ammonium and nitrate in the biofilter media.

3.2.2. 1991-2000

From 1990 up to the present day, CHRS have faced a great expansion taking as reference the past technologies.

Having seen the usefulness of utilizing compost heat, many efforts have been directed towards the creation of large, small, medium, commercially, and waste-fed heat recovery systems and the increased activity of peer-reviewed literature helped to confirm many findings reported from independent organizations and individuals.

Hong, Park, and Sohn (1997) conducted a study looking at the effects of composting underground soil temperatures within a 55 m^2 greenhouse in Korea; Kostov and colleagues (1995) made a similar study in Bulgaria, comparing the growth and production of cucumbers in a 142 m^2 greenhouse, using compost heat.

An innovative integrated system was developed by an organic lawn care company in Nebraska (Anon 1991). This CHRS combined a geothermal, solar, and composting system to heat water.

The functioning began by warming city water through an underground geothermal tank. The heated water was then sent to a second tank, and it was heated again with a solar system. The warm water was then sent through tubing within a composting pile of where it was heated another 10°C to a final temperature of 34°C. One of the most important results obtained with this system was the gain of awareness about the possibility to exploit different and sustainable sources of thermal energy combined with the thermocomposting process.

This system corrected one of the faults of within-pile CHRSs, where cold water circulating through the composting pile can reduce microbial activity and future compost temperatures.

3.2.3. 2001-2010

During these years CHRS faced an important implementation as small-scale and pilot projects were scaled up to the commercial level.

One of the first large-scale commercial CHRS was created in 2006. The system applied in Vermont, consisted of an aerated static pile composting method: a suction fan pulled air through the compost into the system of pipes and into heat exchange system.

Heated water was used to warm milk formula and to provide floor heating in the calf barn.

A second commercial CHRS was developed by Allain in 2007. It was designed to prevent snow and ice from freezing compost covers to the ground at a biosolids composting facility in Canada.

Allain found out that if the heated fluid was pumped too frequently, compost pile temperatures decreased.

During this period, researchers also studied how much heat could be extracted from commercial CHRSs. Di Maria, Benavoli and Zoppitelli in 2008, implemented a model to simulate heat recovery from a system in Italy. The recovery system was a vapor compression heat pump that had heat transfer coils within the composting mass. The authors reported that the 55°C-65°C compost temperature could be increased to 80°C-90°C with a heat pump, recovering 4000 to 5000 kJ/kg of thermal energy from the compost.

3.2.4. 2011-2016

Due to the verified feasibility and utility of using compost heat directly in growing beds, buildings' heating installation for space and sanitary domestic water, solid efforts have been made for the creation of large, small, medium, commercially, and waste-fed heat recovery systems.

This distinct shift from pre-2011, which was dominated by lab-based systems, suggested a great trust in recovering thermal energy from composting, considering it as a new viable alternative energy source.

One of the small-scale prototypes, thought to be installed in U.S households, was developed utilizing waste from only the home for heating needs (Li, Yu, and Yu in 2012). Other two small-scale lab-experiments were conducted in India (2012) and Japan (2014) analyzing the net energy that could be recovered by the different technologies.

Two organizations played an important role in the diffusion of CHRS systems: the American Compost Power Network (CPN) and the German Native Power.

Both organizations provided workshops and technical details on how to replicate these heat recovery systems.

4. LEGISLATION

In the following pages, a brief overview about energy and waste regulations is illustrated.

It is important to underline that in Italy there are no specific rules regarding the Thermocompost but we know that the construction of the thermocompost do not fall within the waste application field.

In fact, as reported by the Italian law (Law n. 154/2016) are not waste: straw, grass clippings and prunings as well as any other non-hazardous agricultural or forestry material destined for normal agricultural and livestock practices or used in agriculture, in forestry or for the production of energy from such biomass, even outside the place of production or with transfer to third parties, through processes or methods that do not damage the environment or endanger human health.

4.1. Energy regulations

The legislation on the theme of "energy" is constantly evolving at the European, national and regional levels.

Energy networks have historically been constructed and operated on a national basis with the state's interest exercised either by central or regional governments, so energy policy has been primarily nationally based, with limited cross-border trading.

Since 1980, with the growing interest in enhancing cooperation and integration of EU energy networks, an efficient internal market was developed, which is nowadays even more important due to environmental sustainability as it facilitates the connection of energy generated by renewable sources to the energy grids.

In fact, policy in Europe with respect to energy has three main key components: market competition, sustainability, and security.

In 1989 was established the first energy regulator in Europe and in 1997 an informal cooperation among some energy regulators was created.

In 2003 a more mature legislative framework for the internal energy market and an institutionalization of regulatory cooperation at EU level was established.

During the last years, these phases has been consolidated by the enlargement of the EU from 15 to 27 members, by the introduction of independent energy regulators in all member States and by new legislation.

The national targets for energy from renewable sources are established in Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directive 2009/28/EC, 2003/30/EC, 2001/77/EC. This Directive also established accounting criteria for the share of energy from renewable sources, setting up a common system across the different sectors and a financial framework to encourage investment in projects involving the use of renewable sources.

In parallel, Directive 2018/2002/EU raised the target of *energy efficiency*, set by Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012, which impose a target for the share of energy from renewable source from a 20% in 2020 to 32.5% in 2030.

However, the increased use of this energy from renewable sources is an important part of the package of measures needed to reduce greenhouse gas emissions and to comply with the 2015 Paris Agreement on Climate Change and the EU policy framework for climate and energy (2020 to 2030). This last EU policy framework aims to reduce the 40% of GHG emissions by 2030.

EU intends to ensure its ambitious climate and energy targets for 2030 aimed at combating climate change, increasing the energy security within Europe, and strengthening its competitiveness.

The framework sets 3 objectives to reach by 2030, which are stricter than the ones imposed by the previous 2020 climate & energy package:

- at least 40 % cuts in EU greenhouse gas emissions (from 1990 levels)
- at least 32,5 % improvement in the EU's energy efficiency
- at least 32% share EU's energy from renewables (biomass, solar, wind etc.)

Another important climate action to report is the 2050 long-term strategy in which EU aims to be climate-neutral by 2050 developing an economy with net-zero greenhouse gas emissions.

The European Council endorsed in December 2019 the objective of making the EU climate-neutral by 2050, in line with the Paris Agreement. Finally, the EU submitted its long-term strategy to the United Nations Framework Convention on Climate Change (UNFCCC) in March 2020.

4.2. Italian energy regulations

On 4 July 2014, Legislative Decree no. 102/2014 was issued "Implementation of Directive 2012/27/EU", amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/CE. The decree, in implementation of Directive 2012/27/EU, established a framework of measures for the promotion and improvement of energy efficiency that contribute to the achievement of the national energy savings target established in the Ministerial Decree of the March 15, 2012. The decree was then updated by Legislative Decree n.141/2016.

Ministerial Decree of March 15, 2012 "Definition and quantification of regional objectives in the field of renewable sources and definition of how to manage cases of non-achievement of objectives by the regions and autonomous provinces (so-called Burden Sharing)", issued in implementation of article 37 of Legislative Decree n. 28/2011, defines and quantifies the intermediate and final objectives that each autonomous region and province must achieve in order to reach the national targets for 2020 on the overall share of energy from renewable sources on gross final consumption of energy and share of energy from renewable sources in transport.

On June 26, 2015, the Ministry of Economic Development issued the following three decrees that complete the regulatory framework on energy efficiency of buildings:

1. Ministerial Decree 26 June 2015 - National guidelines for the certification of the energy performance of buildings (APE)
2. Ministerial Decree 26 June 2015 - Application of the calculation methods for energy performance and definition of minimum building requirements and requirements.
3. Ministerial Decree 26 June 2015 - Schemes and reference methods for the compilation of the technical project report for the application of the minimum requirements for energy performance in buildings.

With the signing of the Kyoto Protocol, the European Union, and its Member States, committed themselves at fighting climate change through a series of EU and national policies.

This path was confirmed with the adoption of the Paris Agreement in 2015 which was signed by Italy on 22 April 2016.

As said previously, 2020 Climate & Energy Package was formulated to reach an integrated approach between policies and the fight against climate change.

The targets of the package have been transposed into the Italian national legislation in 2009.

Italy commitments are to reduce greenhouse gas emissions by 13% by 2020, compared with 2005 levels and to achieve a 17% share of energy from renewables in the gross final consumption of energy by 2020.

This last target was achieved in 2017 as in the heating sector had an overall energy consumption originated from renewable sources less than 20%.

The renewable source that was most utilized in 2017 for heat consumption was solid biomass primarily used in the household sector in the form of firewood and pellets.

Italy’s path towards sustainability beyond 2020 follows the standard of the Energy Union strategy, based on five dimensions: decarbonization (including renewables), energy efficiency, energy security, a fully integrated energy market, research, innovation, and competitiveness, and the new 2030 Framework for Climate and Energy approved by the European Council.

The declared objective is to limit more and more methane and GPL that represent the vast majority of energy sources used in our country. More and more importance will be given in future to the use of solar and photovoltaic panels in combination with heat pumps or solid biomass generators such as wood, woodchips and pellets.

On 10 November 2017 the Decree of the Minister of Economic Development and the Minister of the Environment and Land and Sea Protection approved the new National Energy Strategy (NES2017).

The latter had the go-ahead from the Unified Conference on 18 December 2019 but according to the Minister of Economic Development it will be subject to further additions.

Summing up, currently there are three position papers concerning the environmental policies, in line with the NES2017:

- the Integrated National Energy and Climate Plan (INECP)
- the National Strategy for Sustainable Development (laid down in the "Collegato ambientale" Law 221/2015)
- the 2050 long-term strategy for GHG reduction.

The INECP is a thorough and wide-ranging document that integrates energy and environment strategies, covering also topics from the other two papers.

The main goals (by 2030) concern the energy production: 30% share of renewable energy in gross final energy consumption, and 21.6% of renewable energy in gross final energy consumption in the transportation sector. Moreover, INECP forecasts a reduction of primary energy consumption by 43%, compared to the scenario PRIMES 2007, and a reduction in the GHG emissions by 33%, with respect to the 2005 level, for the non-ETS (Emission Trading Systems) sectors.

The second paper identifies strategies to encourage the "green economy" and reducing the use of natural resources.

The 2050 long term strategy is a long-term vision for a climate-neutral economy, in order to achieve the goal of reducing the GHG emissions by 80-95%, when compared to the 1990 levels, by 2050.

4.2.1. Veneto Region regulations

According to Article 117 of the Italian constitution, energy is governed by coherent legislation between central government and the regions. Central government is responsible for defining the general principles, while the regions have full legislative power in relation to the object.

Therefore, the transposition of EU energy policy directives is a matter of every individual region of Italy which must implement the necessary legislation with a regional energy plan.

To implement the various directives, each individual region is supposed to define a regional energy plan.

At regional level it is necessary to mention L.R. 27/12/2000 n. 25 *"Rules for regional energy planning, incentives for energy saving and the development of renewable energy sources".*

It states that the Veneto Region promotes, in a coordinated way with the State and Local Authorities, interventions in the energy sector aimed at the rational use of energy, the containment of energy consumption, to the reduction of greenhouse gases by exploiting and encouraging the use of renewable energy sources.

