

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/316191443>

# A combined assessment of the energy, economic and environmental issues associated with on-farm manure composting...

Article in *Journal of Cleaner Production* · April 2017

DOI: 10.1016/j.jclepro.2017.04.111

CITATIONS

0

READS

66

6 authors, including:



**Alessandro Piccolo**

University of Naples Federico II

372 PUBLICATIONS 8,929 CITATIONS

[SEE PROFILE](#)



**Assunta Maria Palese**

Università degli Studi della Basilicata

119 PUBLICATIONS 592 CITATIONS

[SEE PROFILE](#)



**Carlo Ingrao**

Kore University of Enna

43 PUBLICATIONS 220 CITATIONS

[SEE PROFILE](#)



**Giuseppe Celano**

Università degli Studi di Salerno

228 PUBLICATIONS 1,487 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Biogeophysical [View project](#)

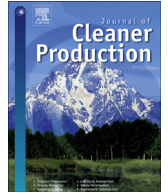


Biofactor EU-Project [View project](#)



Contents lists available at ScienceDirect

## Journal of Cleaner Production

journal homepage: [www.elsevier.com/locate/jclepro](http://www.elsevier.com/locate/jclepro)

# A combined assessment of the energy, economic and environmental issues associated with on-farm manure composting processes: Two case studies in South of Italy

M. Pergola <sup>a</sup>, A. Piccolo <sup>b</sup>, A.M. Palese <sup>a,\*</sup>, C. Ingrao <sup>c</sup>, V. Di Meo <sup>d</sup>, G. Celano <sup>e</sup>

<sup>a</sup> Ages s.r.l.s. Spin-off Accademico, Università degli Studi della Basilicata, Viale dell'Ateneo Lucano, 10, 85100 Potenza, Italy

<sup>b</sup> Centro Interdipartimentale di Ricerca sulla Risonanza Magnetica Nucleare per l'Ambiente, l'Agro Alimentare ed i Nuovi Materiali (CERMANU), Università degli Studi di Napoli Federico II, Via Università, 100, 80055 Portici, NA, Italy

<sup>c</sup> Department of Economics, Università degli Studi di Foggia, Via Romolo Caggese, 1, 71121 Foggia, Italy

<sup>d</sup> Centro di Sperimentazione di Castel Volturno, Dipartimento di Agraria, Università degli Studi di Napoli Federico II, via Pietro Pagliuca, 1, 81030, Castel Volturno, CE, Italy

<sup>e</sup> Dipartimento di Farmacia (DIFARMA), Università degli Studi di Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy

## ARTICLE INFO

## Article history:

Received 7 July 2016

Received in revised form

3 February 2017

Accepted 18 April 2017

Available online xxx

## Keywords:

Cow-buffalo manure

LCA

Energy analysis

Production cost analysis

Bioeconomy

Southern Italy

## ABSTRACT

Livestock effluents “surplus” is a very sensitive issue for farmers who have several difficulties to manage them and ensure their safe disposal. In this regard, composting is a very strategic way to break down environmental impacts associated with manure management.

This study was aimed at assessing the production sustainability of one ton of compost from dairy cattle/buffalo manure in two on-farm facilities operating in Southern Italy and using different bulking agents (wood chip from Short Rotation Forestry, straw and pruning residues). A combined assessment approach was used in 2013 to investigate all the aspects of the composting processes studied, to identify strengths and weaknesses and then optimize the operative steps. Particularly, Life Cycle Assessment, Energy Analysis and Life Cycle Costing were used to calculate environmental impacts, the involved energy and the cost of the production of 1 ton of compost, respectively, and to compare the various composting scenarios.

Regardless of the type of composting scenarios, one ton of on-farm compost caused essentially ecotoxicity potential and abiotic depletion and its cost ranged from 10 to 31 euro. Compost production required from 233 to 756 MJ of energy. Particularly, the lesser impacts and the lesser energy and cost requirements occurred when maize straw or pruning residues were used as bulking agents. The proposed study, which linked together the three above mentioned methodologies, is unusual within the available literature on dairy cattle/buffalo manure composting. This combined approach allowed to define a complete landscape of sustainable possibilities in managing organic residues (especially manure) at the farm level giving useful information to promote the diffusion of these low technology composting processes and the agronomic use of compost thus obtained. All this to ensure sustainable resource use alleviating stress on the environment as claimed by the Europe's Bioeconomy Strategy.

© 2017 Elsevier Ltd. All rights reserved.

## 1. Introduction

A smart and green growth in Europe is expected according to the Europe 2020 Strategy and bio-economy can be seen as a key element to follow in a sustainable growth pathway. As stated in [Ingrao et al. \(2016\)](#), ‘bio-economies’ are bio-based economies

characterised by both reduced dependence upon imported fossil fuels and reduced greenhouse gas (GHG) emissions. However, it is fundamental that such economies are sustainably implemented and managed in the short and long-term to ensure the essential production and consumption transitions to reduce fossil GHG emissions ([Ingrao et al., 2016](#)). The bio-economy should be such as to: ensure food security for a growing world population; mitigate climate change; and preserve soil fertility and biodiversity. So, there is the urgent need for transition from the current fossil-based

\* Corresponding author.

E-mail addresses: [dinapalese@hotmail.it](mailto:dinapalese@hotmail.it), [palesedina@gmail.com](mailto:palesedina@gmail.com) (A.M. Palese).

economy to a bio-based one that pursues both production and utilisation of renewable resources and materials in efficient, responsible and sustainable manners (European Commission, 2012).

In order to meet the increasing global population, the rapid depletion of many resources, the increasing environmental pressures and climate change, Europe should change its approach to production, consumption, processing, storage, recycling and disposal of biological resources (European Commission, 2012). For this purpose, it is urgent to substantially improve our current ways of production and consumption by adopting an holistic approach to sustainability, so promoting and fostering the transition to truly equitable, sustainable, post-fossil carbon societies (Blok et al., 2015; Ingrao et al., 2016). For instance, nowadays, irrigation plays important roles in the hydrological cycle and the accurate knowledge about the cycle phases can help for scheduling and forecasting in water resource management (Valipour et al., 2015), so contributing to its optimisation. Water resources should be accessed in a sustainable manner not only to ensure survival on our planet, but also to improve quality of life. Although the use of modern pumps can help to improve water supply and to extend irrigated agriculture in the world, extreme extraction of groundwater also represents a serious threat to sustainable development. So, research priorities should be undertaken towards the development of cost-effective approaches and practises in all sectors (Yannopoulos et al., 2015).

As a matter of fact, the numerous existing technological advances that have been made in several fields like, for instance, energy generation and agriculture - as above mentioned with respect to water sector - may result not to be effective in the reduction of the related socio-economic and environmental impacts due to a lack of attention to the behavioural dimensions of consumption. This should be attributed to the complexities of the ways by which consumers interact with products and services. So, in agreement with Blok et al. (2015), the authors of this paper strongly believe that there cannot be sustainability if: the economic, environmental, social and time dimensions, as well as their interconnections, are not duly addressed and accomplished; and production and consumption systems are not considered and interconnected.

In this context, livestock effluent “surplus” is a very sensitive issue for the majority of farmers, due to the difficulties that they experience in their management and correct, safe disposal. As claimed by several authors (De Vries et al., 2012; Prapaspong et al., 2010; Sandars et al., 2003; Thomassen et al., 2008), manure management contributes to: soil acidification and particulate matter formation; climate change through emissions of GHGs, mainly through volatilisation of ammonia (NH<sub>3</sub>) and nitrogen oxides (N<sub>y</sub>O<sub>x</sub>); eutrophication, mainly through leaching of nitrate (NO<sub>3</sub><sup>-</sup>) and phosphate (PO<sub>4</sub><sup>3-</sup>) to soil and surface water; and depletion of fossil energy sources as a result of its management. Therefore, sustainable ways of manure management and treatment should be found and pursued, so contributing to the biomass usage optimisation in bio-economy based systems. A sound biowaste management is a promising solution towards post-fossil carbon societies (Mihai and Ingrao, 2016), as it is characterised by good levels of energy, economic and environmental performance.

In this context, manure composting can be considered as a solution to break down the aforementioned environmental impacts and other related ones. Composting is an organic waste management system that provides the formation of piles to create a recycled product known as ‘compost’. According to Brown et al. (2008), composting can be considered as a C-based system, similar to reforestation, agricultural management practices, or other waste management industries. As a matter of fact, compost is a stable

humus-like product, generally rich in carbon and free of most pathogens and weed seeds (ALBERTA, 2005). It is usable as a soil amendment and derives from the processing of organic residues by means of aerobic and, secondly, anaerobic microorganisms.

In accordance with the Europe’s Bioeconomy Strategy, compost can be used in agriculture to improve chemical, physical, microbiological and phytosanitary properties of soils (Celano et al., 2012; Martínez-Blanco et al., 2013; Komilis et al., 2011; Pane et al., 2013). At the same time, it is known that the composting process generates indirect and direct emissions of GHGs like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (NO), so contributing to global warming and, as a result, to climate change (Hellebrand and Kalk, 2001; Santos et al., 2016).

This study was aimed at assessing the sustainability of manure composting process, using different on-farm facilities and bulking agents, testing its energy efficiency, as well as its economic and environmental performance. The research was designed to investigate two composting plants of dairy cattle/buffalo manure operating in Italy and was based upon a combined assessment of the related energy, economic and environmental aspects. In particular, to assess and compare those three aspects, Life Cycle Assessment (LCA), Energy Analysis (EA) and Life Cycle Costing (LCC) were applied.

