Life cycle assessment of municipal solid waste technologies, organic waste, and compost application to crops

Roberto Quirós Vargas

Doctoral thesis

Supervisors: Dr. Xavier Gabarrell
Dra. Gara Villalba

A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology.

Sostenipra research group
Institut de Ciència i Tecnología Ambientales (ICTA)
Universitat Autònoma de Barcelona (UAB)

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The present thesis entitled "*Life cycle assessment of municipal solid waste technologies, organic waste, and compost application to crops*" has been carried out at the Institute of Environmental Science and Technology (ICTA) at the Universitat Autònoma de Barcelona (UAB) by:

Roberto Quirós Vargas

The thesis was under the supervision of Dr. Xavier Gabarrell and Gara Villalba, from the ICTA and the Department of Chemical Engineering at the UAB. Furthermore, the thesis was developed with the collaboration of Group d'Investigació en Compostatge (GICOM) at the UAB and the Environmental Horticulture Unit at the Institute of Agriculture and Food Research and Technology (IRTA).

Dr. Xavier Gabarrell　　　　　　　　Dra. Gara Villalba

Bellaterra (Cerdanyola del Vallés), July 2014

“El principio de la sabiduría es honrar a Dios…,
…hace venir como lluvia la inteligencia y la ciencia”

Santa Biblia

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ADC-M	Anaerobic digestion mesophilic range
ADC-T	Anaerobic digestion thermophilic range
ADP	Abiotic depletion potential
AP	Acidification potential
ARC	Agencia de Residuos de Catalunya
C_2H_4 eq.	Ethylene equivalent emissions
C_2O	Carbon dioxide
CC	Climate changue
CCW	Composting in confined windrows
CED	Cumulative energy demand
CFC-11	Trichlorofluoromethane equivalent emissions
CH_4	Methane
CML	Institute of Environmental Sciences (Leiden)
CO_2 eq.	Carbon dioxide equivalent emissions
CONICIT	Comision Nacional de Investigaciones Científicas y Tecnológica de Costa Rica
CT	Composting in tunnels
DRI	Dynamic respiration indexo
EP	Eutrophication potential
EP	Eutrophication potential
EU	European Union
GICOM	Grup d’Investigació en Compostatge (UAB)
GHG	Greenhouse gas
GWP	Global warming potential
HC	Home compost
HC-HE	Home compost high emissions
HC-LE	Home compost low emissions
HIG	Horticultural inactivity gap
IC	Industrial compost
ICTA	Institute of Environmental Science and Technology (UAB)
IDESCAT	Instituto de Estadística de Cataluña

IPCC	Intergovernmental Panel on Climate Change
IRTA	Institute of Agriculture and Food Research and Technology
ISO	International Standarisation Organisation
K	Potassium
KNO_3	Potassium nitrate
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFRV	Leftover of fruit and vegetables
LHV	Low heating value
MAL	Maximum autoricé load
MBT	Mechanical biological treatment
ME	Marine eutrophication
MF	Mineral fertilizers
MJ ex.	Mega joules equivalent
MSW	Municipal solid waste
MSWI	Municipal solid waste incinerator plant
N	Nitrogen
N_2O	Nitrous oxides
NH_3	Antonia
NMa	Allocation procedure base on mineralization N degree in soil
OF	Organic fiber
OFMSW	Organic fraction of municipal solid waste
OLDP	Ozone layer depletion potential
OM	Organic matter
P	Phosphorus
POP	Photochemical oxidation potential
RuralCat	Catalan Agricultural Meteorology Net
Sb eq.	Antimony equivalent emissions
SETAC	Society of Environmental Toxicology and Chemistry
Sostenipra	Sustainability and Environmental Prevention
Ta	Allocation procedure base on time duration

TE	Terrestrial eutrophication
TW	Turning windrows composting
UAB	Universitat Autònoma de Barcelona
VOC	Volatic organic compounds

Acknowledgments

The author want to thanks Erasmus Mundus (E2HANCE Program) by grant with a three years scholarship; the Universidad de Costa Rica and the Comisión Nacional de Investigaciones Científicas y Tecnológicas de Costa Rica (CONICIT) by the personal and family supplementary grants for the four-years doctoral studies. Additionally, the author want to thanks Zero Waste Project TRACE 2009 0216 and Ecotech Sudoe Project SOE SOE2/P1/E377 for supporting the researches developed in this dissertation.

A Dios quien me dio la salud y la fe para perseverar y poder cumplir con este objetivo de vida. A la memoria de mis padres Arnoldo y Miriam por darme la vida y quienes estarían muy contentos de este logro.