On 22 January 2010, with the L.R n.10 a series of rules for authorizations and incentives for the construction of solar, thermal and photovoltaic systems has been promulgated along with the Regional Law no. 5 of the 11 February 2011 "*Energy production from biomass or biogas plants or from other renewable sources".*

With DGR n. 453 of 2 March 2010, the Veneto Region has defined, in compliance with art. 12 of Legislative Decree n. 387/2003, the regional procedures for the authorization of plants to produce electricity from renewable sources (biomass, biogas and landfill gas, photovoltaic, wind, hydroelectric).

Finally, during the session of 9 February of the Veneto Regional Council, the DCR. n. 6, the Regional Energy Plan for *Renewable Sources, Energy Saving and Energy Efficiency,* was adopted.

4.3. Waste management regulations

Waste policy has evolved over the last 30 years in Europe through a series of environmental actions and regulations; waste management is now considered as one of four top priorities in the EU's Seventh Environment Action Program.

This long-term strategy aims to reduce negative environmental and health impacts and create an energy and resource-efficient economy.

The 2005 Thematic Strategy on Waste Prevention and Recycling resulted in the revision of the Waste Framework Directive of 2006 (Directive 2006/12/EC), one of the most important EU waste policies.

Waste went from being considered an unwanted burden, to a valued resource and so the Directive stated some targets for EU Member States like the necessity to recycle 50% of their municipal waste and 70% of construction waste by 2020.

The Directive introduces a five-step waste hierarchy where prevention is the best option, followed by re-use, recycling and other forms of recovery, with disposal such as landfill as the last resort with the aim of achieving much higher levels of recycling and of minimizing the extraction of additional natural resources.

A correct waste management is the key element to ensure resource efficiency and the sustainable development of European economies taking in mind the needs of the present generations and of the future ones.

In July 2009 the EU Commission adopted the review of Sustainable Development Strategy (EU SDS) underlining that the EU has mainstreamed sustainable development into a broad range of its policies, in the fight against climate change and the promotion of a low-carbon economy.

Moreover, the idea of waste disposal is gradually changing from a linear approach, which is characterized by the uptake of resources, their transformation and utilization and the final disposal, to a circular economy which aims to eliminate waste passing through "repair, recycle, and reuse" processes, to close the loop, minimizing waste and maximizing resources. Differences between circular economy and linear economy are represented in figure 14.

Figure 14: Differences between circular economy and linear economy schemes

4.4. Composting regulation

The composting process is a perfect example of circular economy, and the separate collection of urban waste has therefore encouraged the improvement of the treatment that this kind of plants perform for the recovery of heat.

However, agricultural by-products are very often burned, generating pollution, contributing to climate change and emissions of fine dust.

The use of biomass for the composting process coming from pruning, mowing, manure and so on, contributes to an exploitation of renewable resources which are otherwise a waste, avoiding the use of no renewable resources.

The result is the production of an excellent compost, utilized as soil improver in the agricultural sector and it can minimize land degradation and soil erosion, but it can be also used as landfill cover to abate greenhouse gas emissions.

Another important thing to be considered is that the heat recovered from the process can be also used.

There are many EU legal instruments which address the issue of treatment of bio-waste; the revised *Waste Framework Directive* contains specific bio-waste related elements and a mechanism allowing setting quality criteria for compost (end-of-waste criteria). The *IPPC Directive* lays down the main principles for the permitting and control of bio-waste treatment installations of a capacity exceeding 50 tones/day.

The EU regulatory framework then puts it in a close relationship the themes of organic matter recovery and organic waste management with soil, land protection and the broader environmental issues addressed by the Kyoto Protocol on protecting the planet from climate change. The *Thematic strategy for soil protection* (COM 2006, 231) identifies the threats to the integrity of the soil resource, among which erosion and the reduction of organic matter must certainly be mentioned.

In Italy the composting process refers to two main sectors: the waste management and the consequent environmental aspect regulated by Legislative Decree 152/06 better known as “Testo Unico Ambientale” and the use and marketing of fertilizers.

Legislative Decree 217 of the April 29, 2006, "Revision of the regulations on fertilizers ", repealed law n. 748 of 1984, "Rules on fertilizers", and adapted the legislation to the European community one on fertilizers, in compliance with the provisions of the Regulation (EC) 2003/2003. In this way all competences concerning the definition of the characteristics of compost quality that can be used in agriculture were treated by the Decree 152 avoiding the great regulatory confusion in the management of compost as there were two laws (the Law 748/84 and D.C.I. of 27/07/1984) which governed its production and use without clear results.

Moreover, the Decree designates Regional and Municipal Administrations as entities responsible to create the incentives schemes supporting composting activities. In Annex C of part IV, compost is defined as “product, obtained from the composting of separately collected organic waste, which complies with the requirements and characteristics established by annex 2 of the legislative decree 29 April 2010, n.75, and subsequent modifications”. The latter summarizes the characteristics that a soil improver must possess, the matrices allowed for its production and the limits to define its agronomic and environmental quality.

In particular, three classes of soil conditioner from composting processes are presented:

- Green composted soil conditioner: obtained through stabilization of organic residues consisting of waste from the maintenance of ornamental greenery, crop residues, other vegetable waste, with the exclusion of algae and other marine plants.
- Mixed compost soil conditioner: obtained through stabilization of organic residues constituted by the organic fraction of MSW, coming from differentiated collection, animal waste including zootechnical sewage, from residues of agro-industrial activities and processing of untreated wood and textile, from similar residues, as well as from the matrices provided for the green composted soil conditioner.
- Peat compound improver: obtained by mixing peat (min 50%) with green and / or mixed composted soil conditioner.

To summarize, Italian composting regulation can be framed by:

- *Legislative Decree 152/2006*, which designates Regional and Municipal administrations as entities entitled to create the incentive schemes supporting composting activities (integrated with in 2008 by Legislative Decree 4/08)

- *Legislative Decree 75/2010*, which defines and classifies fertilizers, regulating their production, commercialization, and use

- *EU directive 91/676/CEE*, which defines practices to avoid poisoning of water and habitats due to nitrate spillages.

- *EU directive 2008/98/CE*, which encourages waste recycling and composting to reduce environmental impact.

- *DDL 1328-B 6/6/16*: enlarge the list of biomass waste excluded from the OFMSW; among them, green waste from maintenance activities becomes a resource with the advantage of an enormous reduction of bureaucratic requirements for companies and operators in the sector, as well as considerable savings for municipalities and public administration. Moreover, *UNI EN 13432* standard of March 2002 defines the requirements and characteristics that a material must possess to be defined as compostable.

According to *EN 13432:2002*, the characteristics that a compostable material must have, are the following:

- Biodegradability, determined by measuring the actual metabolic conversion of the compostable material into carbon dioxide. This property is evaluated quantitatively using a standard test method: *EN 14046* (also published as *ISO 14855:* biodegradability under controlled composting conditions). The acceptance level is 90% to be reached in less than 6 months.
- Disintegrability, fragmentation and loss of visibility in the final compost (absence of visual contamination). Measured with a pilot scale composting test (*EN 14045*).
- The material under examination is biodegraded together with organic waste for 3 months. At the end of this process the compost is sieved with a sieve of 2 mm. The residues of the test material with dimensions greater than 2 mm are considered to be non-disintegrated. This fraction must be less than 10% of the initial mass.
- Absence of negative effects on the composting process: this is a requirement verified with a pilot scale composting test.
- Low levels of heavy metals: values below the predefined maximum values and absence of negative effects on the quality of the compost (example: reduction of the agronomic value and presence of ecotoxicological effects on plant growth). A plant growth test (modified OECD 208 test) is performed on compost samples where the degradation of the test material has occurred. No difference must be highlighted with a control compost.

- Other chemical-physical parameters that must not differ from the control compost after biodegradation are pH, salt content, volatile solids, N, P, Mg and K.

4.4.1. Italian Composting Consortium

The *Consorzio Italiano Compostatori* (*CIC*) is a non-profit organization composed of companies and public and private bodies producers of compost and other organizations that are still interested in composting activities.

The Consortium, active in Italy since 2003 has the aim of promoting the waste reduction policy, the implementation of separate collection for separation, processing, recycling, and valorization of biomass and in general of compostable organic fractions.

This consortium allows voluntary verification of the quality of the compost, to which the Quality Mark was established.

CIC Mark was created because of the frequent lack of information on the quality of compost from the point of view of the origin and controls.

The quality marks assure the quality and determines the safety of use both from an environmental and agronomic point of view. The release of the brand involves several stages:

- Preliminary phase: consist on the collection of data and related information to the composting plant
- Release phase: inspections and sampling that, if they comply with the requirements identified by the Regulation, may allow the manufacturer to use the *COMPOST C.I.C.* logo
- Maintenance Phase: which aims to guarantee with a sampling frequency variable according to the quantities of products, to constantly monitor the quality of the batches entered on the market

Second part: Scientific report

ABSTRACT

Since energy demand is growing up rapidly worldwide, the sustainable production of renewable and clean energy is seen as one of the best options to mitigate the global warming and the environmental pollution connected with the exploitation of fossil fuels.

Exothermic aerobic biodegradation of biomasses (composting) releases a huge amount of heat, reaching temperatures of up to 65 °C.

The implementation of compost heat recovery systems (CHRS) represents an innovative technology that allows to recover the produced thermal energy from biodegradation, to power underfloor heating systems (UHS) or domestic hot water systems (DHWS), lowering impacts and costs of thermal energy production.

These plants are typically implemented in rural or decentralized area, at domestic or farm scale, where lignocellulosic materials coming from forestry management, agricultural activities, along with organic wastes from farms and households are largely available.

Also, CHRS represent a sustainable waste management strategy to obtain compost, which can be further applied to soils as a beneficial amendment, fully implementing the principles of circular economy with waste being fully valorized and finally returned to the soil.

However, Heat Recovery System shows some limits: the low thermal energy efficiency produced and its considerably short operative period, which lasts up to a maximum of 12- 18 months; after that new biomass is necessary.

The aim of the experimental activity was the construction and the following monitoring of a full scale CHRS managed with innovative optimizations: an integrated monitoring system and the addition of external feedstocks.

Various heat extraction trials were performed to analyze the maximum recovered heat.

The plant provided an average heating power in the operative phase of 6 months, of 0.06 kW/m^3, in accordance with literature data.

The optimization measure of external feeding, resulted of great importance in prolonging plant operative lifetime and in particular to sustain the process during the whole heat extraction, increasing energy production and internal biomass temperatures.

1. INTRODUCTION

According to the present worldwide socio-economic and environmental situation, caused by the extensive and excessing use of fossil fuels, a transition towards sustainable energy production is needed.

As energy demand is increasing rapidly, bioenergy is seen as one of the primary possibilities for preventing global warming.

Everyday a large quantity of solid waste is generated and with the increasing global population, urbanization and shifts in consumption behaviors, how to manage these increasing amounts of wastes has become one of the major issues regarding the sustainable development.