## 2. A review of the specialised scientific literature

Compost naturally contains both macroelements (mainly nitrogen, phosphorus and potassium) and microelements that are essential for plant nutrition (Celano et al., 2012): hence, its use contributes to the improvement of soil chemical fertility. Also, soil physical fertility is increased as compost contributes to the creation of a soil structure that ameliorates soil aeration and water retention capacity, as well as soil softness and workability (Martínez-Blanco et al., 2013). Compost distribution stimulates microorganism activity which enhances the availability of nutrients for plants and produces hormone-like substances that are able to promote crop growth (Komilis et al., 2011). The plant phytosanitary status improvement is the result of the direct antagonistic action by microorganisms developed during the composting process, such as the thermophilic bacteria of *Bacillus* genus but, also, as a consequence of the growth stimulation of those antagonistic microorganisms already present in soils. All those microorganisms hinder the development of plant pathogenic bacteria and fungi in soils through mechanisms of competition for space and nutrients and the production of antibiotic substances (Pane et al., 2013). Furthermore, compost utilisation allows for quality and sustainability related benefits like: the improvement of the sanitary conditions of livestock; the decrease of manure cost-management; the enhancement of the role of soil carbon sequestration of the farms; the savings of external inputs such as fertilisers, pesticides and water; and the bioremediation of polluted soils in order to build an equitable, sustainable bio-economy with greening effect upon agriculture (Ingrao et al., 2016).

During composting, heat and carbon dioxide (CO<sub>2</sub>) are released by the microorganisms as they transform the organic matter into compost. According to de Mendonça Costa et al. (2015), Sun et al. (2011) and Rynk et al. (1992), the following conditions should occur for the composting process to develop correctly:

- a carbon to nitrogen ratio (C/N) ranging from 20 to 30;
- a pore space containing water (accounting for at least 50%);
- piles under aerobic conditions.

The organic matter decomposition releases to the atmosphere direct emissions of GHGs (i.e. CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub>) and NH<sub>3</sub>, though their

measurement is not easy because it depends upon several factors that occur during composting. Water content, ventilation, pore distribution and bulk density, composition, and weather conditions are some of those. In addition to them, pH, temperature, and the C to N ratio of organic matrices constitute other influencing factors (Hellebrand and Kalk, 2001). Lack of oxygen is usually linked with the emission of methane during composting. The content of ammonium, urea and other organic nitrogen in the composting biomass directly influences the emission of NH<sub>3</sub>, which is developed based upon the temperature, aeration and pH value of the biomass itself. Temperature, nitrogen content (especially nitrate) and aeration influence N<sub>2</sub>O-emissions. For livestock waste, aeration and C to N ratio determine the type of nitrogen transformations (Hellebrand and Kalk, 2001). High aeration and low carbon content result in nitrite accumulation and incomplete ammonium oxidation. Low aeration and sufficient carbon content enhance nitrification and denitrification as sources of N<sub>2</sub>O-emissions (Beline et al., 1999).

As regards the indirect emissions, they have been analysed by means of LCA in many researches which were focalised upon the processing technologies along the entire life cycle of manure and its end-products (Hamelin et al., 2011; Lopez-Ridaura et al., 2009; Prapasongsa et al., 2010). Industrial composting and waste management systems were also studied using LCA (Benetto et al., 2009; Dalemo et al., 1997; Diaz and Warith, 2006; Diggelman and Ham, 2003; Fruergaard et al., 2010; Güereca et al., 2006; Muñoz et al., 2009; Sharma and Campbell, 2003; Sonesson et al., 2000), as well as bio waste treatments (Bernstad and la Cour Jansen, 2012). From the developed LCAs, composting resulted to be less environmentally impacting than other organic waste disposal scenarios, such as landfill and incineration (Saer et al., 2013). For contrast, no papers regarding environmental assessments of on-farm manure composting systems (by means of open windrow systems) were found by the authors, thereby remarking the need for studies like the one discussed in this paper.

Conventional agricultural production systems are characterised by a huge consumption of fossil energy; this latter is represented by: the operational energy, which is consumed by the activities contained within the systems investigated; and the energy which is embedded in the production of the fertilisers, plant protection products, agricultural machineries and other equipment utilised (Kaltsas et al., 2007). In this context, an in-depth EA would be desirable to indicate ways to decrease the energy inputs and, at the same time, increase energy efficiency. Recently, there has been a renewed interest in the control of energy consumption following sustainable approaches. According to Ozkan et al. (2004), considerable researches were performed upon the energy consumption in agriculture with particular regard to the fruit sector (Esengun et al., 2007; Gezer et al., 2003; Gündoğmuş, 2006; La Rosa et al., 2008; Namdari et al., 2011; Ozkan et al., 2004; Polychronaki et al., 2007). For contrast, the authors found a gap in the specialised scientific literature as regards the assessment of the energy consumption associated with on-farm compost production by means of open windrow systems. In this regard, it should be noticed that the Cumulative Energy Demand (CED) has been evaluated by Martínez-Blanco et al. (2010) for home and industrial composting of the source-separated organic fraction of municipal solid waste (OFMSW). They found that the electricity consumption for operations within both composting systems together with the collection of the OFMSW and the pruning waste - used as bulking agent - had the higher contributions (32% each item) for CED. In another study, Colón et al. (2010) performed CED analysis of an experimental home composting process of leftovers of raw fruits and vegetables. They found that the composter was the major contributor for the CED reaching values of 73%

From an economic point of view, Mu et al. (2017) analysed composting food wastes in an in-vessel composter, found that the composting system could generate a profit of \$13,200 a year by selling vegetables grown with compost. Proietti et al. (2016) integrated the cost analysis of managing individual composting plants with the physical-chemical properties of materials to be composted, to determine the quantities of different raw materials to be mixed to obtain the mixture subjected to composting. Ruggieri et al. (2009) analysed the technical and economic feasibility of composting waste from wine making, assessing the environmental impact and energy performance using the LCA methodology. In particular, the study compared the costs of the composting system designed with those of disposing of the waste.

In the light of the above, it seems that no studies have assessed in a single study the energy, economic efficiency and environmental sustainability issues associated with manure composting processes. That is what the authors have done and discussed about in this paper, because a comprehensive analysis of the economic, environmental and energy issues related to a given production system can support the process of finding and applying the best management strategies (Bowers, 1992; Pimentel et al., 2005; Pimentel, 1992; Reganold et al., 2001). The authors included also the economic issues in the assessment to define the production costs and their affordability, so making the whole assessment more scientifically relevant and useful.

Therefore, the study could contribute to fill the aforementioned gaps and enhance the international literature and knowledge in the compost supply chain field.

### 3. Description of the composting plants

The first plant is located in the Caserta province (Castel Volturno, Campania, Italy, 41°3'52.58"N, 13°59'27.25"E), it is able to treat around 600 ton manure per year and it is managed by CER-MANU, a research institution of the University of Naples. It is a prototype for on-farm compost production based on confined windrows. This composting plant (called from now on 'CV Plant') treats buffalo/cow manure using different bulking agents (conventional straw, wood chip from Short Rotation Forestry - SRF, maize straw) and involves some farms to create a network for the optimisation of the compost chain management. In this way, it could be possible to solve the problems associated with manure disposal through the production and the use of on-farm compost without resorting to the market.

CV Plant consists of four main areas and all equipments (canals and tank) for leachate collection; in particular, these areas are utilised as follows:

- one for storage/mix of the raw material inputs;
- one for the active composting phase;
- one for the compost maturity (curing phase); and, finally,
- one for compost storage, outlet from the curing phase (mature compost).

As shown in Fig. 1, the building where the organic matrix piles are placed is open and has a 400 m<sup>2</sup> usable area within. In structural terms, the building is made of cast-in-situ concrete as regards the pillars, the foundations and the pavement, whilst a load bearing structure made of steel section bars coupled with aluminium panels is used for the building covering. Additionally, the plant is provided with: a blower and 3 polyethylene tubes (two 20 mm diameter holes each 300 mm) for the forced ventilation of the windrows; an irrigation system; a continuous control and data collection unit (monitoring of oxygen concentration and temperature).



Fig. 1. Castel Volturno composting plant (CV Plant).

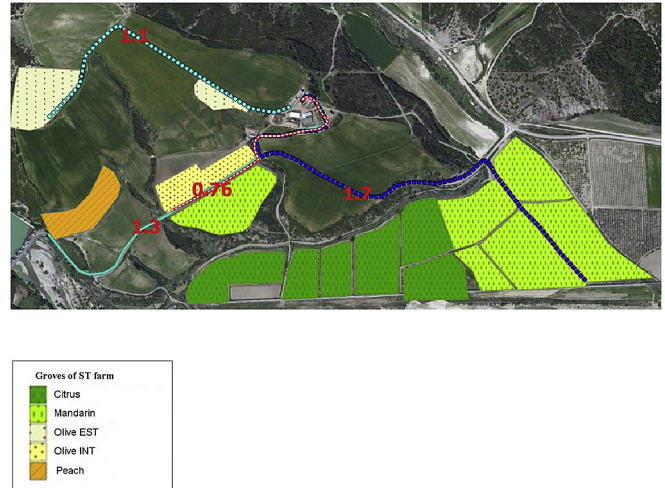


Fig. 3. Composting plant in Matera province (Stigliano Plant – ST Plant). In particular, the figure shows the distance in km between the composting plant and the groves for the procurement of the pruning residues.

The composting process consists of a decomposition phase in actively aerated windrows with controlled aeration for 40 days followed by 120 days in an open-air phase. Actually, manure treated in the CV Plant comes from a door-to-door residue collection system from two farms located in the surroundings of the farm at very low distances (550 m and 850 m, respectively) (Fig. 2). The obtained compost is used in agriculture by these two farms and by the Naples University experimental station for maize production.