En especial quiero agradecer a mis directores Dr. Xavier Gabarrell y Dra. Gara Villalba por su guía y todo el apoyo incondicional que me brindaron durante el período de estudio. Xavier y Gara infinitas gracias por vuestros consejos no solo en el campo académico sino también en el personal y por la amistad y empatía durante estos cortos cuatro años de estudio.

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A Xavi Font y el Grup d'Investigació en Compostatge (UAB) de la Universidad Autónoma de Barcelona de quienes recibí apoyo constante mediante la aclaración de dudas técnicas de la producción de compost y suministro de datos. Y a todos los profesores (as) y personal de apoyo de Ingeniería Química de la UAB con quienes tuve la oportunidad de compartir momentos muy agradables.

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A todos (as) muchas gracias.

Summary

The increased generation of municipal solid waste (MSW) due to population growth and new patterns of consumption is an important issue for European Union (EU) and countries around the world. Policies for managing MSW in a sustainable manner have been key components of EU directives (Directives 1999/31/EC and 2008/98/EC).

This doctoral thesis aims to study technologies for the treatment of MSW and assess the environmental impacts of using organic waste to fertilize crop in order to optimize resources and reduce waste. The studies are based on life cycle analysis using CML and ReCipe methodologies.

Chapter 2 is dedicated to the assessment of autoclaving a technology normally used for the sterilization of pharmaceutical waste. This technology offers the possibility of recovering the valuable portion of mixed MSW such as the organic fiber (OF). The processes of autoclaving, sorting and biological treatment were compared to two known technologies: incineration and landfill. The results showed that the systems which considered the anaerobic digestion had the lowest impacts in eutrophication potential and global warming potential. Meanwhile, incineration had the best results for the remainder five impact categories studied. On the other hand, landfill had the highest impact in all studied categories.

Chapter 3, the second case study was carried out to compare the environmental and agronomical results of two composts (industrial and home) with mineral fertilizers. Fertilizers were applied to horticultural cauliflower crops. The results showed a better yield (fruit · ha^{-1}) for the crops fertilized with mineral fertilizers but the best environmental performance was for the crops fertilized with home compost.

Chapter 4, the third case study, two home composts were produced by two different methods (i.e. production management), resulting in significant differences in terms of emissions. Emissions of methane, nitrous oxides and ammonia were experimentally measured for both composts. The results showed that nitrous oxides and methane

emissions contributed considerably the category of global warming potential. While ammonia emissions contributed to the categories of acidification potential, eutrophication and photochemical oxidation. It was observed that these gaseous emissions depend on the management practices employed when producing the compost such as: quality and type of waste stream, frequency mixing of the composting material, rigorous control of some physico-chemical characteristics (humidity, pH, temperature, etc.), among others.

Chapter 6, the fourth case study was carried out to compare the environmental performance of organic and mineral fertilizer in a crop sequence of cauliflower and tomato. Furthermore, two procedures for allocating life cycle impacts to crops were also studied. The first one was based on time allocation and the other one in the mineralization N degree in soil. In general, the results showed a better environmental performance for cauliflower crop than tomato in all impact categories considered. Meanwhile, in both crops, the fertilization treatment with home compost showed the lowest impacts than industrial compost and mineral fertilizers in the most impact categories studied. Additionally, the total impacts for the crop sequence (sum of impacts of cauliflower and tomato) were lower than single (i.e. cauliflower and tomato) impacts for the three fertilization treatments.

Finally, the dissertation also includes guidelines for organic waste management (Chapter 5). These guidelines focused on domestic compost production and its application in horticulture. The guidelines show the V2V “vegetables to vegetables” model, a closed loop model starting from food waste (e.g. vegetables and fruits) compost until it is again transformed in organic fertilizer to be applied to crops. The guidelines are targeted towards farmers and anyone interested in domestic compost production.

Resumen

El aumento en la generación de residuos sólidos municipales (RSM) debido al crecimiento de la población y nuevos patrones de consumo es un asunto importante en la Unión Europea (UE) y para la mayoría de países alrededor del mundo. Políticas para la gestión de los RSM de una manera sostenible han sido componentes claves en las directivas de la UE (Directivas 1999/31/EC and 2008/98/EC).

Esta tesis doctoral tiene como objetivo estudiar tecnologías para el tratamiento de los RSM y evaluar los impactos ambientales originados por usar la materia orgánica como fertilizante en cultivos. Los estudios están basado en el análisis del ciclo de vida usando las metodologías de CML and ReCipe.

Capítulo 2, se refiere a la evaluación ambiental de la autoclave, la cual es una tecnología normalmente utilizada para la esterilización de residuos farmacéuticos. Esta tecnología ofrece la posibilidad de recuperar una parte importante de los RSM mezclados tales como: la fibra orgánica (OF) y los reciclables. Los resultados de la evaluación ambiental de los sistemas (autoclave + separación + tratamiento biológico) fueron comparados con incineración y vertedero. Los resultados indicaron que los sistemas que consideraron la digestión anaeróbica tuvieron los menores impactos para las categorías de eutrofización y calentamiento global. Mientras que, incineración tuvo los mejores resultados para el resto de las categorías estudiadas.