Considering that organic waste, which includes food scraps, yard waste, agricultural waste and process residues, accounts for the largest proportion (46%) of the overall generated solid waste, it is of extremely importance to dispose and recover such materials in the best way.

Aerobic stabilization via composting is recognized as a valuable method for treating organic solid waste because of the low operating costs and high environmental benefits.

At the end of the process, a stabilized organic material is obtained and can be used for agronomical uses, making it a significant bio-recycle process.

However, composting process releases a great amount of thermal energy, that is generally dispersed into the surrounding environment.

Such neglect has been the focus of several studies in the last decades, leading to the ideation of a process that makes it possible to recover and use both thermal energy and compost from this organic waste treatment.

Thermocompost improves the possibility to recover the heat, representing both a technology for to produce decentralized thermal energy from residual biomasses and at the same time an innovative waste management strategy.

One of the most used set-ups consists of a pile of organic lignocellulosic material undergoing aerobic biodegradation, inside which polyethylene pipes containing an exchange fluid are placed to recover the heat produced during the degradation process and use it for heating buildings through underfloor heating systems and sanitary hot water. Currently, these traditional thermocomposting plants mainly exploit green wastes coming from forestry or agricultural activities.

It has been recognized that the average thermal power output provided by these CHRS is usually between 0.05 and 0.1 kW/m^3 (Malesani et al., 2021; Native Power, 2019), depending on the plant dimensions, the operative lifetime and on the biomass used.

Naturally, they present some limits: once the operative lifetime of the plants ends, the thermocompost system must undergo a dismantling and reconstruction phase.

This project started with the construction of a full-scale traditional CHRS (Compost heat recovery system) of about 38 m^3 with an internal volume of woodchips equal to 25 m^3, and a greenhouse heated by the thermocompost.

The basic scope of this research was to work on a full-scale CHRS with a scientific approach to monitor and collect data about thermal power outputs according to external feedstocks (whey) injections, and to optimize system process and maintenance.

2. MATERIALS AND METHODS

2.1. Design of the CHRS plant

A full scale CHRS was constructed on the 27 of January 2023 in the "Centro di ricerca di Ingegneria Ambientale Voltabarozzo "LISA" Laboratory – Dipartimento ICEA", located in Padova Province (PD).

Also, a greenhouse was installed as close as it was possible to the plant to minimize heat dispersion.

The greenhouse heated up through the heat produced by the thermocompost has the dimensions of 2,5 m x 1,9 m x 1,95 m, for a total volume of 7,6 m^3.

The external cylindrical body of the CHRs measures about 5 meters in diameter and 2 in height. The support structure was created with a welded iron mesh (20x20, D 8 mm), which was shaped accordingly to the final plant form and secured to the ground.

At the base of the pile, three different layers were laid: a non woven fabric (400 gr/m^2), an impermeable PVC sheet, and another non woven fabric (400 gr/m^2) to achieve both insulation from the ground and to limit leachate dispersion in the environment.

Above these sheets, a homogeneous layer of rocks (D= 0,2 m) was distributed to achieve a good aeration of the pile, and then, a geotextile (400 gr/m^2) was placed above rocks to avoid the falling of the biomass into the spaces between rock and rock.

The waterproof membrane placed on the bottom of the rocks layer is also meant to collect the leachate which is produced during composting, in an underfloor plastic tank (V= 1 m^3) housing a recirculation pump that can recirculate it from the top of the heap.

The pile was insulated with straw parallelepiped bales (0,45 x 0,45 x 0,95 cm) which were placed all around the mesh from the inside to avoid heat dispersion as much as possible.

The biomass was composed of 25 m^3 of woodchips obtained by shredding wood waste, having a size between 2-5 cm and a density equal to 400 kg/ m^3.

Characteristics of the plant are reported in table 1.

Table 1: General plant and biomass data

PARAMETER	VALUE
Internal diameter	4, 00 m
External diameter	4,90 m
Height	2 m
Internal base area	12,6 m^2
External base area	18,8 m^2
Internal volume (Woodchips)	25 m^3
External volume	37,7 m^3
Woodchips density	400 kg/ m^3
Woodchips MC	59%
Woodchips weight	10 tons
Straw bale - length	0,95 m
Straw bale - width	0,45 m
Straw bale - height	0,45 m

In order to control rainwater infiltration and provide the optimum humidity value (around 40–60%), a nylon cover was placed on the top of the plant to control rainwater infiltration.

To ensure the adequate aeration of the degrading material and oxygen required by microorganisms, 6 perforated polyvinylchloride pipes which promote the airflow by means of a chimney effect (static aeration) are used.

The perforated pipes have a diameter of 0.1 m and are placed vertically inside the plant body, entering parallel to the ground, from the bottom side and outgoing from the top with a 90-degree angle.

The generated heat is recovered by means of spirally arranged PE pipes (D = 25 mm) inserted in the woodchips pile. These pipes were placed at three parallel levels from the bottom for a total of 300 meters of length.

Inside these pipes, the exchange fluid, that is water, flows, runs through the degrading material, collects the heat produced and takes it to a heat exchanger placed inside the greenhouse, dissipating the thermal energy by providing warm water to the heating system (two radiators). Then the cooled fluid returns to the plant.

The circulation system was originally composed by a radiator, a heat exchanger but also an expansion vessel, a flow meter and valves for flow management and mixing. Another radiator was installed after some time to make further tests.

Three probes, “BOT”, “MED”, “TOP” were placed at three different levels inside the reactor’s body (-0.5 m, -1.0 m and -1.5 m) to measure its internal temperature while another two probes were installed to measure external and greenhouse temperatures. The external temperature probe was placed on the northern part of the plant.

Further remote temperature probes were added: two regarding the thermocompost circuit and two regarding the radiators’ circuit were installed to measure the temperature of the exchange fluid (water) during its recirculation passages between the heat source (plant) and the heat exchanger (radiator).

Also, a calorie counter was installed for the monitoring of thermal output values.

Figure 1 shows the plant and the section of the CHRS and the related greenhouse.

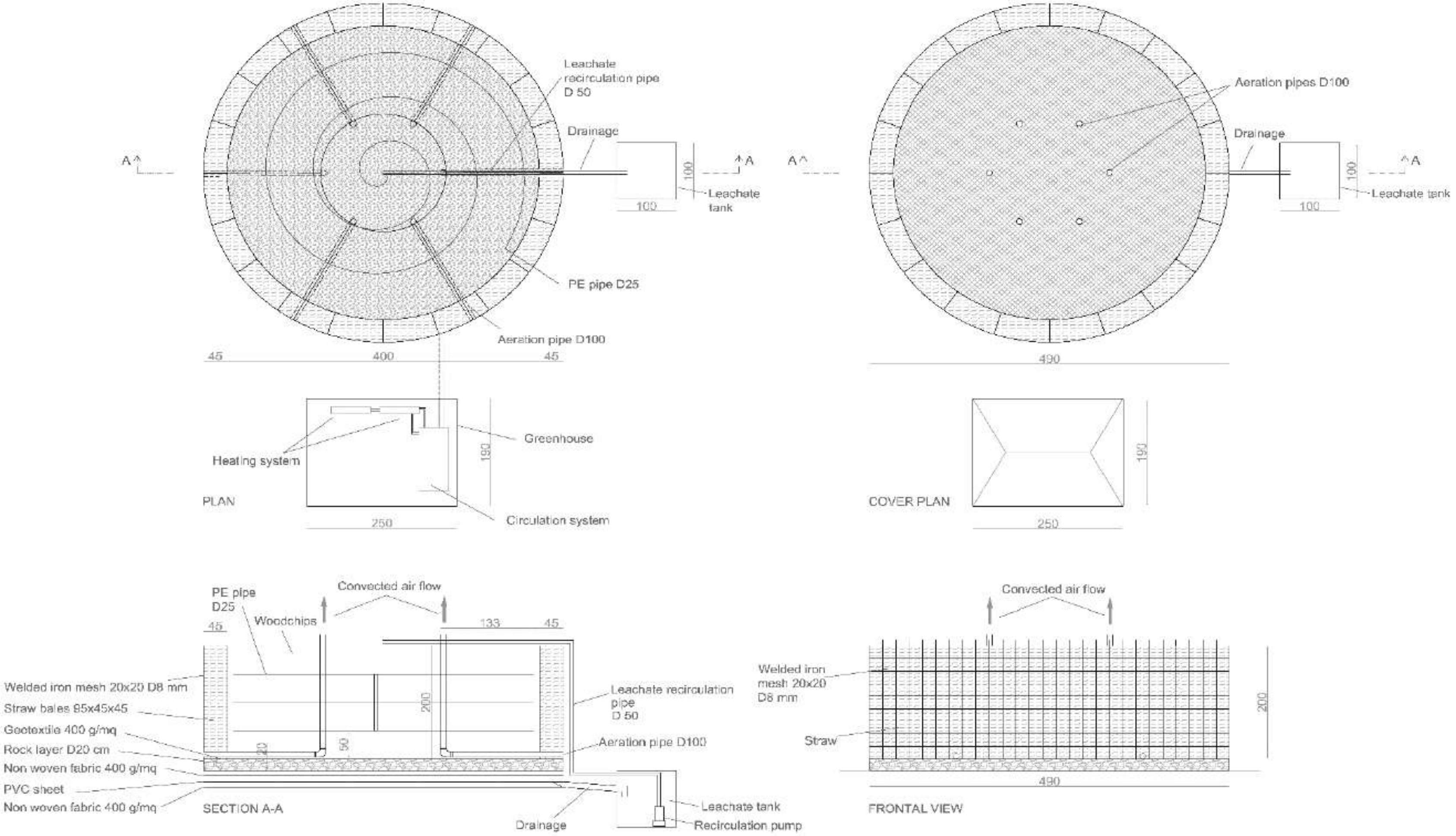


Figure 1: plant scheme

2.2. Material characterization

The materials involved in the experiments, namely woodchips and whey, were obtained from local facilities within the province of Padua (PD) and Treviso (TV).

Woodchips were provided by company that deals with chipping services, operating in Padua. The material prevalently consisted in bio-shredded wood chips of mixed twigs, without foliage having a size between 2-5 cm, and a density equal to 400 kg/ m^3.

Whey, which is a readily degradable substrate, rich in proteins, containing essential amino acids, minerals and low in fat, was furnished by a diary situated in Treviso (TV).

Whey composition is variable depending on factors such as the animal species, the lactation phase, the animal feeding and the mode of obtaining the product, but basically it is composed of 90-93% by water, lactose, soluble milk proteins, low lipids, calcium, B vitamins, branched-chain amino acids, sulphur-containing amino acids, and all 9 essential amino acids (EAAs) required by humans (Campos et al., 2022).

With regard to the samples collection, woodchips were picked up more or less weekly from the top of the plant, digging the heap 15-20 cm deep, in order to obtain the best characterization of the biomass.

Also, leachate and whey samples were collected: leachate samples were collected more or less weekly, directly from the leachate tank, while samples of whey were collected before every injection.