The second composting plant (called from now on 'ST Plant') is located in the province of Matera (Stigliano, Basilicata, Italy,  $40^{\circ}17'50.05''N$ ,  $16^{\circ}28'28.85''E$ ) within a private farm, and it is able to treat around 500 tons of manure per year. In particular, it is a mixed livestock-fruit farm of approximately 231 ha in which dairy cattle are raised; additionally, meadows, arable crops and fruit orchards (citrus, peach and olive groves) are cultivated (Fig. 3). The

manure is used for compost production which is re-used within the farm as organic fertiliser in the croplands and fruit orchards. The plant includes four cells which are equipped with aeration pipes connected to a blower supplying an intermittent airflow. Tree cells are 20 m long and 6 m wide, whilst another one is 17 m long and 6 m wide. The total cell volume exceeds the quantity of manure produced within the farm (about 500 ton per year), but makes it possible to correctly perform the storage and curing of the compost produced developing an efficient composting process (Fig. 4). The cells are placed at three sides of an almost 0.8 m height perimeter wall, with the short side allowing free access of the mechanical equipment involved. The platform has a slope of 2% for the conveyance of leachate to the collection system and storage present within the plant (Fig. 4). In the past, the farm adopted a manure management system based upon the maturity of the material shovelled in the platform for a period ranging from 5 to 6 months and a manure distribution in the field with a manure-spreader.

Then, an on-farm composting technology, with low investment and management costs, has been developed for both re-integration



Fig. 2. The door to door residue collection system in Castel Volturno composting plant (CV Plant). In particular the figure shows the distances in meters between the composting plant (A) and the manure procurement farms (B).



Fig. 4. Stigliano Plant (ST Plant): cells for the collection of manure.

of the soil organic matter and minimisation of the adverse environmental impact of livestock manure due to the large production of polluting leachate. This new composting approach was proposed within a EU-Basilicata Region project (Agreement program MATTM UNCCD-Basilicata Region: Pilot Project to Combat the Desertification-Basilicata). Particularly, a trial was planned with the aim of accelerating the maturation of cattle manure using, as bulking agent, poplar wood chips obtained from the maintenance of the riparian areas. Therefore, a composting plant was implemented to provide static piles and forced ventilation for the simplicity of its management, the availability of materials and equipment within the farm, the low labour requirement, as well as the low (economic and environmental) processing costs. Tubes and drip-lines, commonly used for irrigation systems, were used for the aeration and the humidification of the mass; a common blower was used for air insufflations.

#### 4. Materials and methods

The research discussed in this paper was designed to investigate on-farm manure compost production systems in Southern Italy, by assessing: energy efficiency; environmental impact; and production costs.

An in-depth analysis was conducted for each of the aforementioned indicators and was performed using the LCA approach, according to the ISO 14040-44:2006 (ISO, 2006a,b). Each of the three analyses was articulated in the following four interrelated phases: goal and scope definition; life cycle inventory; life cycle impact assessment; and interpretation.

##### 4.1. Goal and scope definition, functional unit and system boundary

The goal of the analyses carried out in the present research was to verify the environmental, energy and economic sustainability of four composting alternatives for CV Plant and two for ST Plant to produce compost. Particularly, the alternatives differed for the usage of diverse bulking agents, important local biological resources in Southern Italy (wood chip from SRF, maize and conventional straw) and for their combination in stables and in the composting plants (Table 1). Their combination helped to find the most sustainable solution as bedding for the animals and discover the most appropriate materials to become bulking agent and to have the major beneficial structuring function for the composting process.

The results obtained could be useful for farmers, farmer associations, LCA practitioners, technicians and local politicians to solve the problems associated with manure disposal through the production and the usage of compost on-farm in a sustainable way. The study could be considered as a first step forward to support the creation of a regulated barter based upon a network of farms that

**Table 1**

Composting alternatives for Castel Volturno Plant (CV Plant) and Stigliano Plant (ST Plant). The alternatives differed for the use of diverse bulking agents and for their combination in stables and in the composting plants.

Alternatives	Stable	Plant
CV Plant		
A	CS + MS	WC
B	CS + MS	MS
C	WC	WC
D	MS	MS
ST Plant		
E	PR	CS
F	WC	CS

CS: conventional straw; WC: wood chip from Short Rotation Forestry; PR: pruning residues; MS: maize straw.

exchange manure and compost. This could lead to ancient forms of efficient and sustainable agriculture, so fostering the transition to equitable, sustainable, local bio-economies.

For the development of the whole assessment, both the Functional Unit (FU) and the system boundaries were defined. The FU in LCA provides a reference to which the inputs and outputs of the inventory are related and allows the comparison between systems or alternatives (International Organisation for Standardisation, 2006a, b). The function of the plants under study was to produce compost from manure. Therefore, the basis for the comparison of the different alternatives, named the functional unit of the service delivered, was defined as the production of one ton of compost with a 70% dry matter, as reported also in other studies (Saer et al., 2013; Norhasmillah et al., 2013). Consequently, to meet the objectives of the present research, the system boundaries started with the processing of the organic residues (wheat straw -WS; wood chip from SRF - WC; maize straw - MS; orchard tree pruning residues - PR) and the collection of manure from the stables to the composting plants and finish with the compost production. The transportation of the produced compost to its final destination was excluded because it was outside the scope of this research.

Referring to the wood chip processing, the following farming operations were taken into account: arboretum plantation (soil preparation, pre-plantation fertilisation, tree plantation); soil tillage; fertilisation; tree harvesting and transportation to farms. Instead, referring to conventional straw and maize straw processing, the following phases were taken into account: chopping, raking, baling, harvesting, loading and transportation. For pruning residues, chopping and transportation from fruit orchards to the composting plants were considered.

As the Recycled Organics Unit (2007) reports, a conventional composting system generates impacts and avoided impacts in a number of unit steps. So, the system boundaries was designed in order to enable the accounting of the main impacts coming from the following unit phases:

- the processing of the bulking agents (WS, WC and MS for the CV Plant; conventional straw and WC from pruning residues for the ST Plant);
- the transportation of those materials to the stables or the composting plants;
- the collection of manure and its receiving;
- the construction of the capital equipment and infrastructures; and, finally,
- the compost processing.

To be consistent with the aims of this study, attention was focalised upon:

- the construction of the capital equipment or infrastructures in all processes;
- the fuel usage in the various agricultural and composting operations;
- the electricity consumption associated with the composting phase and facility;
- the fertilisers used in the SRF production.

For greater understanding and appreciation of the study, the system boundaries with indication of the input and output flows considered were depicted in Fig. 5.

##### 4.2. Inventory data collection

All data needed for the study development was inventoried by means of a survey questionnaire which was administered to plant

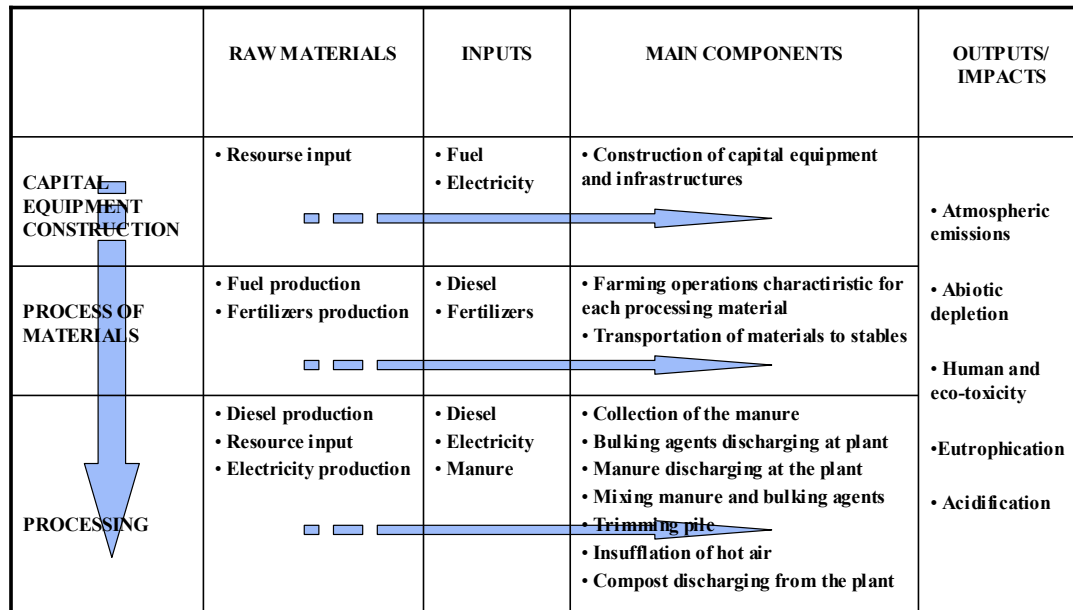


Fig. 5. System boundaries and input and output flows for the analysed composting systems.

managers and farmers. Inputs used in the examined composting scenarios were reported in Table 2. As in a similar study (Cadena et al., 2009), data on the questionnaire related to composting operational phases (days of treatment, aeration conditions, etc.) were also checked and confirmed *in situ*.

For the study development, since a particularly specialised system was assessed, priority was given to using primary data in terms of input material typologies and amounts used. Additionally, as a standard practice in LCAs, secondary data were extrapolated from international databases of scientific importance and reliability, like the Ecoinvent 3 (Ecoinvent, 2013). In particular, this was done for:

- the production of the diesel, electricity, fertilisers used in the systems investigated, including the accounting of the resulting emissions; and
- the construction of the capital equipment.

Referring to electricity, the dataset describes the transformation from medium to low voltage, as well as the distribution of electricity at low voltage. In particular, it encompasses the electricity production in Italy and from imports, the transmission network as well as the direct SF6-emissions to air. Also, electricity losses during low-voltage transmission and transformation from medium voltage were accounted for (Ecoinvent, 2013). The fuel consumption model included the transportation of the product from the refinery to the end user.

Moreover, the inventory of agricultural vehicles took only into account the use of resources and the amount of emissions during their production, maintenance, repair and final disposal. The Ecoinvent module for the fertiliser utilised (urea) took into account its production from ammonia and carbon dioxide. Transports of the intermediate products were included, as well as the transport of the fertiliser products from the factory to the regional storehouse.