Capítulo 3 corresponde al segundo caso de estudio el cual se llevó a cabo para comparar los resultados ambientales y agronómicos de dos composts (industrial y casero) con fertilizantes minerales. Los fertilizantes fueron aplicados a cultivos de coliflor. Los resultados mostraron un mejor rendimiento agronómico (fruta$\cdot$ ha^{-1}) para los cultivos fertilizados con fertilizante mineral pero el mejor desempeño ambiental fue para los cultivos fertilizados con el compost casero.

Capítulo 4, corresponde al tercer caso de estudio, en el cual dos composts caseros fueron producidos por dos sistemas de gestión de producción diferentes en los cuales se observaron diferencias significativas en términos de emisiones. Emisiones de

metano, óxido nitroso y amoniaco fueron experimentalmente medidos para ambos composts. Los resultados mostraron que las emisiones de óxido nitroso, y metano contribuyeron considerablemente en la categoría de calentamiento global. Mientras que las emisiones de amoniaco contribuyeron en las categorías de acidificación, eutrofización y oxidación fotoquímica. Se observó que esas emisiones gaseosas dependen considerablemente de las prácticas de gestión cuando se produce el compost, tales como: calidad y tipo de residuos, frecuencia de mezclado del material, control riguroso de algunas características físico-químicas tales como: humedad, pH, y temperatura, entre otras.

Capítulo 6, corresponde al cuarto caso de estudio en el cual se comparó el desempeño ambiental de fertilizantes orgánicos y minerales en una secuencia de cultivos de coliflor y tomate. Además se compararon dos procedimientos para la asignación del compost a los cultivos. El primero estuvo basado en el tiempo de duración del cultivo y el otro en el grado de mineralización del nitrógeno en el suelo. En general, el cultivo de coliflor mostró un mejor desempeño ambiental que el del tomate en todas las categorías de impacto estudiadas. Por otro lado, en ambos cultivos, el tratamiento de fertilización realizado con compost casero mostró un menor impacto ambiental que el compost industrial y el fertilizante mineral en la mayoría de las categorías estudiadas. Por otro lado, los impactos totales de la secuencia de cultivos (suma de impactos de la coliflor y el tomate) fueron menores que los impactos individuales (coliflor y tomate) para los tres tratamientos de fertilización.

Finalmente, la tesis incluye recomendaciones para la producción y gestión de los residuos orgánicos (Capítulo 5). Estas recomendaciones se enfocaron en la producción de compost doméstico y su aplicación en horticultura. Se incluye el modelo V2V "vegetables to vegetables" que es un modelo de bucle cerrado empezando desde la generación de residuos de cultivos (hortalizas, vegetales y frutas) hasta que los mismos son transformados nuevamente en fertilizantes orgánicos para ser aplicados en cultivos.

Resum

L'augment en la generació de residus sòlids municipals (RSM), principalment degut al creixement de la població i als nous patrons de consum, és un assumpte important per a la Unió Europea (UE) i per la majoria de països d'arreu del món. Polítiques sostenibles per a la gestió dels RSM han estat components claus en les directives de la UE (Directives 1999/31/EC and 2008/98/EC).

Aquesta tesis doctoral te com a objectiu estudiar les tecnologies per al tractament dels RSM i avaluar els impactes ambientals derivats de l'ús de la matèria orgànica (compost) com a fertilitzant en cultius. Els estudis s'han basat en la anàlisis del cicle de vida utilitzant les metodologies CML i ReCipe.

El capítol 2, fa referencia a l'avaluació ambiental de l'autoclavatge de residus, tecnologia que fins al moment ha estat principalment utilitzada per a l'esterilització de residus sanitaris. Els resultats de l'avaluació ambiental dels processos autoclave, separació i tractament biològic varen ser comparats amb els escenaris d'incineració i abocador. Els resultats mostraren, que els sistemes que consideraven la digestió anaeròbica, tenien els menors impactes per les categories d'eutrofització i escalfament global. En canvi, la incineració obtingué els millors resultats per la resta de categories d'impacte ambiental estudiades. Per altra banda, l'abocador obtingué els majors valors en totes les categories d'impacte.

El capítol 3, correspon al segon cas d'estudi que es va dur a terme per comparar els resultats ambientals i agronòmics de dos compost (industrial i casolà) amb fertilitzant mineral. Els fertilitzants varen ser aplicats a cultius de coliflor. Els resultats varen mostrar un major rendiment agronòmic (fruita·ha^{-1}) per cultius abonats amb fertilitzant mineral; en canvi, el millor perfil ambiental va ser pels cultius fertilitzats amb compost casolà.