Since the construction of the plant process parameters like Total solids (TS) and Volatile solids (VS) were analyzed on the solid sample as well as Lower Heating Values (LHVs), performing a calorimetry test.

Total organic carbon (TOC), total Kjeldahl nitrogen (TKN), NH_3 and pH both on the leachate and on the whey were analyzed.

TKN was measured through a distillation-titration procedure after an acid digestion phase, while NH_3 was measured through a distillation-titration procedure.

2.3. Set up of experimental trials

The system was built on 27 January 2023 and was immediately connected to the hydraulic and electrical circuit.

All the probes were connected from the start and the pumps have been set up as follows:

- both pumps turn on when the temperature inside the system body exceeds 35 degrees
- Heat is only exchanged when the return temperature to the THC is above 40 degrees

- The radiator is set to operate at 30 degrees; when the water temperature is higher than 30 degrees, it is mixed with cold water, when it is lower than 30 degrees, no heat is exchanged.

On February the 2nd heat exchange settings were set as following: return water temperature to the thermocompost was changed to 35°C and the operating temperature of the radiator was raised to 33°C.

The following day, settings were changed again after connecting the calorie counter to the monitoring system; operating temperature of the radiator was raised to 40°C to try to extract more heat.

On February the 12th, as temperatures inside the plant were too high, 250 liters of water were injected to cool down the biomass, to avoid the death of microorganism and to avoid excessive evaporation.

On February the 14th the operating temperature of the radiator were raised 45°C while return water temperature to the thermocompost was raised to 40°C to avoid cooling the material too much.

On the 22nd of February, the plant was wet for 15 minutes, until percolation. Calculating a water rubber flowrate equal to 20 l/min, 300 liters of water entered the reactor.

Again, the plant was wet on March the 6th with 250 l of water, to avoid excessive water evaporation.

On March the 9th, it was collected the first sample of woodchips and leachate, all the other samples were collected on a weekly basis.

In order to give a boost to microorganism to increase heat production rates, and to prolong the lifetime of CHRS an external feeding of whey, a readily biodegradable, nutrient-rich organic substance, was provided.

On March the 22nd, 250 liters of whey and 320 liters of water were added from the top.

Whey was spread manually over the biomass heap in order to obtain a good distribution of the substance in the whole area of the plant and along the whole height.

Heat started to be extracted on March the 22nd, after the first whey addition.

The plant was producing heat continuously being a biological process, but heat was extracted during specific intervals, modified week by week.

It must be taken in mind that, at a given flowrate, more heat is extracted as the temperature of the return water decreases, taking in mind that warming water through conduction can have the side effect of cooling the heap of organic material, inhibiting the microbial processes.

Also, lower is the temperature inside the greenhouse, higher is the heat exchanged: punctual values of power depend on the punctual temperatures inside the greenhouse and so they are directly influenced by external temperatures.

It was then decided to start the heat extraction test for a limited number of hours at night, when outside temperatures were milder than during the day.

It was set a return water temperature to the thermocompost equal to 25°C and an operating temperature of the radiator equal to 45°C so that it could dissipate all the heat.

From the 23rd to the 31st of March, the extraction was performed from 5 to 7 a.m, while on March the 31st the number of maximization hours was increased from 3:00 to 7:00 until April the 4th.

On April the 4th, due to a general decrease of external temperatures of the following days, it was decided to let the greenhouse's door opened to decrease the temperature inside the greenhouse, decreasing the thermal delta. The extraction time was shifted, from 4 to 6 a.m. until April the 13th to run the trial during the colder hours.

On April the 14th, the extraction time was shifted, from 4 to 6 a.m, letting the greenhouse door open, until April the 19th.

On April the 19th, another whey injection was performed: 200 l of whey were spread over the biomass heap.

The number of maximization hours was reduced to just two hours, from 4 to 6 a.m, in order not to stress the already relatively cold system with a long extraction period. The greenhouse door was left open.

On May the 5th, the extraction period was increased from 2 to 6 a.m, with the door open until May the 16th, when other 200 liters of whey were injected.

A final injection of 200 liters of whey plus 50 liters of water to wash the drums containing the whey, was performed on May the 19th.

The extraction period was let unchanged (from 2 to 6 a.m with the door open) and the setting have been maintained until the end of the heat extraction trials.

2.4. Process monitoring

The biological process was monitored according to internal and external temperatures values, while heat extraction maximization trials were meant to evaluate the maximum thermal output values, in particular the punctual power values (kW) and the related cumulated values of energy (MWh) produced.

Four PT 1000 wire temperature probes (SAF 002) were installed to measure the exchange fluid temperature in the thermocompost and radiator's circuit.

These probes are specifically designed for detecting the temperature of a fluid circulating in a pipe; the sensor is housed in a protective brass sheath and is connected directly to a bipolar cable.

Five other identical probes were installed, three measuring the internal biomass temperature, and two measuring respectively the external and the greenhouse temperature.

All the probes were provided by "Coster Group" as well as the calorie counter (UHF 15-1,5) and the remote-control system ("WebGarage"), for the remote monitoring (through Wi-Fi) of the process parameters and of the circulation fluid.

Data were recorded continuously every 15 minutes and stored on the above online graphical interface.

During the monitoring process we faced some problems with WebGarage platform that sometimes didn't work correctly and consequently didn't recorded the data.

In fact, several times of missing data were recorded: the system, apparently for no reason, stopped recording right at the start of the heat extraction periods, returning operational only thanks to the technical assistance of Coster Group.

About halfway through the monitoring period, it was necessary to recreate the program and reprogram the probes as they no longer recorded correctly.

In general, the lost data did not create much inconvenience, and monitoring continued in a more or less timely manner.

3. RESULTS

3.1. Physicochemical parameters characterizing the process

Measured values of leachate and whey samples, are shown in Table 2.

Table 2: analysis values results for whey and leachate

SAMPLE	Date	TC (mg/l)	TOC (mg/l)	TKN (mg N/l)	NH_3 (mg N/l)	pH	NOTE
Leachate	09/03	360	228	48,4	18,2	7,04	
Leachate	16/03	393	257	< 5,0	< 5,0	6,70	
Leachate	22/03	398	220	< 5,0	< 5,0	7,05	Before whey injection
Whey	22/03	19900	17000	1642	175	4,71	
Leachate	31/03	334	229	22,8	5,77	7,68	
Leachate	11/04	198	83,8	9,2	10,1	7,26	
Leachate	19/04	174	74,4	10,7	7,3	7,28	Before whey injection
Whey	19/04	13900	12600	1454	178	4,27	
Leachate	03/05	195	92,2	16,5	5,1	7,58	
Leachate	09/05	200	83,4	12,1	< 5,0	7,37	
Leachate	16/05	192	92,3	13,0	< 5,0	7,49	Before whey injection
Whey	16/05	26350	22650	1457	172	6,07	
Whey	19/05	30200	26500	1573	180	5,9	

It can be observed that the TOC values confirmed the internal temperature trend.

In fact, the last injection, characterized by the greatest TOC value and so the greatest biodegradable organic substance, returned the highest internal temperatures increase.

A decreasing trend of leachate TOC value is observed: after an initial washout in which values rose slightly, values dropped, indicating that a correct biodegradation was occurring, but such slowly decreasing trend means that the process is slow.

The very low values of TOC mean that almost no organic substance is leaching as it remains inside the biomass.

Comparing the TC values, which are greater than the TOC ones, we can affirm that almost half of the mass is organic, while the other half is composed by carbonates, bicarbonates, CO_2 that are oxidation products.

It can be noticed that all the samples of whey don't differ too much regarding TKN and the low reported values state that leachate contain virtually no nitrogen.

NH_3 leachate values resulted also in the absence of ammonia growth meaning that proteins are not degrading, in fact, as described by the TC-TOC graph, almost only carbon can be found in leachate and the only presence of proteins in the reactor is given by whey injections.

pH values of leachates samples resulted around neutrality, meaning that the biomass is not facing acidosis, so no anaerobic fermentation is observed.

Whey samples resulted in having a more acid pH: it has to be paid attention that the lower values of whey pH samples are given by analyzes carried out several days after the sampling.

The fermentation of those samples which occurred some days after the collection, made the lactose transform in volatile acids with a subsequent drop in pH, as opposed to those analyzed immediately which reported a slightly higher pH value.

With regard to the solid samples, woodchips analysis didn't reveal any statistically significant variation: final VS values didn't differ too much from the initial samples ones, meaning that a modest variation in the organic substance content due to the action of the micro and macroorganisms present in the reactor was observed, showing a slow biodegradability of the biomass.

High medium value of VS, indicated a massive presence of organic substrate.

All the analyzed parameters confirmed that, although a degradative process was occurring, the biomass, due to its composition, is facing slowly degradation kinetics.

3.2. Temperature

Figure 2 represents temperatures data of the monitoring probes inside the CHRS body and the external temperatures registered. Blue arrows represent punctual water injections performed during the management of the plant, while red arrows represent whey injections and the related TOC values.

Start-up phase goes from the construction of the plant to the first introduction of whey, after that, monitoring phase is considered.

Missing data were due to technical problems.