Referring to direct emissions of GHGs during the composting process, the emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were derived from Hao et al. (2004), whose study is the only one in literature that investigated GHG emissions both during composting of straw-bedded manure (SBM) and wood chip-bedded manure (WBM) and the only one that can be adapted to our research. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions were 165 kg C Mg<sup>-1</sup>, 8.92 kg C Mg<sup>-1</sup> and 0.077 kg N Mg<sup>-1</sup> for SBM and 145.6 kg C Mg<sup>-1</sup>, 8.93 kg C Mg<sup>-1</sup> and 0.084 kg N Mg<sup>-1</sup> for WBM, respectively. At the same time, in accordance with the recommendation of the Intergovernmental Panel on Climate Change (IPCC, 2006) and other authors of composting LCAs (Amlinger et al., 2008; Bjarnadóttir et al., 2002; Boldrin et al., 2009; Chen and Lin, 2007; Edwards and Williams, 2011; Quirós et al., 2014; Saer et al., 2013; Zhao et al., 2009), CO<sub>2</sub> emitted from composting is biogenic and not fossil-derived, so it was not considered as a greenhouse gas emission and not included in the global warming potential (GWP) accounting.

Table 2

Inputs used in the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are referred to one ton of compost produced.

Operations	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
<b>Material processing and transport</b>						
Machinery and farm tools (h)	1.60	0.63	3.04	0.24	0.35	2.88
Human labour (h)	1.19	0.32	2.72	0.13	0.18	2.40
Diesel oil (kg)	5.25	3.51	5.94	1.32	1.98	7.27
Lubricants (kg)	0.08	0.06	0.10	0.02	0.03	0.12
SRF cuttings (kg)	1.94	–	5.82	–	–	4.65
Fertilizers (kg)	0.26	–	0.78	–	–	0.63
<b>Stable management and collection of manure</b>						
Machinery and farm tools (h)	0.06	0.06	0.06	0.06	0.13	0.13
Human labour (h)	0.03	0.03	0.03	0.03	0.07	0.07
Diesel oil (kg)	0.35	0.35	0.35	0.35	0.93	0.93
Lubricants (kg)	0.01	0.01	0.01	0.01	0.02	0.02
<b>Plant management</b>						
Capital equipment (kg)	1.24	1.24	1.24	1.24	1.45	1.45
Machinery and farm tools (h)	0.19	0.19	0.19	0.19	0.22	0.22
Human labour (h)	0.11	0.11	0.11	0.11	0.13	0.13
Diesel oil (kg)	1.19	1.19	1.19	1.19	1.07	1.07
Lubricants (kg)	0.02	0.02	0.02	0.02	0.02	0.02
Electricity (kWh)	0.06	0.06	0.06	0.06	0.02	0.02

#### 4.3. Life Cycle Assessment (LCA)

The environmental assessment was carried out using SimaPro 8.02 software, with the problem oriented LCA method developed by the Institute of Environmental Sciences of the University of Leiden (Guinée et al., 2002). The impact categories considered in the present analysis were global warming (GWP100), air acidification (AA), photochemical oxidation (PO), eutrophication (EU), ecotoxicity (ET), and ozone layer depletion (ODP). Such categories were considered in similar studies (Banar et al., 2009; Blengini, 2008; Cadena et al., 2009; Emery et al., 2007; Eriksson et al., 2005). Moreover, in agreement with Bernstad and la Cour Jansen (2011), they were considered by the authors as environmentally relevant and internationally accepted in accordance with ISO 14042 recommendations (ISO, 2000). Furthermore, the impact assessment was conducted following a mid-point approach and, so, using equivalent indicators (specific for the impact categories considered) to express the LCA results in the form of characterisation values. In order to assess the contribution of each impact category on the overall environmental problem, ‘Normalisation’ of the characterisation results was done using as “Normal” value for the region “Europe 25” (PRé, various authors, 2015).

#### 4.4. Energy analysis

Following Namdari et al. (2011), the energy analysis (EA) method was used to calculate the energy involved in the production of 1 ton of compost. To combine the EA results with those coming from the LCA, the analysis was conducted with the same system boundary and the same life cycle inventory described for the LCA. The data collected covered the duration of each operation and the quantities of each input (machinery, fuel, electricity, fertilisers, labour, and so.). Energy values of unit inputs were given in mega joules (MJ) by multiplying each input by its own coefficient of equivalent energy factors taken from the literature (concrete: 3 MJ kg<sup>-1</sup>; wood: 14.64 MJ kg<sup>-1</sup>; fuel: 46.2 MJ kg<sup>-1</sup>; iron: 54.39 MJ kg<sup>-1</sup>; lubricant: 78.13 MJ kg<sup>-1</sup>; machinery: 80 MJ kg<sup>-1</sup>; plastic: 83.68 MJ kg<sup>-1</sup>) (Monarca et al., 2009; Page, 2009; Pimentel and Pimentel, 1979; Volpi, 1992). In order to calculate machinery energy, the following formula was used:

$$ME = [(Eq * G / T)] * H \quad (1)$$

where *Eq* was the machinery energy equivalent (MJ kg<sup>-1</sup>), *G* the weight of machines (kg), *T* the economic life of machines (h), and *H* the numbers of hours the machine used to carry out the various operations (h) (Ozkan et al., 2007). Energy consumption for machinery maintenance was estimated as a percentage of energy in manufacturing and materials (23% for tractors; 30% for tillage machines) (Milà i Canals, 2003).

The energy input was examined as direct and embodied forms, renewable and non-renewable energies. Direct energy included human labour, electricity, diesel fuel and lubricants used in the various scenarios described; whilst embodied energy covered machinery and maintenance. Renewable energy consists of diesel fuel, lubricants, electricity, and machinery energies. In the present study, renewable energy includes only human labour (Namdari et al., 2011). Specifications on the EA methodology can be found in Page (2009).

#### 4.5. Production cost analysis

The Life Cycle Costing (LCC) method was applied to evaluate the costs related to different compost production scenarios analysed in the two composting plants. This method is currently applied to

calculate the total cost throughout the product's life including acquisition, installation, operation, maintenance, refurbishment and disposal (Bai, 2009). LCC is a complementary tool, which provides an economic analysis of the operations composing the supply chain of a product or service (Brandão et al., 2010). In addition to this, it does not have a standardisation framework to follow, though application of life cycle methodologies, like LCA, according to the ISO 14040-44:2006 can be extended to the economic aspects (ISO, 2006a).

So, similarly to what done for the EA, in order to join LCC and LCA findings, the analysis was performed using the same system boundary (Fig. 5) from the processing of the organic residues, the collection of the manure from the stables to the composting plants, to the production of the compost (as explain in section 4.1) and the same life cycle inventory described for LCA (Table 2).

Based upon the assumption that the production techniques (processing of bulking agents, collection of the manure, composting process) of all composting alternatives are quite the same, the analysis identified three main life cycle phases of compost production: bulking agents processing, manure collection, and composting process. As a standard practice of microeconomic analysis (Mohamad et al., 2013) and as reported in Proietti et al. (2016), for each phase, the main typologies of operation management were identified along with the associated fixed and variable costs. Consequently, in order to: 1) make a complete economic analysis; 2) be consistent with the other two analyses and 3) understand the importance of each cost item, the cumulative costs of compost production were evaluated for each phase taking into account: the expenses related to materials, labour and services, which represent the variable costs; and the quotas and the other duties, which are the fixed costs. In the present study, for the materials, the costs considered were those of all non-capital inputs such as fertilisers, fuel, energy and other crop specific; with regard to the labour, the cost of workers involved in bulking agents production and composting process were taken into account; quotas and services included machinery, equipment and depreciation costs (Pappalardo et al., 2013).

In order to analyse the amount of the total cost of 1 ton of compost, as reported in Ruggieri et al. (2009) and in Mu et al. (2017), the lifespan of the composting plants (fifteen years) was considered and each value of the annual costs, whose current prices referred to 2013, was indexed and aggregated using a rate anticipation  $(1/q^n)$ , where: *n* refers to the individual years of the lifespan of the composting plants (*n* = 1,...,15) and *q* represents an indexing factor, whose interest rate was assumed to be equal to 2%. All values of the indexed costs were then added together.

To evaluate the whole LCC, expressed as the sum of the costs for each phase of the compost plant life cycle, the cumulative value was calculated by taking into account the indexing of costs for different production phases as follows:

$$\sum_1^{15} LCC = \left[ \sum_1^{15} BAP \times \left( \frac{1}{q^n} \right) \right] + \left[ \sum_1^{15} MC \times \left( \frac{1}{q^n} \right) \right] + \left[ \sum_1^{15} CP \times \left( \frac{1}{q^n} \right) \right] \quad (2)$$

where:

- $\sum_1^{15} LCC$  is the sum of the “Life Cycle Costs” of each year in the life cycle of the composting plant
- $\sum_1^{15} BAP$ : is the “bulking agents processing phase” from 1st to 15th year. It includes, for wood chip processing, the following



**Table 3**  
Life cycle impact assessment analysis of the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are referred to one ton of compost produced. Bold numbers refer to the maximum and minimum values for each impact category.

Impact category	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
AD (kg Sb eq)	0.28	0.22	<b>0.31</b>	0.16	<b>0.12</b>	0.28
GWP (kg CO <sub>2</sub> eq)	233.64	231.34	<b>235.49</b>	228.96	<b>225.86</b>	232.32
ODP (kg CFC-11 eq)	0.00	0.00	<b>0.00</b>	0.00	<b>0.00</b>	0.00
ET (kg 1,4-DB eq)	10792.00	8828.00	<b>11771.00</b>	6479.00	<b>4116.00</b>	9818.00
PO (kg C <sub>2</sub> H <sub>4</sub> )	0.07	0.06	<b>0.07</b>	0.06	<b>0.06</b>	0.06
AA (kg SO <sub>2</sub> eq)	0.13	0.12	<b>0.14</b>	0.10	<b>0.07</b>	0.11
EU (kg PO <sub>4</sub> <sup>3-</sup> eq)	0.02	0.02	<b>0.02</b>	0.02	<b>0.01</b>	0.02

AD: abiotic depletion; GWP: global warming potential (GWP100); ODP: ozone layer depletion; ET: ecotoxicity potential; PO: photochemical oxidation; AA: air acidification; EU: eutrophication.

farming operations: arboretum plantation, soil tillage; fertilisation; tree harvesting and transportation of the material to the farms; for conventional straw and maize straw processing, the following operations: chopping, raking, baling, harvesting, loading and transportation; for pruning residues, the following operations: chopping and transportation from fruit orchards to the composting plant.