El capítol 4, correspon al tercer cas d'estudi en el qual dos composts procedents d'auto-compostatge van ser produïts mitjançant dos sistemes de gestió diferents, la diferent gestió va donar lloc a diferències significatives en termes d'emissions. Les

emissions de metà, òxid nitrós i amoníac van ser experimentalment mesurades en ambdós composts. Els resultats mostraren que les emissions d'òxid nitrós i metà contribuïren considerablement a la categoria d'impacte d'escalfament global. En canvi, les emissions d'amoníac contribuïren a les categories d'acidificació, eutrofització i oxidació fotoquímica. Es va observar que aquestes emissions gasoses depenien considerablement de les pràctiques de gestió durant la producció del compost, tals com: qualitat i tipus de residus, freqüència de barreja del compost, control rigorós d'algunes característiques fotoquímiques (humitat, pH, temperatura), entre d'altres.

El Capítol 6, correspon al quart cas d'estudi en el qual es va comparar la idoneïtat ambiental de fertilitzants orgànics i minerals en una seqüència de cultius de coliflor i tomàquet. A més a més, es compararen dos procediments per l'assignació del compost als cultius. El primer basat en el temps de duració del cultiu i el segon en el grau de mineralització del nitrogen al sòl. En general, el cultiu de coliflor mostrà un millor perfil ambiental que el del tomàquet en totes les categories d'impacte estudiades. Per altra banda, els impactes totals de la seqüència de cultius (suma d'impactes de la coliflor i tomàquet) varen ser menors que els impactes individuals (coliflor i tomàquet) pels tres tractaments de fertilització.

Finalment, la Tesis conclou recomanacions per la gestió dels residus orgànics (Capítol 5). Aquestes recomanacions varen ser enfocades a la producció de compost domèstic i la seva aplicació hortícola. S'inclou un model V2V "vegetals a vegetals". Aquest és un model de bucle tancat que comença des de els residus de cultius (hortalisses, vegetals i fruites) fins la transformació d'aquests novament en fertilitzants orgànics per ser aplicats a cultius. Les recomanacions van dirigides als agricultors i qualsevol persona interessada en la producció de compost domèstic.

Preface

The thesis *"Life cycle assessment of municipal solid waste technologies, organic matter, and compost application to crops"* was developed from November 2010 to June 2014 at the Department of Chemical Engineering under "Environmental Science and Technologies" Phd programme of the Institut de Ciència i Tecnologia Ambientals (ICTA). The thesis was developed with the participation of the research group Sostenibilitat i Prevenció Ambiental (Sostenipra) at the Universitat Autónoma de Barcelona with the collaboration of Group d'Investigació en Compostatge (GICOM) of the Universitat Autónoma de Barcelona and the Institut de Recerca i Tecnología Agroalimentaries (IRTA). Additionally, the autor was awarded with three grants for personal and family financial support: Erasmus Mundus E2HANCE, and the Universidad de Costa Rica and the Comisión Nacional de Investigaciones Científicas y Tecnológicas de Costa Rica (CONICIT).

The thesis aims for a sustainable management of MSW through the environmental assessment of technologies to treat unsorted MSW and the transformation of the organic matter to produce compost which was applied in horticultural crops. The thesis is structured in seven chapters.

Chapter 1 corresponds to introduction, objectives and methodologies used in the dissertation.

Chapter 2 focuses on the environmental assessment of the organic fiber **(OF)** which is a sub-product resulting from the autoclaving unsorted MSW. The OF was processed through biological treatments (aerobic and anaerobic digestion). The environmental results of the whole system comprised of autoclaving, sorting and biological treatment were compared with two reference technologies: incineration and landfill.

The others there case studies presented in **chapters 3, 4, 5 and 6** are related to the use of fertilizers (i.e. organic and mineral) applied in horticultural crops. These chapters mainly focus in the use of waste as sustainable alternative for the organic matter from MSW.

Chapter 3 presents the environmental and agronomical comparison of three fertilizers (i.e. industrial compost, home compost and mineral fertilizer) applied in horticultural cauliflower crops.

Chapter 4 focuses in the environmental assessment of two home composts with low and high gaseous emissions (ammonia, methane, nitrous oxides and volatile organic compounds) of the composting process. The aim of this chapter is to study the consequences of gaseous emissions of the composting process in the environmental performance of horticultural systems.

Chapter 5 presents guidelines for the organic waste management focused on domestic compost and its application in horticulture. The model was oriented to farmers and any person interested in domestic compost production.