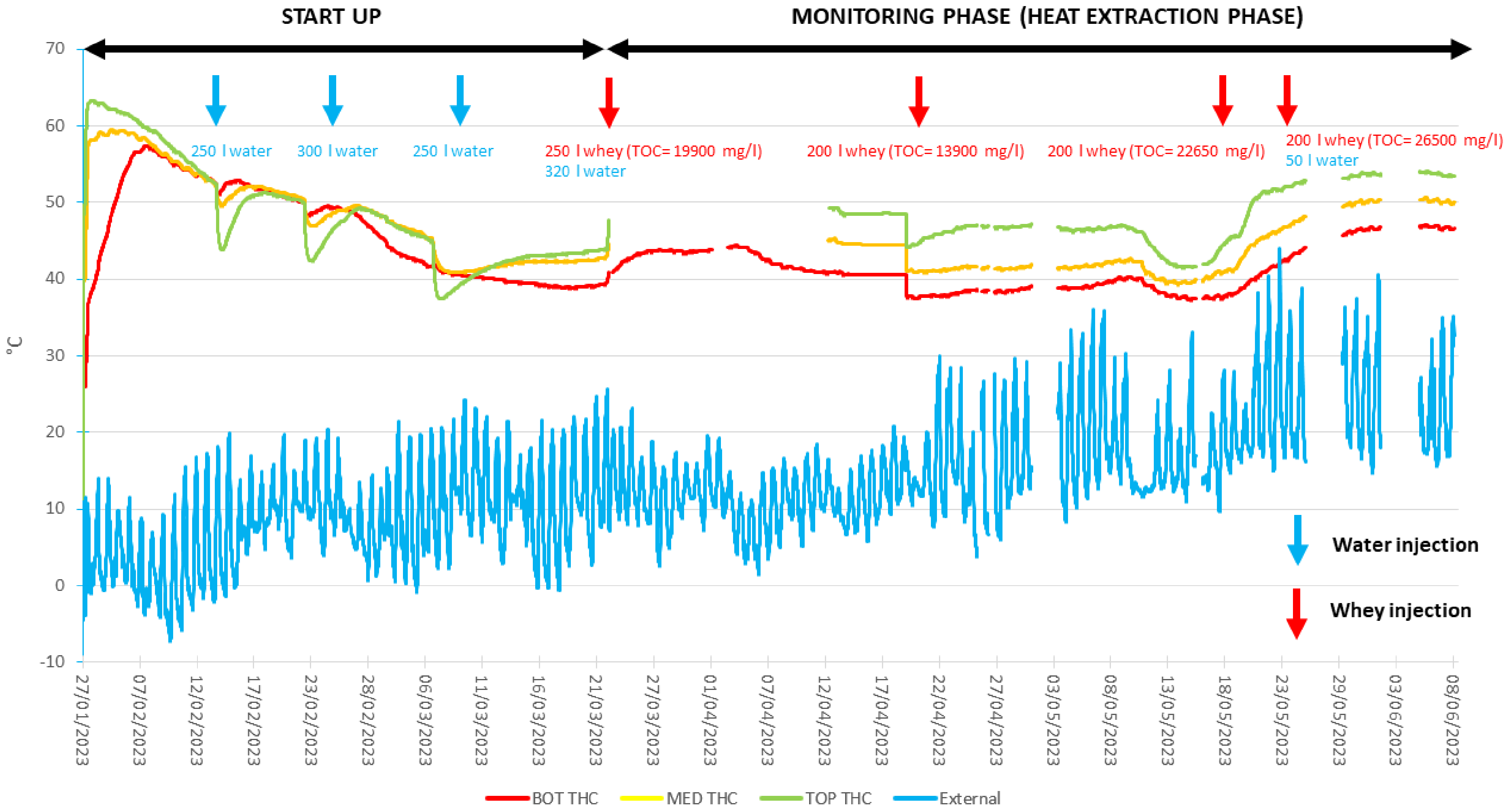


Figure 2: Temperatures data recorded at Voltabarozzo plant through temperature monitoring probes inserted inside the plant body at different depths and the external registered temperatures

The construction of the plant was followed by an immediate peak of the internal temperature which slowly began to decrease with time.

Two weeks after the construction, in the start-up phase, three drops of the internal biomass temperature were registered corresponding to the injection of water in the plant: temperatures decreased more in the top layer while bottom and medium layer were hardly perturbated, probably because they were already completely soaked.

With regard to the optimization measures studied, the external whey feeding increased as expected the performances of the process, in particular: the injection of whey demonstrated to accelerate the rate of temperature increase, shortening the period to reach temperature peaks and maintaining higher and more stable temperatures inside the plant, resulting in quite good heat extraction performances.

The most interesting aspect is that every whey injection provoked a general increase of the internal temperatures: the top layer reached and exceeded 50°C after every whey injection, and a peak of 54°C of the top layer was reached around the first days of June.

Having said that, the addition of whey unfortunally didn’t always returned the expected values.

Whey with high values of TOC resulted the best solution for the injection: in fact, microorganisms reacted very well to the injected organic substance, resulting in a prompt increase of the internal biomass temperature and heat extraction power outputs.

Whey with lower TOC values returned very low internal temperatures increase, not exceeding 47 °C in the upper layer.

In particular, after the second injection of whey, characterized by the lowest TOC value, we observed an immediate decrease of the internal temperatures, followed, the day after, by a slowly increase which however didn’t lead to high peaks of temperature.

Temperatures began to drop less than a month after the above whey addition and only the injection of a whey with a high TOC value, was able to raise them.

From external temperatures side, it can be stated that from the construction of the plant to the first whey injection, external registered temperatures remained relatively low, not allowing the upper layer to increase too much in temperature, compared to the other two: almost no temperature difference between the top and the bottom layer turned out.

Subsequently, as the external temperatures increased, a stronger top layer temperature increase was observed, further detaching the medium layer and even more, the bottom one.

In fact, during all the monitoring phase a difference of temperature between the top and the medium layer equal to 4 °C was observed.

The explanation of the higher temperature increase of the upper layer with respect to the other two layers must not only be sought in the increase of external temperatures.

According to our thoughts, the higher difference between layers’ temperature can either be due to the fact that, during the feedstock injection, whey quantity reached only minimally the medium and bottom layer, not returning any beneficial effect, or these two layers were so moist that they couldn't rise in temperature unlike the top one, which being in contact with the surrounding environment, was subjected to higher external temperatures.

3.3. Real power extraction

The performed heat extraction trials were further summarized graphically through boxplot, which allows to quickly visualize the degree of dispersion of the data.

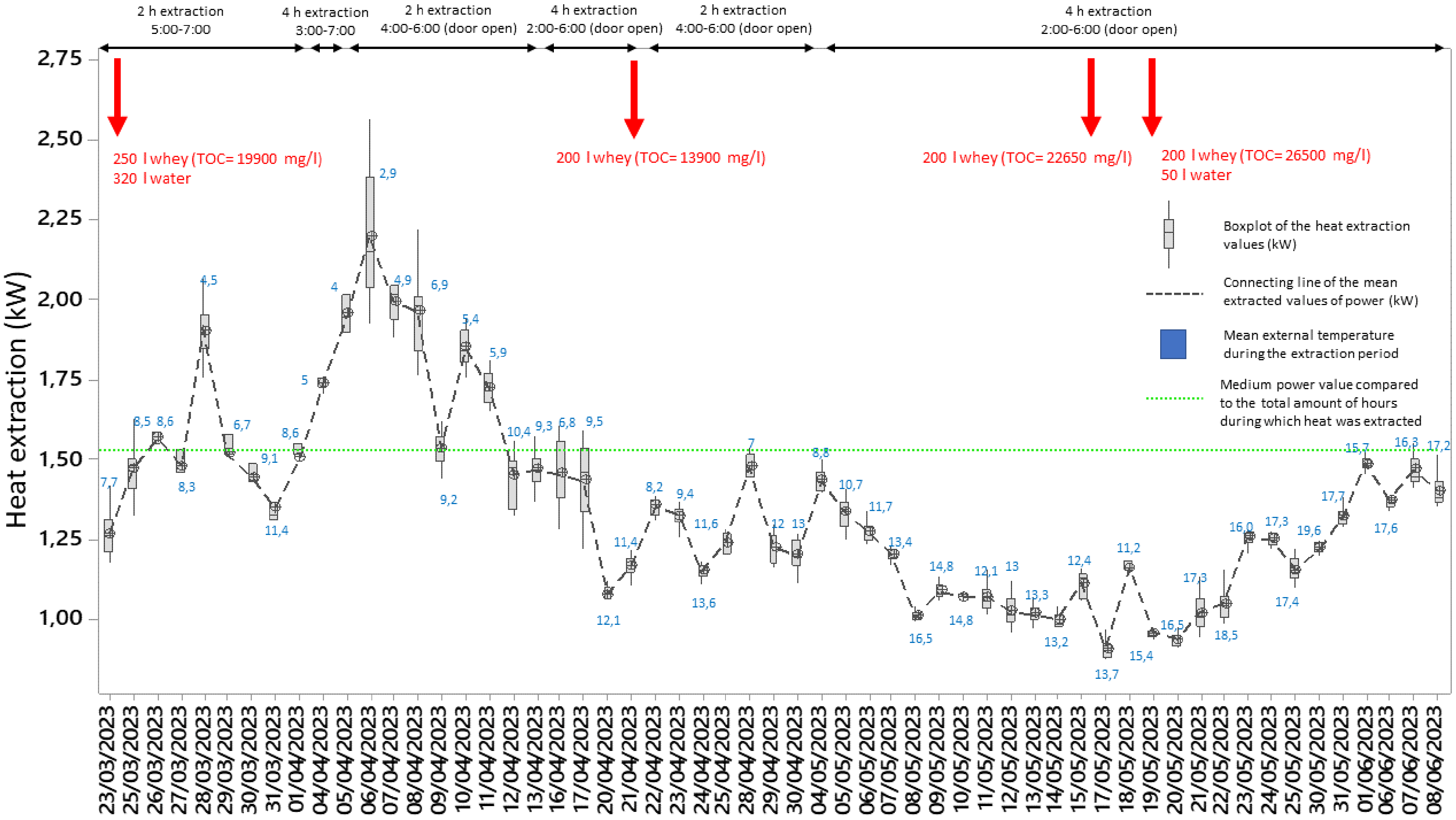


Figure 3: boxplot of the heat extraction values (kW), the connecting line of the mean extracted values of power and the medium value of the external temperatures during the extraction period (244h)

Figure 3 confirms that power values are directly and strongly influenced by external temperatures.

Some days after the first whey injection (TOC = 19900 mg/l), at the beginning of April, external registered temperatures at night decreased a little bit with respect to the previous days: a maximum power value equal to 2,57 kW was registered on April the 6th when the external temperature reached a minimum of 2,9 °C.

On the contrary, some days after, comparing and combining inside plant temperatures which began to cool down, the low TOC values (TOC = 13900 mg/l) of the second injected whey and the increasing external temperatures, it can be seen that a lower medium value of power equal to 1,33 kW, was obtained until a new addition of whey with a high value of TOC was performed.

The two close injections of whey performed at the end of May resulted in promising thermal power outputs also if external temperatures were constantly increasing.

Also, the medium value of power compared to the total amount of hours during which heat was extracted, is graphed.

The thermal power generated over time by a CHRS can be evaluated from several available literature data of plants performing heat extraction from composting processes.

According to the Native Power association and Biomeiler, which are both commercial enterprises that focus on woodchip composting to propose a list of preferable dimensions based on their experience, to maximize heat production starting from an available volume of woodchip, a traditional plant (volume ranging from 25 to 80 m^3) fed with chipped woody biomass yields an average thermal power output ranging between 0.05 and 0.1 kW/m^3.

According to the data collected from the plant, it was possible to estimate the efficiency of thermal energy recovery from CHRS starting from the potential heat production and monitoring the actual heat extraction.

The potential heat production is estimated starting from the Lower Heating Values (or Net Calorific Value) of the biomass and from the degradation efficiency of the biomass in the analyzed period.

The principle is that the heating value of the composting substrate decreases gradually due to the microbial degradation during composting process. The microbes, indeed, decrease the volatile solids portion of the material during composting process, decreasing the heating value, and a change in heating value provides a mean of measuring changes in the amount of energy available from compost over time (Ahn et al., 2007).

Since usually CHRSs are fed with different kind of residual lignocellulosic biomasses, several values of LHV were collected from literature, therefore LHVs were calculated by an external laboratory, performing a calorimetry test and the analysis confirmed literature data on the selected biomass typology.

The data about LHV of lignocellulosic biomasses found in literature, provided an average value of 17.13±2.00 MJ/kgDM and this value was considered to perform the estimation of the potential heat production.