- $\sum_1^{15}MC$ : is the “manure collection phase” from 1st to 15th year. It refers to the transport of the manure from the stables to the plants.
- $\sum_1^{15}BCP$ : is the “composting process phase” from 1st to 15th year.

Specifications on this methodology are reported in [Pergola et al. \(2013\)](#).

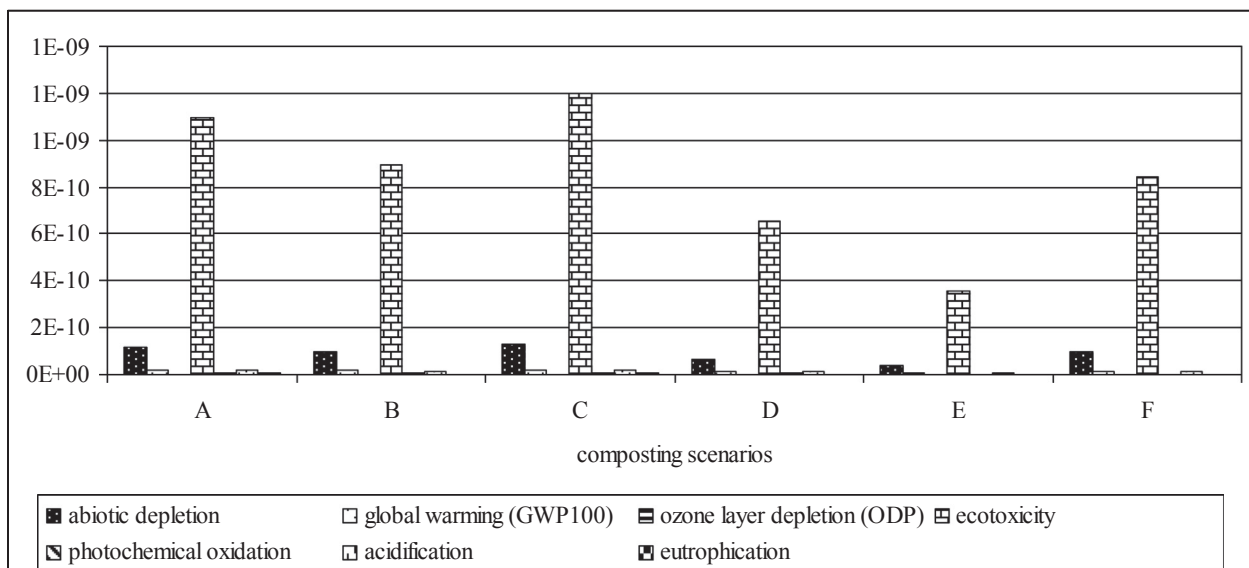
## 5. Results and discussion

### 5.1. Environmental impacts

Results on life cycle impacts per ton of compost produced according to the different composting scenarios are shown in [Table 3](#), which reports that the production of 1 ton of on farm compost consumed from 0.12 to 0.31 kg of natural resources (including energy resources), such as iron ore and crude oil given in kg of

antimony equivalent (Sb eq), and it emitted from 226 to 236 kg of CO<sub>2</sub>eq, responsible of GWP. More than 90% of GWP100 was due to direct emissions of CH<sub>4</sub>-C and N<sub>2</sub>O-N occurred during the composting process. Moreover, the environmental analysis showed that the production of 1 ton of compost issued from 4.116 kg to 11.771 kg of 1,4 dichlorobenzene equivalent, namely some substances (such as heavy metals) that can have impacts upon human health and environment; produced from 0.06 to 0.07 kg of C<sub>2</sub>H<sub>4</sub> responsible of photochemical oxidation; emitted from 0.07 to 0.14 kg of SO<sub>2</sub>eq causing air acidification; produced from 0.01 to 0.02 kg PO<sub>4</sub><sup>3-</sup>eq, responsible of eutrophication. Consequently, the alternative E was the less impacting combination, whilst the alternative C the most impactful ([Table 3](#)).

Without considering direct emissions (which were not experimentally measured), such results were less impacting than others found in the literature such as those found by [Clavreul et al. \(2012\)](#), who analysed two waste management systems (incineration and anaerobic digestion), or by [Cadena et al. \(2009\)](#), who worked on composting of the organic fraction from OFMSW through two aerobic composting technologies (composting tunnels and confined windrows) or by [Lopez-Ridaura et al. \(2009\)](#), who analysed the treatment of slurry in a collective biological treatment station. Similarly, this study evidenced lower impacts than those described by [Saer et al. \(2013\)](#) on a windrow composting system of food waste, or by [Colón et al. \(2010\)](#) on home composting, or by



**Fig. 6.** Normalisation of the Impact Categories of the examined composting scenarios.

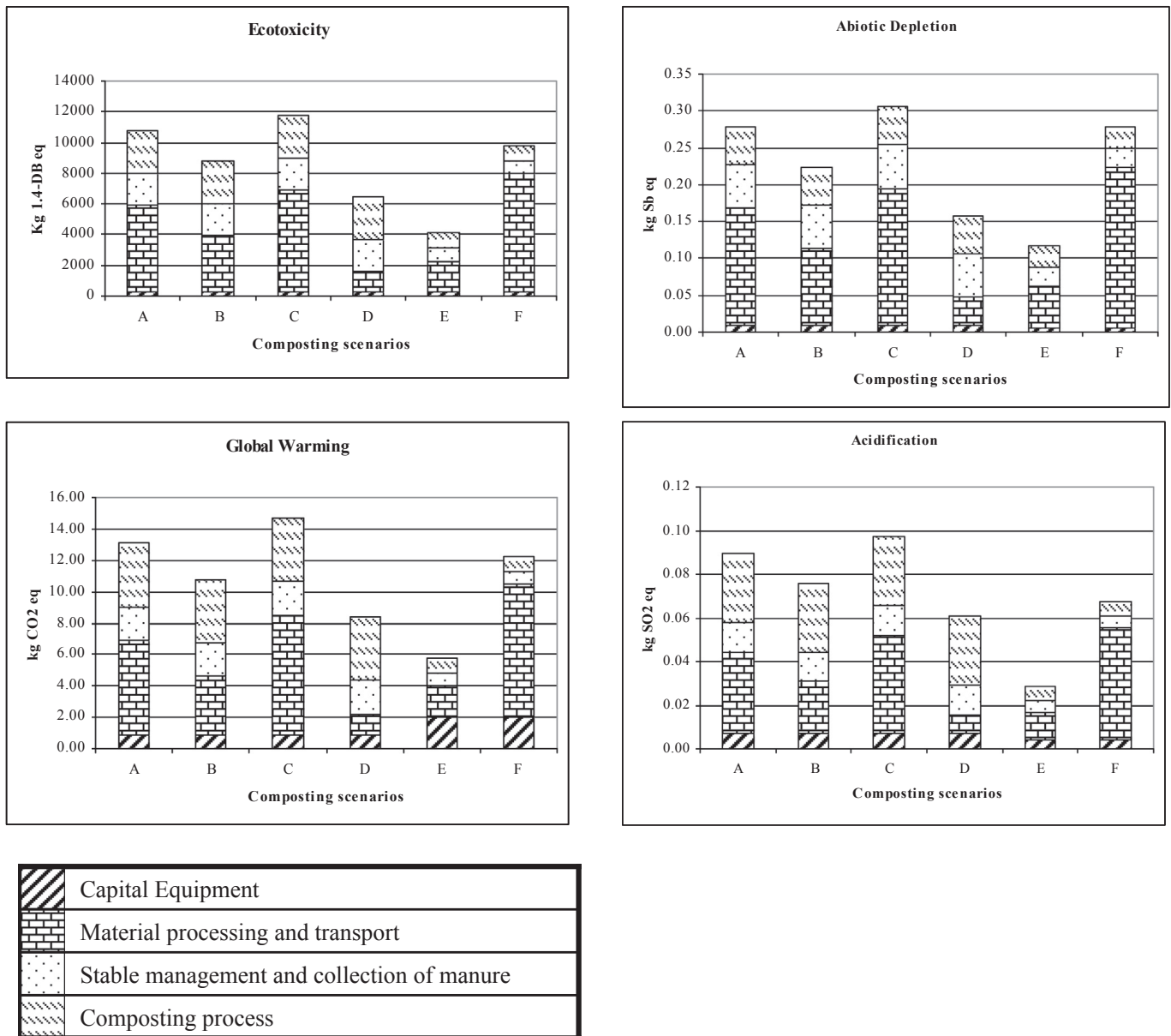


Fig. 7. The contribution of composting operations to Ecotoxicity, Abiotic Depletion, Global Warming Potential and Air Acidification for the examined composting scenarios without direct emissions. Values are referred to one ton of compost produced.

Martínez-Blanco et al. (2010) on home and industrial composting of the source separated organic fraction of municipal solid waste. Such differences in findings can be probably due to the different composting systems analysed, and the diverse system boundaries,

inventory analysis, software and method used for the impact characterisation.

The normalisation of the impact categories of the different composting scenarios showed as scenarios C and A led to higher

Table 4

Energy consumption in the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are expressed as MJ ton<sup>-1</sup> of compost. Values in bold refer to the composting alternatives showing the maximum and the minimum energy consumption.