Chapter 6 analyzes the environmental performance of organic and mineral fertilizers applied in a crop sequence of cauliflower and tomato. The impacts of each crop were also compared with the entire crop sequence (sum of impacts of cauliflower and tomato crop). Furthermore, this case study analysed the environmental performance of the crop sequence using two procedures for the allocation of compost to crops.

Chapter 7 includes a general discussion and summarizes the main outlines, the conclusions and future perspectives that arise from the dissertation.

The chapters were structured following the general guidelines of scientific journals for the publication of papers. Each chapter has its own introduction, methodology, results and discussion, the main conclusions and references. The original contents of the published papers have kept unchanged to avoid duplication of some introductory material or methodological interpretations. The references and annexes are presented at the end of the manuscript. References were kept according to Journal Cleanner Production format.

Most of the mentioned researches (i.e. chapters) were funded by European projects (Zero Waste Project TRACE 2009 0216 and Ecotech Sudoe Project SOE SOE2/P1/E377). Likewise researches were prepared in paper format and submitted to journals for its publication as follows:

Article 1

"The application of LCA to alternative methods for treating the organic fiber produced from autoclaving solid waste: Case study of Catalonia".

Authors: Quirós R, Gabarrell X, Villalba G, Barrena R, García A, Torrente J, Font X.

Project: Zero Waste Project TRACE 2009 0216

Funded by: 1G/MED08-533 ZERO WASTE

Article published in Journal of Cleaner Production, 2014.

Article 2

"Environmental and agronomical assessment of three fertilization treatments applied in horticultural open field crops".

Authors: Quirós R, Villalba G, Muñoz P, Font X, Gabarrell X

Project: ECOTECH SUDOE SOE2/P1/E377

Funded by: Europa/ERDF Funds, FEDER and Interreg IV B

Article published in Journal of Cleaner Production, 2014.

Article 3

"Environmental assessment of two home composts with low and high gaseous emissions of the composting process"

Authors: Quirós R, Villalba G, Muñoz P, Colón J, Font X, Gabarrell X.

Project: ECOTECH SUDOE SOE2/P1/E377

Funded by: Europa/ERDF Funds, FEDER and Interreg IV B

Article published in Resources, Conservation & Recycling, 2014

Article 4

“Environmental assessment of organic and mineral fertilizers in a crop sequence”

Authors: Quirós R, Villalba G, Gabarrell X, Muñoz P.

Project: ECOTECH SUDOE SOE2/P1/E377

Funded by: Europa/ERDF Funds, FEDER and Interreg IV B

Submitted to Resources, Conservation & Recycling (second revision), 2014

In addition, the main results of the researches were presented in international seminars and congresses as follows:

Presentation 1

Title**:** Environmental assessment “closing flows and vegetables production”: from urban waste and with Roof Top Greenhouse V2V “vegetables to vegetables” model.

Authors: Quirós R, Villalba G, Muñoz P, Font X, Gabarrell X, Rieradevall J.

Participation: Oral presentation

Congress: Symposium on Ecoinovation in the Sudoe Region

Place: Tolousse, France

Date: June 2013

Oranized by: Ecotech Sudoe Project

Presentation 2

Title: Environmental assessment of two home compost applied in horticultural cauliflower crops

Authors: Quirós R, Villalba G, Muñoz P, Font X, Gabarrell X, Rieradevall J.

Participation: Poster and oral presentation

Congress: International Solid Waste Association (ISWA) World Congress

Place: Viena, Austria

Date: October 2013

Organized by: ISWA

Presentation 3

Title: Quantification and validation of GHG emissions from Municipal Waste Management with CO2ZW ® tool

Authors: Quirós R, Villalba G, Savigné E, Gasol C, Ferrany R, Gabarrell X, Rieradevall J.

Participation: Oral presentation

Congress: International Solid Waste Association (ISWA) World Congress

Place: Viena, Austria

Date: October 2013

Organized by: ISWA

Presentation 4

Title: Technologies to treat unsorted municipal solid waste in urban areas

Authors: Quirós R, Villalba G, Font X, Gabarrell X, Rieradevall J.