Considering the available data of plant and biomass, in particular: woodchips volume = $25\ m^3$, woodchips density = $400\ kg/m^3$, woodchips MC = 59%, woodchips weight was calculated as follows:

$Woodchips_{\ weight} = \ \rho * \mathrm{V} = 10000\ kg$, which can be expressed in KgDM:

$Woodchips_{\ weightDM} = Woodchips_{\ volume} * \rho * (1 - \frac{MC}{100}) = 25\ \ m^3 * \ 400\ kg/m^3 * \left(1 - \frac{59}{100}\right)$ = 4100 kgDM

During the composting process, not all the biomass is degraded: since the efficiency of degradation of woody materials tested in laboratory experiments (Malesani, 2021) resulted 27% on the dry matter, the degraded woodchip material is equal to

$Woodchips_{\ degraded} = 4100\ kgDM * \frac{27}{100}$ = 1107 kgDM

Considering a LHV = 17 MJ/KgDM, and a conversion factor of 3,6 MJ/kWh, a potential energy to be released in the form of heat can be calculated as follows:

$$Potential\ extracted\ energy = \frac{17\ [\frac{\mathrm{MJ}}{\mathrm{KgDM}}] * 1107\ [\mathrm{KgDM}]}{3{,}6\ [\mathrm{MJ/kWh}]} = 5227{,}5\ kWh$$

The actual heat extraction could be estimated according to all the values reported in Table 7 in Annex D.

Anyway, it is difficult to quantify the energy released from a CHRS during its life cycle, due to the fact that the biological process depends on many factors (humidity, oxygen content, C/N ratio, pH, etc.) and if conditions are not optimal, the process can be inhibited.

Since the punctual values are not representative of the real amount of thermal power output of the plant, power was calculated according to the total amount of MWh produced and the total amount of heat extraction hours.

Given a reference time of 6 months, considering the various operative (extraction) phases, the hours of functioning were equal to 244, while the total amount of MWh produced from March the 23rd to June the 8th was equal to 0,37 MWh which can be further transformed in 370 kWh.

The medium power value was obtained by dividing energy by the number of extraction hours and resulted equal to 1,51 kW.

This output was then calculated as kW/m^3 considering the volume of the plant and a value equal to 0,06 kW/m^3 was obtained, which is in line with literature data.

The heat recovery efficiency is given by comparing the value of actual extracted energy in 6 months equal to 370 kWh, to the value of potential extracted energy in 6 months equal to 5227,5 kWh

$$Heat\ recovery\ efficiency = \frac{370\ kWh}{5227{,}5\ kWh}\% = 7{,}1\ \%$$

Regarding the ratio between heat production and heat extraction, few data are reported in literature. Values between 48.7% and 71% have been found about the efficiency of heat recovery using the traditional CHRS to recover and use heat produced during composting processes with the tubes buried inside the biomass pile (Kimman et al., 2019; Seki et al., 2014).

Also, from calorimetric analysis (table 5, ANNEX D), it resulted that the biomass, even after whey injections, maintained high lower heating values, thus indicating that a great amount of energy that can be furnished by the system, is still available and thus partly explaining such a low efficiency of the plant with respect to literature average values.

All the analyzed data revealed how the actual amount of heat produced is predominantly linked to many factors such as the dimensions of the plant, feedstock energy content, feedstock degradability, duration of composting, and the conditions prevailing during composting (e.g., moisture, temperature, and substrate consistency) (Smith et al. 2017).

4. CONCLUSIONS

Under a scientific and technical point of view, it is possible to conclude that the research process worked well, and all the measures used during all the trials could be easily replicated in a non-research field, as well as the remote-control system.

The experimentation provided very interesting results: the main conclusions of the thesis are that CHRSs, turned out to be a good technology, requiring low installation, operation, and maintenance costs.

On the design front, the full-scale plant and the hydraulic system for heat recovery proceeded without any interference, while the monitoring system, which at the beginning faced some technical issue, was implemented and perfected.

With regard to the external addition of external organic substance, it was found that it was strongly helpful for the sustenance and maintenance of constant bacterial activity, which translated into a constant production of metabolically generated heat.

In fact, whey insertions, with except for the lowest TOC one, were responsible for maintaining temperature values always higher than 50 ° C, supplying nutrients that were easily assimilated by the microorganisms, encouraging their metabolic and reproductive activity.

On the other side, it must be paid attention to the typology of the injected substance: as it was reported, low TOC values of whey, poorly stimulated the degradation process, not increasing internal temperatures too much and the generated heat, returning low values of power.

This factor is of fundamental importance in thermocompost plants, aimed at recovering and reusing heat.

All the laboratory analysis reported that the degradation process was occurring, with a higher decreasing trend in leachate than in the biomass.

Also, a low efficiency of the plant with respect to literature data, was obtained, and in particular a low extracted energy with respect to the potential one, although power values were in line with literature data.

Despite that, it can be concluded that the plant, if well managed and monitored and implementing the right optimization measures, can have a great potential to furnish higher energetic values in the future.

5. DISCUSSION AND FURTHER DEVELOPMENTS

Based on the objective of optimising waste management, with particular attention to resource conservation and climate protection, the process of energy recovery using CHRS, and biomass recycling should be judged in the future as a complementary system to cover part of the energy need for a building, as required by national policies.

Moreover, economic valorization of residues coming from tree-pruning and similar activities could be an incentive for the implementation of this kind of plant: compost obtained during plant activity can be re-used on the soil as fertilizer, perfectly implementing the principles of circular economy.

Regarding the implementation measures, as power output values were strongly influenced not only by external temperatures but also by whey injection, a constant and more frequent addition of this substance could be evaluated to understand the contribution to biodegradation process and heat extraction.

An implementation for future CHRSs could be the installation of three moisture probes, placed at different depths, in correspondence of the internal temperature ones.

This will surely help to understand why medium and bottom layer temperatures of the analyzed CHRS always increased at a slower rate, compared to the top layer one.

Also, possible future research could be done about the implementation of installments to help the maximization of heat extraction process like a heat exchanger.

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Thirt part: Appendix

ANNEX A: a photographical documentation

On January 2023, a Thermocompost and a greenhouse heated up by the plant, were built in the backyard of "LISA" laboratory.

The following photos represent the construction phases.

Figure 1: CHRS construction phases

Figure 2: greenhouse installation and circulation system

Figure 3: nylon cover, aeration and recirculation pipes detail

ANNEX B: plant and hydraulic schemes

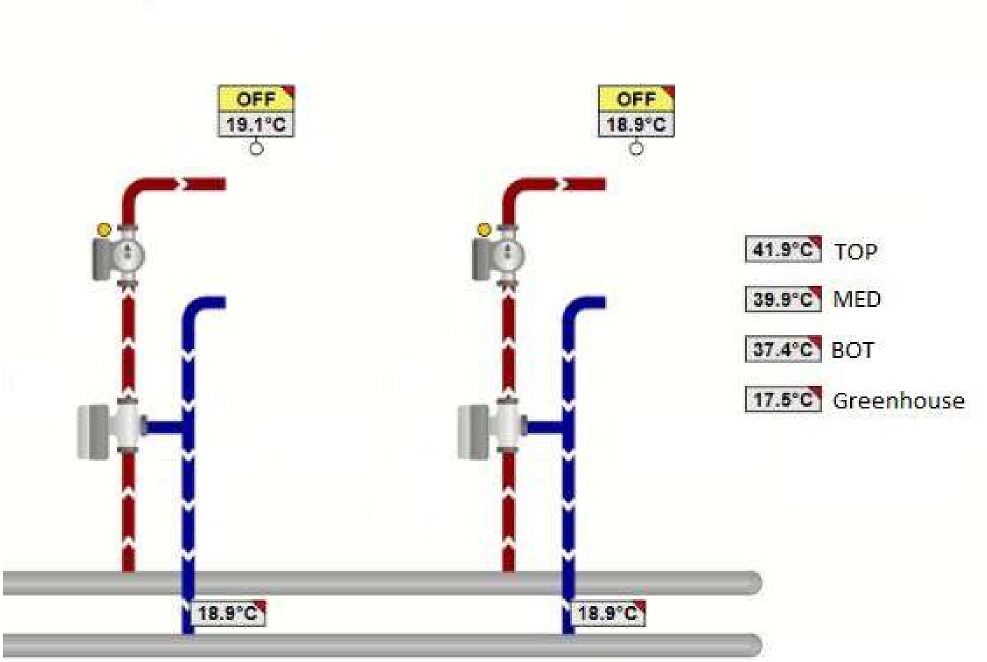

Figure 4: General scheme of the circulation system from WebGarage, the graphic interface

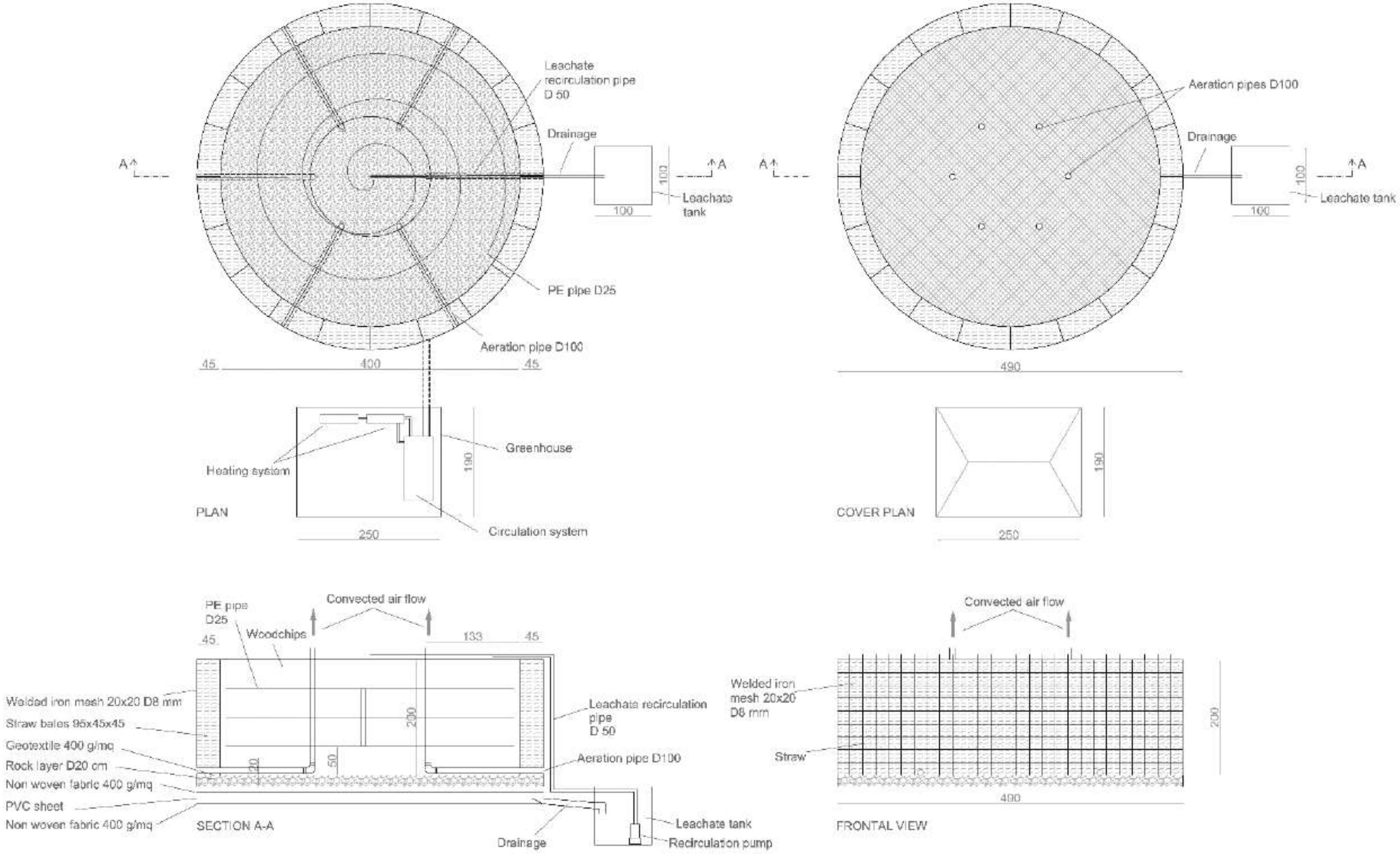

Figure 5: plant general scheme

ANNEX C: laboratory analysis on collected samples

TOC

The total amount of organic carbon on the whey and on the leachate samples, was considered of high relevance as it was used as an indicator of the development of the degradation process. This parameter should in fact decrease as the microorganisms degrade the carbon present in the organic lignocellulosic substance subjected to composting.