Composting operations	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
Material processing and transport	409	203	598	75	118	525
Stable management and collection of manure	20	20	20	20	52	52
Composting process	139	139	139	139	107	107
Total Energy	568	362	<b>756</b>	<b>233</b>	276	684

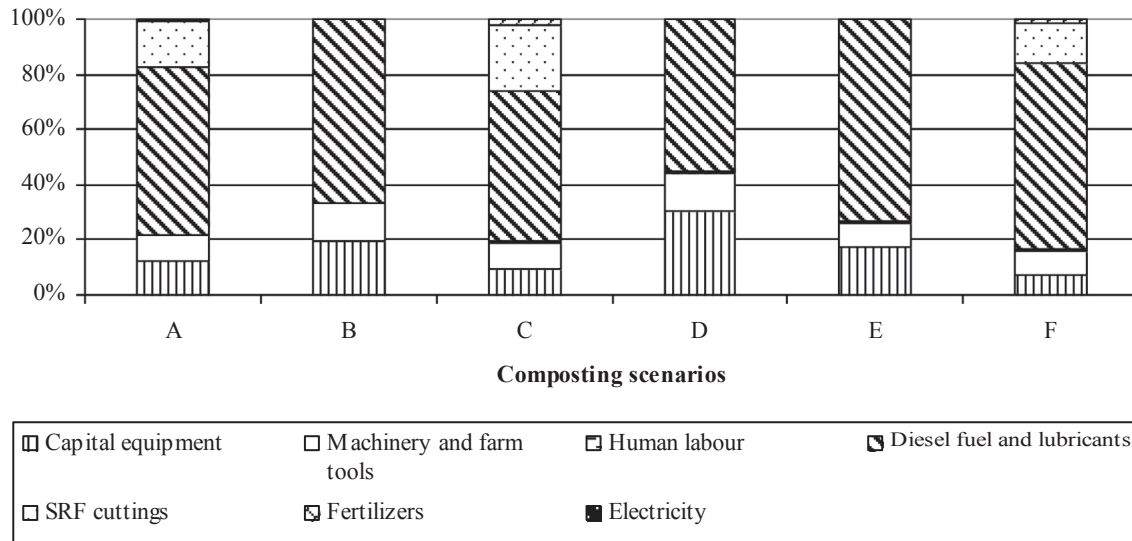


Fig. 8. Comparison of the energy inputs according to the different composting scenarios.

**Table 5**

Some energy forms in compost production according to the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are expressed as MJ ton<sup>-1</sup> of compost. Values in bold refer to the energy form most used by the composting alternatives.

Item	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
<b>Direct energy</b>	<b>350</b>	<b>242</b>	<b>418</b>	<b>130</b>	<b>203</b>	<b>464</b>
Indirect energy	218	120	338	104	73	220
Renewable energy	94	1	189	1	1	105
Non-renewable energy	474	361	567	233	275	580

environmental impacts, particularly in terms of ecotoxicity potential and abiotic depletion (Fig. 6). The contribution of the different composting operations to the most significant impact categories (Ecotoxicity, Abiotic Depletion, Global Warming Potential and Air Acidification) is shown in Fig. 7. In all scenarios, the material processing and its transport to the stable and to the plant were the composting operations with the higher environmental impacts, especially in scenarios A, C and F (Fig. 7). This was essentially due to the production of wood chip from SRF utilised as animal bedding in the stable or as bulking agent in the composting plant.

## 5.2. Energy consumption

The energy analysis showed that the production of 1 ton of compost needed from 233 to 756 MJ of energy (Table 4). Scenarios

D and E, characterised by the use of straw and pruning residues, lead to the minor consume of energy (233 and 276 MJ ton<sup>-1</sup>, respectively). On the contrary, the use of wood chip, as in scenarios C and F, caused a major consume of energy (756 and 684 MJ ton<sup>-1</sup>, respectively).

As observed for the environmental impacts, the structural material processing and the transport of the same to the stable and to the plant were the composting operations leading up to the higher energy requirements in all scenarios. This is true especially for scenarios A, C and F where these operations weighed more than 70% on the total energy requirement for the use of wood chip from SRF as bulking agent.

The distribution analysis of the anthropogenic energy inputs in compost production (Fig. 8) suggested that the highest energy input was provided by diesel fuel and lubricants in all scenarios followed by SRF cuttings in scenarios A, C and F, and by the capital equipment in the other ones. All alternatives used more direct energy (more than 55% of the total energy input) than indirect forms, mainly due to the use of diesel fuel and lubricants. Moreover, all the investigated scenarios were primarily based on non-renewable energy: the share of renewable energy use was very low (0% in B, D, E; 15% in F; 17% in A; 25% in C) (Table 5).

## 5.3. Compost production costs

Life cycle costs were employed to compare the economic results of different composting scenarios in order to better evaluate the sustainability of the on-farm compost production. Alternatives F and C were the most expensive, averaging 30 € for one ton of

**Table 6**

Operating costs in the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are expressed as € ton<sup>-1</sup> of compost. Values in bold refer to the most expensive composting alternatives.

Composting operations	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
<b>Material processing and transport</b>	12.6	5.5	<b>22.4</b>	2.2	4.9	<b>21.5</b>
Stable management and collection of manure	0.5	0.5	0.5	0.5	1.1	1.1
Composting process	7.3	7.3	7.3	7.3	8.8	8.8
<b>Total costs</b>	20.3	13.3	<b>30.1</b>	9.9	14.8	<b>31.5</b>

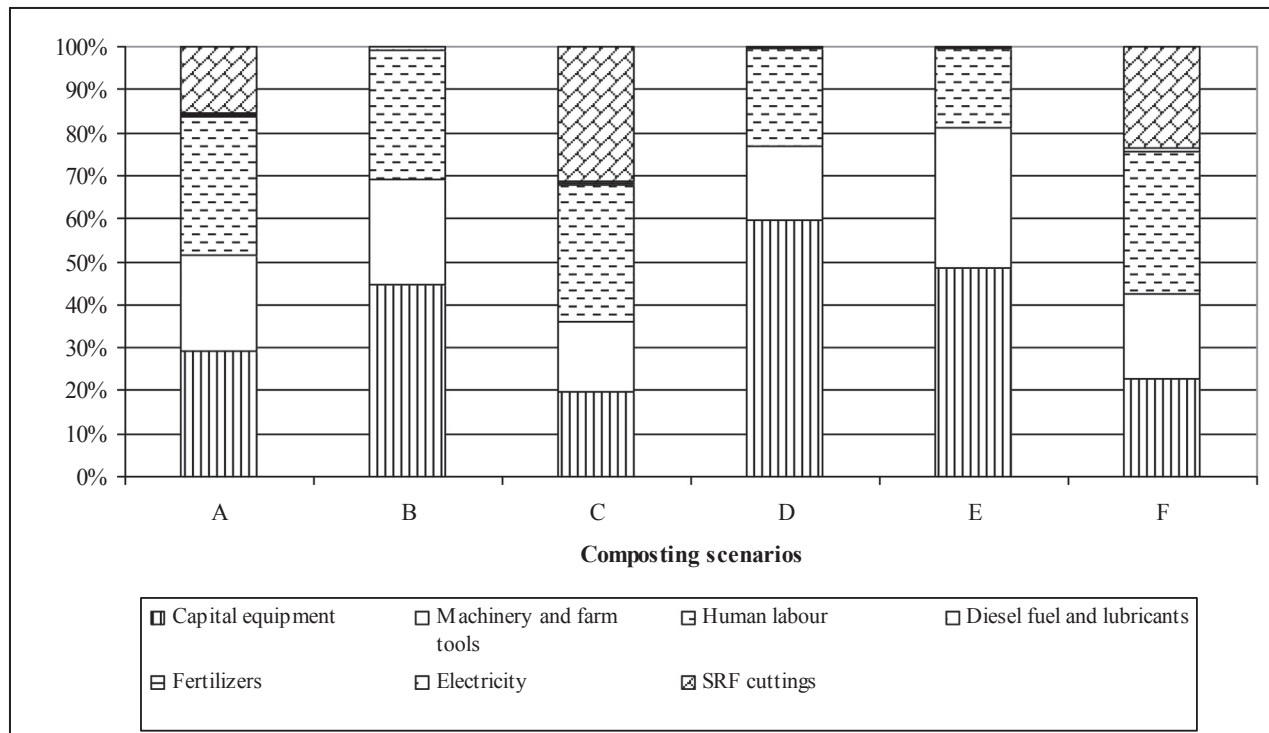


Fig. 9. Comparison of the costs inputs according to the different composting scenarios.

compost produced. Alternatives D and B were the cheapest ones with a cost production of 10 and 13 € ton<sup>-1</sup> of compost, respectively (Table 6). The utilisation of wood chip from SRF as bulking agent was confirmed to be the less sustainable choice. However, from an economic point of view, 1 ton on-farm compost production resulted as more convenient in all the examined cases. As a matter of fact, the price of one ton of commercial compost manure on the Italian market and its cost transport to the final destination can reach 250 € ton<sup>-1</sup>; hence, the need to develop a network of on-farm compost production.

The distribution analysis of the costs within the different items for compost production (Fig. 9) indicated that the capital equipment, machinery and human labour were the most expensive items in scenarios A, B, D and E, accounted for 84%, 99%, 99% and 100% of the total cost, respectively. In scenarios C and F the most expensive cost items were human labour, SRF cuttings and capital equipment (Fig. 9), which together accounted for most than 80% of the total costs.

## 6. Conclusions and future perspectives

Two on-farm composting plants, using manure and different bulking agents (wood chip from SRF, straw and pruning residues), were analysed in 2013. LCA was applied to calculate environmental impact indicators for each facility; EA to calculate the energy involved in the various composting scenarios; and LCC to evaluate the cost production of 1 ton of compost produced. The analyses showed that the production of 1 ton of on-farm compost from manure would have low impacts and needs less than 300 MJ of energy whether maize straw or pruning residues were used as bulking agents. In addition, the economics costs for the production are low, and so would make it cheaper than the commercial compost affordable on the Italian market (purchase price plus compost transport to the final destination).

The authors believe that the reliability of the results make them

be easily accessible and useful by farmers, farmer associations, technicians and local politicians to develop improved manure management systems.