Participation: Oral presentation

Congress: 4th Annual International Conference on Urban Studies & Planning

Place: Atenas, Greek

Date: June 9-12, 2014

Organized by: ATHENS INSTITUTE FOR EDUCATION AND RESEARCH

Chapter 1

Introduction, methodology and objectives

Chapter 1

1 Introduction, methodology and objectives

1.1 Introduction

European economy, as well as developed countries, is characterized by high level resource consumption. This includes resources (metal, mineral resources for construction or wood), energy and land. Main driving forces of European resources consumption are economic growth and technological progress in the changing patterns of consumption and production. With growing demands on the world's limited stock of resources, it is imperative that Europe makes more efficient use of both virgin materials and waste. Every European citizen throws off 492 kg of household waste in 2010 (Eurostat, 2012). Although in recent years waste generation shows a decreasing trend due to the economic crisis, European Union (EU) countries should be alert because otherwise the waste generation could continue to grow. For example, in EU-15 countries the use of material has only slightly changed in the last two decades and still amount is approximately 15-16 tonnes per inhabitant per year (Eurostat, 2012). In the case of Catalonia, the material consumption grew from 12 to 17 tonnes per capita for the period 1990 to 2004 with an annual growing rate of 2.4% (IDESCAT, 2007). In announcements for the period to 2020 it is stated that resource use in EU will continue to grow. Resource use is growing also in other regions of the world. This is partially a result of the aforementioned increased use of goods and services in Europe, which often relies on source, acquired in these other regions. Therefore, it is clearly understood the relationship between resources consumption and waste generation. As stated in Figure 1.1, the biggest currents of waste in Europe originate in construction (34%); mining and quarrying (27%); and destruction and manufacturing (11%) (Eurostat, 2010).

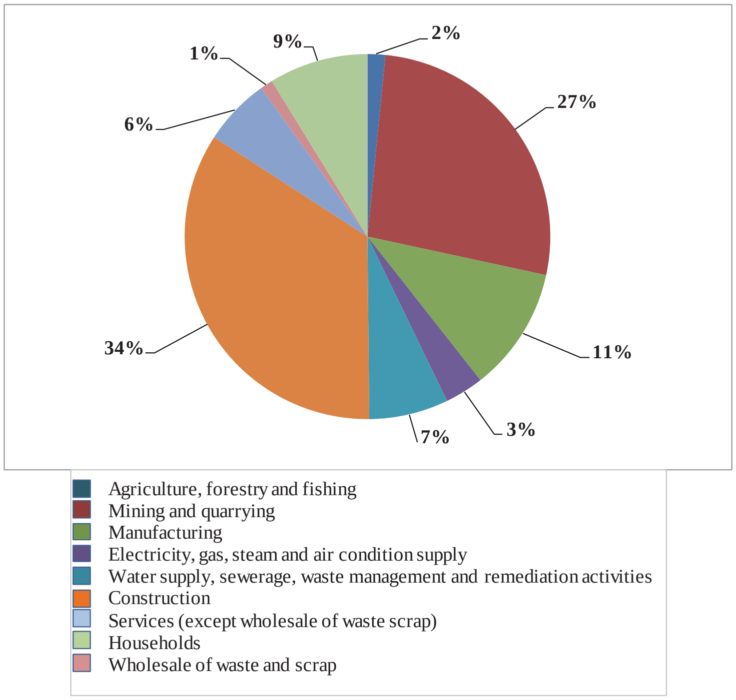


Figure 1.1 Generation of waste per productivity sector EU-27 in 2010
Source: Eurostat, 2010

In the case of Catalonia, as shown in Table 1.1, the most composition of waste was from wastewater and urban and industrial sectors **(ARC, 2001).**

Table 1.1 Waste production per productivity sectors in Catalonia for 2000

Waste stream	Millions of tonnes generated
Industrials	5,6
Municipals	3,5
Debris	5,5
Livestock	13
Urban waste water	>400
Industrial wastewater	>125

Source: Agencia de Residuos de Catalunya (ARC, 2000) cited in Sendra (2008v)

The basis of European policy on waste management is a revised frame on waste from Directive 2008/98/EC. It foresees a modern approach of waste management, where waste is no longer superfluous, but raw materials that end in plants instead of dumping grounds, where they are processed again into useful raw materials, compost or fuel. The goal of European policy's waste management is the reduction of waste effects on environmental and health and increasing resource use efficiency.

The growing generation of municipal solid waste (MSW) due to population growth and new patterns of consumption is an important issue for European Union (EU) countries (Quirós et al., 2014a). Policies for managing MSW in a sustainable manner have been key components of EU directives. In Europe, policies for reducing the amount of waste sent to landfills have been significantly influenced by EU directives 1994/62/EC and 1999/31/EC. These directives limit the amount of degradable waste that can be sent to landfills as a proportion of the waste produced in 1995 (e.g. reduction to 35% of the total amount of biodegradable municipal waste produced in 1995). As shown in Figure 1.2, despite recent efforts to reduce the amount of solid waste sent to landfills, the MSW volume remains high. In the EU-27 countries, 37% of municipal waste was landfilled, 24% was incinerated and 39% was recycled or composted on average in 2010 (Eurostat, 2014). Furthermore, 17 countries of EU-27 (63%) had as landfill as the main treatment option in 2010. Therefore, it is clearly noted that the quantity of MSW to landfill is nowadays high regarding other treatment options.