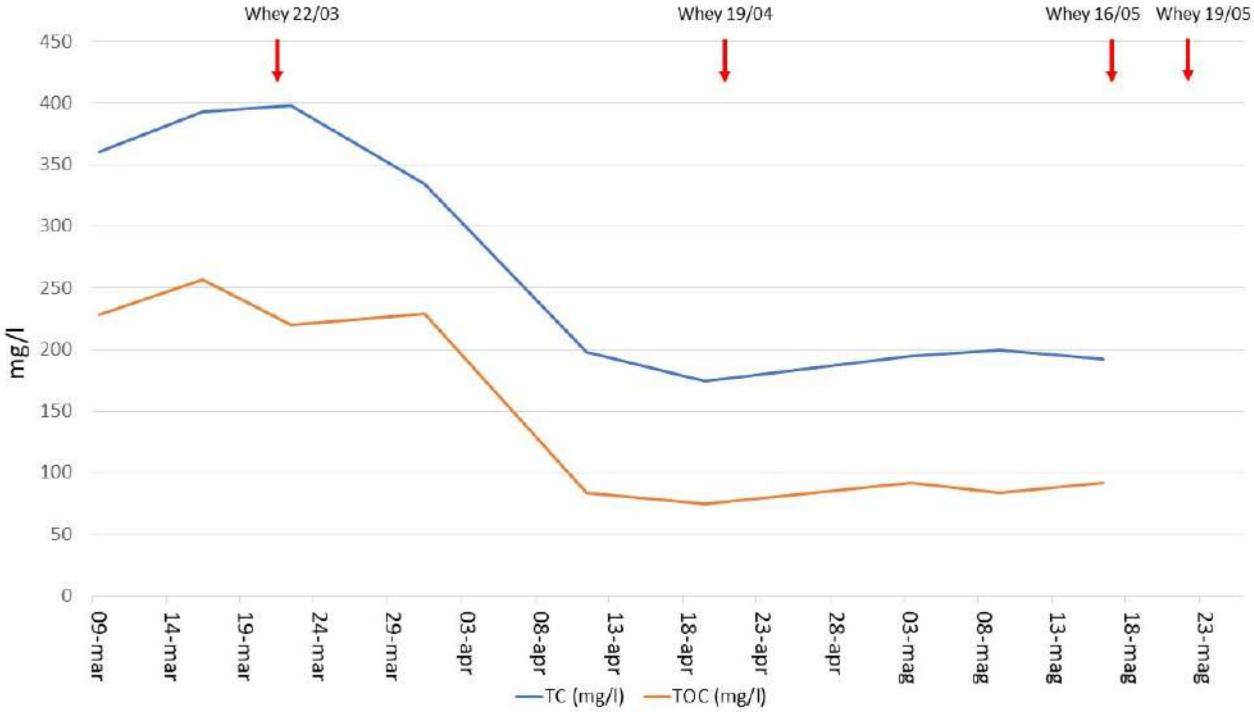

Figure 6: TC – TOC trend of the collected leachate samples

TS – VS

Collected woodchips samples were put in an oven at 105 °C for 24 hours to calculate the total solids, and then in a furnace at 555 °C for 5 hours to calculate the volatile solids.

Weighing the two full containers, the gross weight after 555°C was registered and VS % were easily calculated.

The following table resume the total solids measured as percentage on total weight, and the volatile solids as a percentage on the dry weight, on the different samples of woodchips.

Table 1: ST and VS of woodchips analyzed

SAMPLE	DATE	Sample weight (gr)	Capsule weight (gr)	Gross weight after 105 °C (gr)	ST (%)	Gross weight after 550 °C (gr)	SV (%)
1 – A	27/01	21,0384	102,6127	112,4069	46	103,8353	87
1 - B	27/01	24,2336	102,1193	113,2304	46	103,5950	87
2 - A	09/03	29,9722	72,6468	85,6535	43	74,4897	86
2 – B	09/03	23,9390	105,1026	115,9232	45	106,3412	88
3- A	16/03	34,2810	68,4556	83,9825	45	72,9949	71
3 – B	16/03	31,5767	81,4293	94,0202	40	84,4196	76
4 – A	22/03	43,1423	71,1645	87,1135	37	73,8356	83
4 – B	22/03	36,1207	71,9395	84,6878	35	73,6086	87
5 -A	31/03	34,4059	99,9811	112,3141	36	101,4277	88
5 – B	31/03	39,8954	78,4251	92,6372	36	80,2622	87
6 - A	11/04	16,0842	72,6405	78,7814	38	72,9623	95
6 - B	11/04	19,6450	99,9834	107,3748	38	100,3942	94
7 - A	19/04	21,8684	71,9425	80,3455	38	72,6363	92
7 – B	19/04	19,2721	102,5948	109,5118	36	100,3881	88
8- A	03/05	28,4443	81,4153	91,9921	37	82,3034	92
8 – B	03/05	20,7177	102,1154	109,5049	36	102,5073	95
9 – A	09/05	37,2882	78,3458	91,9963	37	78,6878	97
9 – B	09/05	34,5610	71,1649	83,6646	36	71,7456	95
10 -A	06/06	29,1576	72,6468	83,9357	39	73,5681	92
10 – B	06/06	33,6742	68,4556	81,5394	39	69,7611	90

Two tests (A, B) for each woodchip sample were performed, in order to eliminate any data interference from the inhomogeneity of the collected specimen.

All the passages of the TS-VS procedure are shown in figure 7.

Figure 7: Initial woodchips sample, samples after 24 hours in the oven, samples entering the furnace.

TKN - NH_3 – pH

TKN was measured through a distillation-titration procedure after an acid digestion phase, while NH_3 was measured through a distillation-titration procedure.

Figure 8: TKN and NH_3 analysis procedure

Table 2: values of TKN analyzed

SAMPLE	Sample volume (ml)	N titrant	Titrant volume (ml)	mg N/l
Leachate 09/03	10	0,02	1,731	48,4
Leachate 16/03	10	0,02	-	< 5,0
Leachate 22/03	10	0,02	-	< 5,0
Whey 22/03	5	0,1	5,864	1642
Leachate 31/03	10	0,02	0,813	22,8
Leachate 11/04	25	0,02	0,823	9,2
Leachate 19/04	25	0,02	0,956	10,7
Whey 19/04	5	0,1	5,193	1454
Leachate 03/05	25	0,02	1,474	16,5
Leachate 09/05	25	0,02	1,083	12,1
Leachate 16/05	25	0,02	1,158	13,0
Whey 16/05	5	0,1	5,203	1457
Whey 19/05	5	0,1	5,617	1573

Table 3: Values of NH_3 analyzed

SAMPLE	Sample volume (ml)	N titrant	Titrant volume (ml)	mg N/l
Leachate 09/03	10	0,02	0,65	18,2
Leachate 16/03	10	0,02	0,20	< 5,0
Leachate 22/03	50	0,02	0,31	< 5,0
Whey 22/03	5	0,02	3,13	175
Leachate 31/03	50	0,02	1,03	5,77
Leachate 11/04	50	0,02	1,81	10,1
Leachate 19/04	50	0,02	1,30	7,3
Whey 19/04	5	0,02	3,18	178
Leachate 03/05	50	0,02	0,90	5,1
Leachate 09/05	50	0,02	0,87	< 5,0
Leachate 16/05	50	0,02	0,71	< 5,0
Whey 16/05	5	0,02	3,08	172
Whey 19/05	5	0,02	3,22	180

Table 4: Values of pH analyzed

SAMPLE	pH
Leachate 09/03	7,04
Leachate 16/03	6,70
Leachate 22/03	7,05
Whey 22/03	4,71
Leachate 31/03	7,68
Leachate 11/04	7,26
Leachate 19/04	7,28
Whey 19/04	4,27
Leachate 03/05	7,58
Leachate 09/05	7,37
Leachate 16/05	7,49
Whey 16/05	6,07
Whey 19/05	5,9

CALORIMETRY TEST

Lower Heating Values (LHVs) were analyzed on the solid samples performing a calorimetry test to evaluate thermal energy from lignocellulosic organic mass subjected to composting.