The production of on-farm compost can be a solution to the “surplus” problem of livestock effluents. Therefore, such findings can be used as the starting point to promote - at the farm level - the diffusion of these low technology composting processes. The latter allow for the reuse of different organic matrices within the farm itself (usually considered as wastes) and the agronomic use of the high-quality compost thus obtained. In this way, the impacts of the consumptions decrease because consumers (farms) become more ecologically aware and local production becomes more efficient. As a matter of fact, production and consumption *in loco* do not produce GHG emissions due to transport, allowing the system to foster the transition to societies based upon equitable, sustainable and local bioeconomies.

Finally, findings from this research can fill the gaps of knowledge in the available literature about the environmental, energy and economic evaluation of the sustainability of on-farm composting plants of dairy cattle/buffalo manure.

## Acknowledgements

This research was supported by: Agreement program MATM-UNCCD-Basilicata Region: Pilot Project to Combat the Desertification-Basilicata; CarbOnFarm project Life+ ENV/IT/000719; PON PON03PE\_00107\_1 – Campania Region: BioPoliS.

## References

- Amlinger, F., Peyr, S., Cuhls, C., 2008. Greenhouse gas emissions from composting and mechanical biological treatment. *Waste Manag. Res.* 26, 47–60.
- Bai, Y., 2009. Life Cycle Environmental and Economic Impact of Using Switchgrass-derived Bioethanol as Transport Fuel. Master program graduation thesis, Netherlands University.
- Banar, M., Cokaygil, Z., Ozkan, A., 2009. Life cycle assessment of solid waste

- management options for Eskisehir, Turkey. *Waste Manag.* 29, 54–62.
- Beline, F., Martinez, J., Chadwick, D., Guizou, F., 1999. Factors affecting nitrogen transformations and related nitrous oxide emissions from aerobically treated piggery slurry. *J. Agric. Eng. Res.* 73, 235–243.
- Benetto, E., Nguyen, D., Lohmann, T., Schmitt, B., Schossele, P., 2009. Life cycle assessment of ecological sanitation system for small-scale wastewater treatment. *Sci. Total Environ.* 407, 1506–1516.
- Bernstad, A., la Cour Jansen, J., 2011. A life cycle approach to the management of household food waste – a Swedish full-scale case study. *Waste Manag.* 31, 1879–1896.
- Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – current status and potential improvements. *Waste Manag.* 32, 2439–2455.
- Bjarnadóttir, H., Friðriksson, G., Johnsen, T., Sletsen, H., 2002. Guidelines for the Use of LCA in the Waste Management Sector. Nord test Report TR 517. Nord test, Espoo, Finland.
- Blengini, G.A., 2008. Using LCA to evaluate impacts and resources conservation potential of composting: a case study of the Asti District in Italy. *Resour. Conserv. Recycl.* 52, 1373–1381.
- Blok, V., Long, T.B., Gazululsoy, A.I., Ciliz, N., Lozano, R., Huisingsh, D., Csutora, M., Boks, C., 2015. From best practices to bridges for a more sustainable future: advances and challenges in the transition to global sustainable production and consumption. Introduction to the ERSCP stream of the Special volume. *J. Clean. Prod.* 108, 19–30.
- Boldrin, A., Andersen, J., Møller, J., Christensen, T., 2009. Composting and compost utilisation: accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* 27, 800–812.
- Bowers, W., 1992. Agricultural field equipment. In: Fluck, R.C. (Ed.), *Energy in World Agriculture* 6. Energy in Farm Production. Elsevier, Amsterdam, pp. 117–130.
- Brandão, M., Clift, R., Milà i Canals, L., Basson, L., 2010. A life-cycle approach to characterising environmental and economic impacts of multifunctional land-use systems: an integrated assessment in the UK. *Sustainability* 2, 3747–3776.
- Brown, S., Kruger, C., Subler, S., 2008. Greenhouse gas balance for composting operations. *J. Environ. Qual.* 37, 1396–1410.
- Cadena, E., Colón, J., Artola, A., Sánchez, A., Font, X., 2009. Environmental impact of two aerobic composting technologies using life cycle assessment. *Int. J. Life Cycle Assess.* 14, 401–410.
- Celano, G., Alluvione, F., Abdel Aziz, M., Spaccini, R., 2012. The carbon dynamics in the experimental plots. Use of 13C- and 15N-labelled compounds for the soil-plant balance in carbon sequestration. In: Piccolo, Alessandro (Ed.), *Carbon Sequestration in Agricultural Soils. A Multidisciplinary Approach to Innovative Methods*. Springer Heidelberg Dordrecht London New York, pp. 107–144, 40468 Düsseldorf.
- Chen, T., Lin, C., 2007. Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. *J. Hazard Mater.* 155, 23–31.
- Clavreul, J., Guyonnet, D., Christensen, T.H., 2012. Quantifying uncertainty in LCA-modelling of waste management systems. *Waste Manag.* 32, 2482–2495.
- Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. *Resour. Conserv. Recycl.* 54, 893–904.
- Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jonsson, H., 1997. ORWARE – a simulation model for organic waste handling systems 1: model description. *Resour. Conserv. Recycl.* 21, 17–37.
- de Mendonça Costa, M.S.S., Cestonaro, T., de Mendonça Costa, L.A., Rozatti, M.A.T., Carneiro, L.J., Pereira, D.C., Lorin, H.E.F., 2015. Improving the nutrient content of sheep bedding compost by adding cattle manure. *J. Clean. Prod.* 86, 9–14.
- De Vries, J.W., Groenestein, C.M., De Boe, I.J.M., 2012. Environmental consequences of processing manure to produce mineral fertiliser and bio-energy. *J. Environ. Manag.* 102, 173–183.
- Diaz, R., Warith, M., 2006. Life-cycle assessment of municipal solid wastes: development of the WASTED model. *Waste Manag.* 26, 886–901.
- Diggelman, C., Ham, R.K., 2003. Household food waste to wastewater or to solid waste? That is the question. *Waste Manag. Res.* 21, 501–514.
- Ecoinvent Version 3, 2013. Available on: <http://www.ecoinvent.org/database/database.html>.
- Edwards, D., Williams, C., 2011. Method for Estimating Greenhouse Gas Emission Reductions from Compost from Commercial Organic Waste from: [http://www.arb.ca.gov/cc/protocols/localgov/pubs/compost\\_method.pdf](http://www.arb.ca.gov/cc/protocols/localgov/pubs/compost_method.pdf) (Accessed 01 March 2015).
- Emery, A., Davies, A., Griffiths, A., Williams, K., 2007. Environmental and economic modelling: a case study of municipal solid waste management in Wales. *Resour. Conserv. Recycl.* 49, 244–263.
- Eriksson, O., Reich, M., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J., Granath, J., Baky, A., Thysselius, L., 2005. Municipal solid waste management from a systems perspective. *J. Clean. Prod.* 13, 241–252.
- Esengun, K., Gündüz, O., Erdal, G., 2007. Input–output energy analysis in dry apricot production of Turkey. *Energy. Convers. Manage.* 48, 592–598.
- European Commission, 2012. Innovating for Sustainable Growth: a Bioeconomy for Europe. Available on: [http://ec.europa.eu/research/bioeconomy/pdf/official-strategy\\_en.pdf](http://ec.europa.eu/research/bioeconomy/pdf/official-strategy_en.pdf).
- Fruergaard, T., Hyks, J., Astrup, T., 2010. Life-cycle assessment of selected management options for air pollution control residues from waste incineration. *Sci. Total Environ.* 408 (20), 4672–4680.
- Gezer, I., Acaroglu, M., Haciseferogullari, H., 2003. Use of energy and labour in apricot agriculture in Turkey. *Biomass Bioenerg.* 24, 215–219.
- Güereca, L.P., Gassó, S., Baldasano, J.M., Jiménez-Guerrero, P., 2006. Life cycle assessment of two biowaste management systems for Barcelona. Spain. *Resour. Conserv. Recycl.* 49, 32–48.
- Guinée, J.B., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Wegener Sleswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H. de, Duin, R. van, Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. I: Life Cycle Assessment. II: Operational Annex. III: Scientific Background. Kluwer Academic Publishers, Dordrecht, p. 692. ISBN 1-4020-0228-9.
- Gündoğmuş, E., 2006. Energy use on organic farming: a comparative analysis on organic versus conventional apricot production on small holdings in Turkey. *Energy. Convers. Manage.* 47, 3351–3359.
- Hamelin, L., Wesnæs, M., Wenzel, H., Petersen, B.M., 2011. Environmental consequences of future biogas technologies based on separated slurry. *Environ. Sci. Technol.* 45, 5869–5877.
- Hao, X., Chang, C., Larney, F.J., 2004. Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting. *J. Environ. Qual.* 44, 33–37.
- Hellebrand, H., Kalk, W.D., 2001. Emission of carbon monoxide during composting of dung and green waste. *Nutr. Cycl. Agroecosystems* 60, 79–82.
- Ingrao, C., Bacenetti, J., Bezama, A., Blok, V., Geldermann, J., Goglio, P., Koukios, E.G., Lindner, M., Nemecek, T., Siracusa, V., Zabaniotou, A., Huisingsh, D., 2016. Agricultural and forest biomass for food, materials and energy: bio-economy as the cornerstone to cleaner production and more sustainable consumption patterns for accelerating the transition towards equitable, sustainable, post fossil-carbon societies. *J. Clean. Prod.* 117, 4–6.
- Intergovernmental Panel on Climate Change, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Retrieved 05 01, 2012, from: <http://www.ipccnggip.iges.or.jp/public/2006gl/index.html> (Accessed 02 April 2015).
- International Standards Organisation, ISO, 2000. ISO 14042:2000. Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment. <http://www.iso.org>.
- ISO, 2006a. International Standards Organisation, ISO 14044. Environmental Management Life Cycle Assessment e Requirements and Guidelines.
- ISO, 2006b. International Standards Organisation, ISO 14040. Environmental Management Life Cycle Assessment e Principles and Framework.
- Kaltsas, A.M., Mamolos, A.P., Tsatsarelis, C.A., Nanos, G.D., Kalburtji, K.L., 2007. Energy budget in organic and conventional olive groves. *Agr. Ecosyst. Environ.* 122, 243–251.
- Komilis, D., Bandi, D., Kakaronis, G., Zouppouris, G., 2011. The influence of spent household batteries to the organic fraction of municipal solid wastes during composting. *Sci. Total Environ.* 409 (13), 2555–2566.
- La Rosa, A.D., Siracusa, G., Cavallaro, R., 2008. Energy evaluation of sicilian red orange production. A comparison between organic and conventional farming. *J. Clean. Prod.* 16, 1907–1915.
- Lopez-Ridaura, S., van der Werf, H., Paillat, J.M., Le Bris, B., 2009. Environmental evaluation of transfer and treatment of excess pig slurry by life cycle assessment. *J. Environ. Manag.* 90, 1296–1304.
- Livestock Engineering Unit & Environmental Practices Unit Technical Services Division Alberta Agriculture, Food and Rural Development, 2005. *Manure Composting Manual*. Available on: [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/agdex8875/\\$file/400\\_271.pdf?OpenElement](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex8875/$file/400_271.pdf?OpenElement).
- Martínez-Blanco, J., Colón, J., Gabarrell, X., Font, X., Sánchez, A., Artola, A., Rieradevall, J., 2010. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. *Waste Manag.* 30, 983–994.
- Martínez-Blanco, J., Lazcano, C., Christensen, T.H., Muñoz, P., Rieradevall, J., Møller, J., Antón, A., Boldrin, A., 2013. Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agron. Sustain. Dev.* <http://dx.doi.org/10.1007/s13593-013-0148-7>.
- Mihai, F.-C., Ingrao, C., 2016. Assessment of biowaste losses through unsound waste management practices in rural areas and the role of home composting. *J. Clean. Prod.* <http://dx.doi.org/10.1016/j.jclepro.2016.10.163>.
- Milà i Canals, L., 2003. Contributions to LCA Methodology for Agricultural Systems. Site Dependency and Soil Degradation Impact Assessment. Ph.D. Thesis. Autonomous University of Barcelona, Barcelona, Spain.
- Mohamad, R.S., Bteich, M.R., Cardone, G., Marchini, A., 2013. Economic analysis in organic olive farms: the case of the ancient olive trees in the rural parkland in Apulia. *New Medit.* 12 (4), 55–61.
- Monarca, D., Biondi, P., Panaro, V.N., Colantoni, A., Bartoli, S., Cecchini, M., 2009. Analisi delle richieste di energia per la coltivazione delle colture ortive. In: IX Convegno Naz. Dell'Ass. Italiana di Ingegneria Agraria Memoria, pp. 10–12.
- Mu, D., Horowitz, N., Casey, M., Jones, K., 2017. Environmental and economic analysis of an in-vessel food waste composting system at Kean University in the U.S. *Waste Manag.* 59, 476–486.
- Muñoz, I., Rodríguez, A., Rosal, R., Fernández-Alba, A.R., 2009. Life Cycle Assessment of urban wastewater reuse with ozonation as tertiary treatment: a focus on toxicity-related impacts. *Sci. Total Environ.* 407 (4), 1245–1256.
- Namdari, M., Kangarshahi, A.A., Amiri, N.A., 2011. Input-output energy analysis of citrus production in Mazandaran province of Iran. *Afr. J. Agric. Res.* 6, 2558–2564.
- Norhasmillah, A.H., Puah, C.W., Ibrahim, N.A., Baharuddin, A.S., Choo, Y.M., 2013. Life cycle inventory of the commercial production of compost from oil palm biomass: a case study. *Environ. Dev. Sustain.* 15 (6), 1663–1670.
- Ozkan, B., Akcaoz, H., Fert, C., 2004. Energy input–output analysis in Turkish agriculture. *Renew. Energy* 29, 39–51.
- Ozkan, B., Fert, C., Karadeniz, F., 2007. Energy and cost analysis for greenhouse and