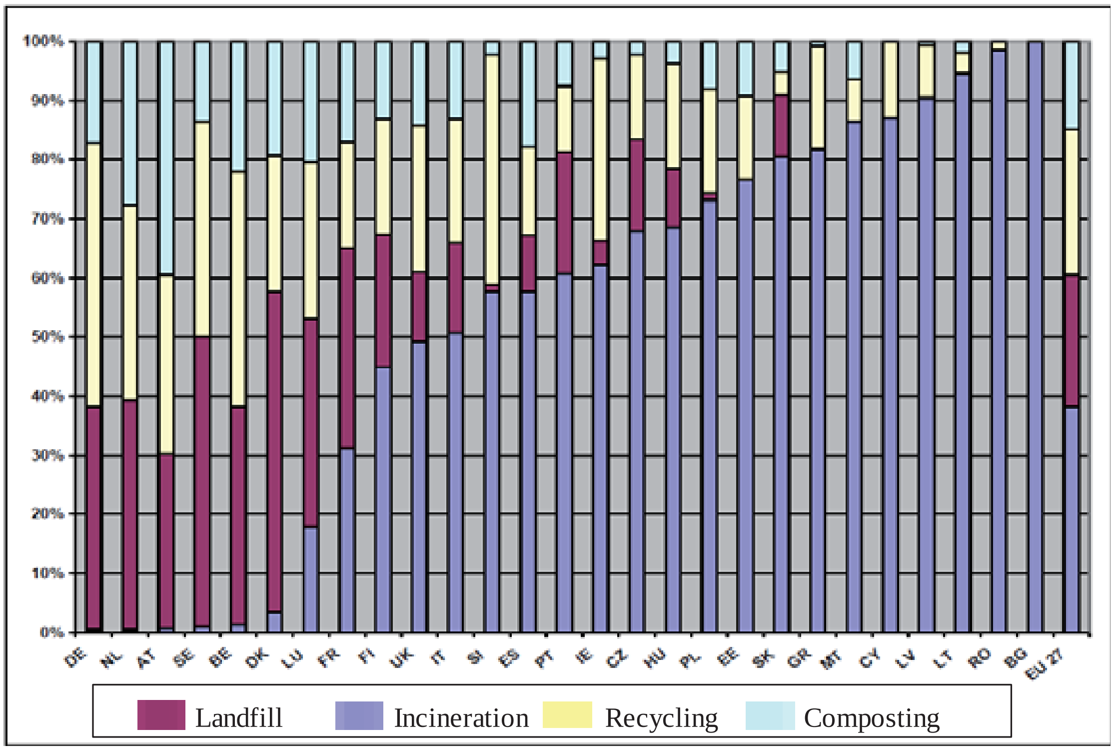


Figure 1.2 Municipal waste per treatment option in EU-27 in 2010

While, despite the introduction of the landfill directive in 1999, currently in EU countries (European Commission, 2009) approximately 40% of bio-waste from MSW ends up in landfills. This MSW practice is a growing problem due the rapid collapse of landfills. To address this problem, the European Union Landfill Directive 1999/31/CE (Council of the European Union, 1999) states the reduction of the biodegradable (e.g. reduction to 35% of the total amount of biodegradable municipal solid waste produced in 1995) waste being dumped to minimize environmental impacts and the loss of organic resources. One alternative, or rather complimentary, technology for the treatment of organic matter from MSW is composting. Furthermore, composting is seeing as a good alternative to be used as mineral fertilizer substitute in agricultural or as soil amendment application. The European countries produce a total of 76.2-102 Mt / year of organic fraction of municipal solid waste (OFMSW) which represents between 30-40% of the municipal waste generated (European Commission, 2008). The potential of quality compost production in EU is estimated at 35-40 million tonnes · year^{-1} (European Commission, 2009), equivalent to 131,000 tonnes of available of organic nitrogen (3.5%). Additionally, the use of compost in agriculture not only reduce the total amount of waste being dumped but also contribute to eliminate most of the pathogenic microorganisms and reduces odor compounds obtaining a valuable product named *"compost"*. Thus, the use of compost in agriculture represents a sustainable way for the treatment of bio-waste from the MSW. In contrast to organic fertilizers, the use of manufactured fertilizers has been increasingly incorporated into regular farming practice in the EU since its introduction in the mid to late nineteenth century. In 2010, the mineral fertilizer consumption (N, P, P_2O_5, K and K_2O) in the EU was 18 million tonnes (Eurostat, 2014).