Table 5: analyzed LHVs on the collected woodchips

SAMPLE	kJ/Kg t.q.	MC %	KJ/kg DM
27/01	7211	59,29	17713,09
09/03	9491	44,44	17082,43
16/03	7395	56,64	17054,89
22/03	6518	62,49	17376,7
31/03	6065	63,31	16530,39
11/04	5135	60,43	12977
19/04	6541	61,64	17051,62
03/05	5831	66,91	17621,64
09/05	6285	62,65	16827,31
06/05	5328	68,49	16908,92

ANNEX D: optimization measures

Figure 9: whey drums

Figure 10: Addition of whey

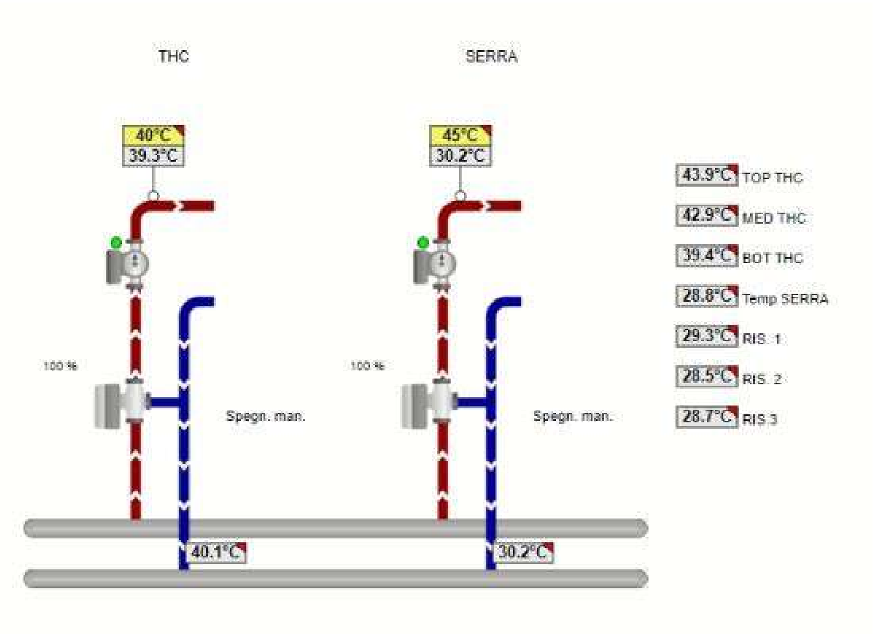

Figure 11: Temperatures of the plant on March the 22nd, before whey injection

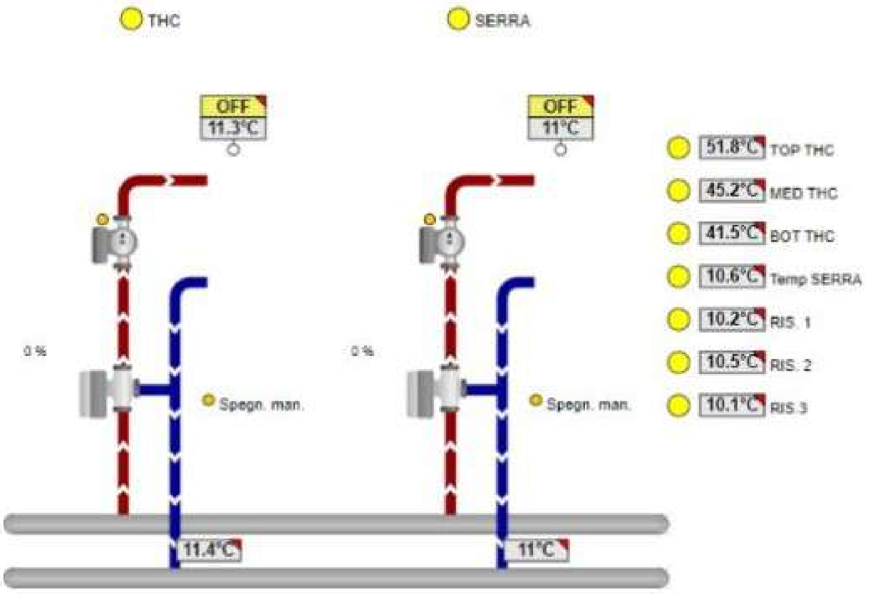

Figure 12: Temperatures of the plant the day after whey injection

Table 6: extracted thermal power output related to the extraction time periods.

DATE	Extraction period	Mean kW
23 – 31 March	5:00 – 7:00 a.m.	1,51 kW
1 – 4 April	3:00 - 7:00 a.m.	1,53 kW
5 – 13 April	4:00 – 6:00 a.m. (door open)	1,77 kW
14 – 19 April	2:00 – 6:00 a.m. (door open)	1,33 kW
20 April – 5 May	4: 00 – 6:00 a.m. (door open)	1,25 kW
6 – 16 May	2:00 - 6:00 a.m. (door open)	1,14 kW
17 May – 8 June	2: 00 – 6:00 a.m. (door open)	1,20 kW

Figure 13: kW daily graph from WebGarage

Table 7: Thermal power output data collection from different on-field prototypes of CHRSs (Malesani, 2022)

	ENERGY RECOVERED (Er)					OPERATIVE CONDITIONS				
MATERIAL	kW/m^3	kWh/m^3	MJ/m^3	kWh/kg	MJ/kg	Operative time (h)	Moisture Content (%)	Bulk density (kg/m^3)	Volume (m^3)	REFERENCES
Woodchips	0.05	406.1	1462	1.015	3.7	8640	70%	1000	55	(Native Power, 2019)
Woodchips	0.05	343.4	1236	0.859	3.1	6480	70%	1000	79	(Biomeiler, 2019)
Woodchips	0.16	112.5	405	0.113	0.4	720	70%	1000	16	(Zantedeschi, 2018)
Chipped brushwood	0.19	820.8	2955	1.492	5.4	4320	45%	550	75	(Pain and Pain, 1972)
Chipped brushwood	0.02	129.6	467	0.324	1.2	6480	NF	NF	197	(Schuchardt, 1984)***
Horse manure, sawdust, woodchips	0.14	83.0	299	0.175	0.6	600	60%	475**	0.9	(Chambers and Supervisor: Allen, 2009)
Bamboo	0.06	56.0	202	0.112	0.4	1008	46%	500	50	(Seki et al., 2014)
Woodchips	0.09	777.6	2799	1.637	5.9	8640	NF	475**	31	Brown, 2014***
Horse manure, woodchips, fresh grass	0.10	85.7	308	1.003	3.6*	864	58%	603	6.7	(Bajko et al., 2019)
Cow manure, grass, sawdust	0.23	70.8	255	0.149	0.5	312	58%	477	2.8	(Mwape et al., 2020)
Green waste	0.10	864.0	3110	1.819	6.5	8640	NF	475**	60	(Cuhls et al., 2020)***
Green waste	0.10	864.0	3110	1.819	6.5	8640	NF	475**	150	(Cuhls et al., 2020)***
Wood	0.06	560.5	1699	1.180	4.2	8760	60%	475**	134	(Kimman et al., 2019)
Woodchip	0.05	438	1577	1.095	3.9	8760	45	400	55	(Malesani et al., 2021a)

The factor used to convert MJ in kWh and vice-versa is 3.6 MJ/kWh. kWh/kg and MJ/kg are expressed in terms of kg of biomass. NF= Not Found.

* MJ/kgDM

** assumed values of biomass density, when not available

***cited after Zimmermann, 2020

Table 8: Literature data about Lower heating Values (or Net Calorific Value) of different lignocellulosic biomasses

LOWER HEATING VALUES (net heating value or net calorific value)	MJ/kg_{DM}	Reference
poplar	9.39	(Lee and Lau, 2017)
corn stover	16.16	(Lee and Lau, 2017)
herbaceous biomass	17.21	H2 tools (Pacific Northwest National Laboratory with funding from the DOE Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office
Corn stover	16.37	H2 tools (Pacific Northwest National Laboratory with funding from the DOE Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office
Forest residue	15.40	H2 tools (Pacific Northwest National Laboratory with funding from the DOE Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office
Broad Bean Husk	16.07	(Erol et al., 2010)
Sunflower Shell	17.86	(Erol et al., 2010)
French Bean Stalk	15.41	(Erol et al., 2010)
Sunflower Stalk and Stover	15.87	(Erol et al., 2010)
Sourcheery Stalk	17.59	(Erol et al., 2010)
Walnut Shell	18.91	(Erol et al., 2010)
Almond Shell	17.96	(Erol et al., 2010)
Peanut Shell	18.46	(Erol et al., 2010)
Cornelian Cheery Stone	19.02	(Erol et al., 2010)
Apricot Stone	18.8	(Erol et al., 2010)
Peach Stone	19.52	(Erol et al., 2010)
Apricot Bagasse	18.56	(Erol et al., 2010)
Peach Bagasse	16.24	(Erol et al., 2010)
Hybrid Poplar	17.14	(Erol et al., 2010)
Ash Tree	18.06	(Erol et al., 2010)
Pine Cone	18.55	(Erol et al., 2010)
Soybean Cake	18.3	(Erol et al., 2010)
Cotton Cake	17.5	(Erol et al., 2010)
Rapeseed	16.61	(Erol et al., 2010)
Potato Peel	17.18	(Erol et al., 2010)
AVERAGE	17.13	

ANNEX E: thermal camera temperature monitoring

Thermography is the recording of the intensity of infrared radiation emitted by a body and its conversion into a visible image.

By measuring infrared radiation, it's possible to determine the surface temperature of the analysed objects: it is basically a measure of radiated heat.

The image obtained by the thermal imaging camera is called a thermogram, characterized by areas of different colors. The yellow and red areas in the photograph, represent areas that dissipate heat, while the violet and dark blue areas are less emissive.

During the monitoring phase, a test with the thermal camera has been performed.

The goal of the measurement was to evaluate any heat dispersions from inside the system to the outside.

In particular, it was possible to evaluate how much the straw bales that act as insulation, shield the heat produced by the biomass, avoiding heat dispersion.

As it can be seen from figure 30, the straw bales, when monitored, returned a medium temperature equal to 15 °C.

Then, 30 cm^2 of straw were manually removed from one side, halfway up the plant until the woodchips mass was reached.

It was then performed another trial with the thermal camera which returned a medium temperature of the biomass equal to 30 °C, thus confirming the high insulation potential of the straw bales.

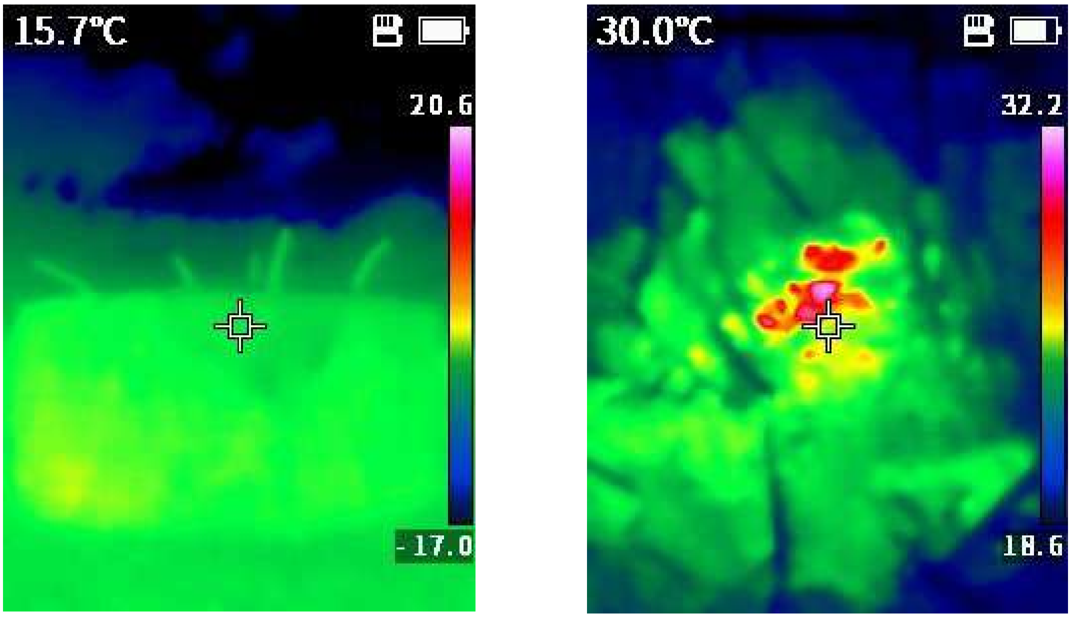

Figure 14: entire plant and particular of the internal biomass registered temperatures