- open grape production. *Energ. Convers. Manage.* 32, 1500–1504.
- Page, G., 2009. An Environmentally Based Systems Approach to Sustainability Analysis of Organic Fruit Production Systems in New Zealand. PhD thesis. Massey University.
- Pane, C., Piccolo, A., Spaccini, R., Celano, G., Vilecco, D., Zaccardelli, M., 2013. Agricultural waste-based composts exhibiting suppressivity to diseases caused by the phytopathogenic soil borne fungi *Rhizoctonia solani* and *Sclerotinia minor*. *Appl. Soil. Ecol.* 65, 43–51.
- Pappalardo, G., Scienza, A., Vindigni, G., D'Amico, M., 2013. Profitability of wine grape growing in the EU member states. *J. Wine Res.* 24 (1), 59–76.
- Pergola, M., D'Amico, M., Celano, G., Palese, A.M., Scuderi, A., Di Vita, G., Pappalardo, G., Inglese, P., 2013. Sustainability evaluation of Sicily's lemon and orange production: an energy, economic and environmental analysis. *J. Environ. Manage.* 128, 674–682.
- Pimentel, D., 1992. Energy inputs in production agriculture. In: Fluck, R.C. (Ed.), *Energy in World Agriculture 6. Energy in Farm Production*. Elsevier, Amsterdam, pp. 13–22.
- Pimentel, D., Pimentel, M., 1979. *Food, Energy and Society*. John Wiley and Sons, New York.
- Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental energetic and economic comparisons of organic and conventional farming systems. *Bioscience* 55, 573–582.
- Polychronaki, E.A., Douma, A.C., Dantsis, T.H., Giourga, C., Loumou, A., 2007. Energy analysis as an indicator of agricultural sustainability: the case of West Macedonia and Epirus, Greece. In: *Proceeding of the 10th International Conference on Environmental Science and Technology*. Kos Island, Greece, 5–7 September.
- Prapaspongsa, T., Christensen, P., Schmidt, J.H., Thrane, M., 2010. LCA of comprehensive pig manure management incorporating integrated technology systems. *J. Clean. Prod.* 18, 1413–1422.
- PRé, various authors, 2015. *SimaPro Database Manual Methods Library*. Available on. <https://www.pre-sustainability.com/simapro-database-and-methods-library> (Accessed 14 January 2015).
- Proietti, P., Calisti, R., Gigliotti, G., Nasini, L., Regni, L., Marchini, A., 2016. Composting optimization: integrating cost analysis with the physical-chemical properties of materials to be composted. *J. Clean. Prod.* 137, 1086–1099.
- Quirós, R., Villalba, G., Muñoz, P., Colón, J., Font, X., Gabarrell, X., 2014. Environmental assessment of two home composts with high and low gaseous emissions of the composting process. *Resour. Conserv. Recycl.* 90, 9–20.
- Recycled Organics Unit, 2007. *Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems*. The University of New SouthWales, Available on. [http://www.environment.nsw.gov.au/resources/warr/2006400\\_org\\_licassesswindrowsys.pdf](http://www.environment.nsw.gov.au/resources/warr/2006400_org_licassesswindrowsys.pdf).
- Reganold, J.P., Glover, J.D., Andrews, P.K., Hinman, H.R., 2001. Sustainability of three apple production systems. *Nature* 410, 926–993.
- Ruggieri, L., Cadena, E., Martinez-Blanco, J., Gasol, C.M., Rieradevall, J., Gabarrell, X., Gea, T., Sort, X., Sanchez, A., 2009. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the composting process. *J. Clean. Prod.* 17, 830–838.
- Rynk, R., van de Kamp, M., Willson, G.B., Singley, M.E., Richard, T.L., Kolega, J.J., Gouin, F.R., Laliberty Jr., L., Kay, D., Murphy, D.W., Hoitink, H.A.J., Brinton, W.F., 1992. *On-Farm composting handbook*. In: Rynk, R. (Ed.), *Northeast Regional 610 Agricultural Engineering Service*, Ithaca, N.Y., pp. 6–13, 106–113.
- Saer, A., Lansing, S., Davitt, N.H., Graves, R.E., 2013. Life cycle assessment of a food waste composting system: environmental impact hotspots. *J. Clean. Prod.* 52, 234–244.
- Sandars, D.L., Audsley, E., Cañete, C., Cumby, T.R., Scotford, I.M., Williams, A.G., 2003. Environmental benefits of livestock manure management practices and technology by Life Cycle Assessment. *Biosyst. Eng.* 84 (3), 267–281.
- Santos, A., Bustamante, M.A., Tortosa, G., Moral, R., Bernal, M.P., 2016. Gaseous emissions and process development during composting of pig slurry: the influence of the proportion of cotton gin waste. *J. Clean. Prod.* 112, 81–90.
- Sharma, G., Campbell, A., 2003. *Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems*. Department of Environment and Conservation, University of New South Wales, Recycled Organics Unit, Sydney.
- Sonesson, U., Björklund, A., Carlsson, M., Dalemo, M., 2000. Environmental and economic analysis of management systems for biodegradable waste. *Resour. Conserv. Recycl.* 28, 29–53.
- Sun, W., Huang, G.H., Zeng, G., Qin, X., Yu, H., 2011. Quantitative effects of composting state variables on C/N ratio through GA-aided multivariate analysis. *Sci. Total Environ.* 409 (7), 1243–1254.
- Thomassen, M.A., van Calker, K.J., Smits, M.C.J., Iepema, G.L., de Boer, I.M., 2008. Life cycle assessment of conventional and organic milk production in The Netherlands. *Agr. Syst.* 96, 95–107.
- Valipour, M., Sefidkouhi, M.A.G., Eslamian, S., 2015. Surface irrigation simulation models: a review. *Int. J. Hydrol. Sci. Technol.* 5 (1).
- Volpi, R., 1992. *Bilanci Energetici in Agricoltura*. Laruffa Editore, Reggio Calabria, Italy.
- Yannopoulos, S.I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A., Angelakis, A.N., 2015. Evolution of water lifting devices (pumps) over the centuries worldwide. *Water* 7, 5031–5060.
- Zhao, W., Van der Voet, E., Zhang, Y., Huppel, G., 2009. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: case study of Tianjin, China. *Sci. Total Environ.* 407, 1517–1526.