Organic wastes which are potentially valuables as fertilizers or amendments must be considered as resources to be managed adequately, instead of pollutants to be removed (Flotats et al., 2008). Although, agriculture is considered a major contributor to some present environmental impacts such as those of water pollution given the intensive use of fertilizers and pesticides (European Commission, 1999). Fertilizers (i.e. organics or minerals) are essential to sustaining agricultural production, increasing the yield and improving soil characteristics. However, mineral fertilizer must be applied according to crop needs. When the quantity of the nutrients applied exceeds the plant's nutritional requirements, there is a higher risk of nutrient losses from agricultural soils into the ground and surface water. Therefore, following the current trend of sustainable agriculture, the home composting represents a good alternative of organic fertilizer to give a sustainable use of organic matter from MSW and related sources.

1.2 European Waste Framework

The European Waste Framework is based on Directive 2008/98/EC. This directive repeals the previous Directive 2006/12 on waste and Directives 75/439/EEC and 91/689/EEC regarding waste oils and hazardous waste, respectively. The revised Waste Framework Directive applies from 12 December 2010 and introduces new provisions in order to boost waste prevention and recycling as part of the waste hierarchy and clarifies key concepts namely, the definitions of waste, recovery and disposal and lays down the appropriate procedures applicable to by-products and to waste that ceases to be waste.

Directive 2008/98/EC demands target quantification for the waste production prevention from the EU member-states, while in other places it poses its own targets. These targets comprise as minimum rate of 70% for recycle at the construction and demolition sector until 2020, a minimum recycle rate of 50% for household waste until 2020, while at least four streams of waste (paper, glass, metals and plastics) are provided until 2015 along with a separate collection for the biodegradable part (Directive 2008/98/EC).

1.3 Waste hierarchy

The waste management is strongly connected to the sustainable issue. It is important to choose policies with the aim of the reduction of waste disposal. The EU Directive 2008/98 (EC, 2008) (article 4) regulates the "waste hierarchy" (Figure 1.3) of the waste management and policy:

a. Prevention
b. Preparing for re-use
c. Recycling
d. Other recovery, e.g. energy recovery
e. Disposal

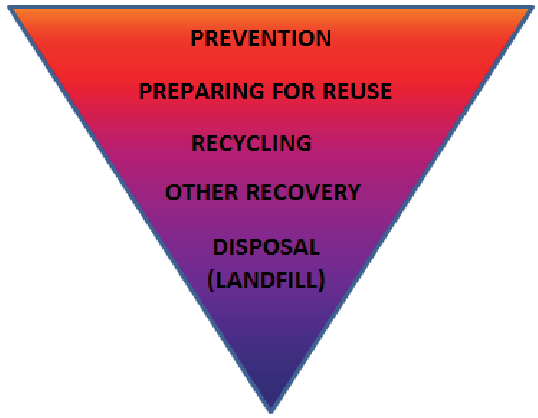


Figure 1.3 Waste hierarchy in EU (EU Directive 2008/98)
Source: Adapted from EEA Report No 2/2013

This directive (EC, 2008/98) lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving efficiency of such use. The hierarchy sets a priority order of what constitutes the best environmental option. The first point highlighted in the Directive 2008/98/EC is the prevention.

1.4 Municipal solid waste management

Waste management is a global problem in developed countries due to the rapid collapse of landfills and the high impacts related to biodegradable waste dumping. The definition of 'municipal solid waste' used in different countries varies, reflecting diverse waste management practices. In the national yearly reporting of municipal waste to Eurostat, 'municipal solid waste' is defined as follows (Eurostat, 2012a):

“Municipal waste is mainly produced by households, though similar wastes from sources such as commerce, offices and public institutions are included. The amount of municipal waste generated consists of waste collected by or on behalf of municipal authorities and disposed of through the waste management system.”

In this context, municipal waste is understood as waste collected by or on behalf of municipalities. However, the definition also can include waste from the same sources and other waste similar in nature and composition that is 'collected directly by the private sector (business or private non-profit institutions) mainly for recovery purposes (Eurostat, 2012a).

MSW is key point in EU countries in part because the 2008 Waste Framework Directive introduced a new 50 % recycling target for such waste. In addition, municipal waste is primarily a public sector responsibility and the current economic situation in many EU Member States demands an added focus on how to achieve policy goals most cost-effectively (EEA Report No 2/ 2013).

Municipal waste prevention can be assessed by analysing trends in the amounts of municipal waste generated; if the amounts of municipal waste generated are decreasing over time, waste is prevented according to the first objective of the waste hierarchy. As shown in **Figure 1.4**, the municipal waste has decreased from 2001 to 2010 in average in the EU-27 Members States, Croatia, Iceland, Norway, Switzerland and Turkey. Overall twenty-one countries generated more municipal waste per capita in 2010 than 2001 and eleven cut per capita municipal waste generation. This suggests that the economic downturn that starts in 2008 may have caused a reduction in municipal waste generation per capita. Overall, the picture is mixed and there is no clear evidence of improved waste prevention across countries between 2001 and 2010 **(EEA Report No 2/2013).**

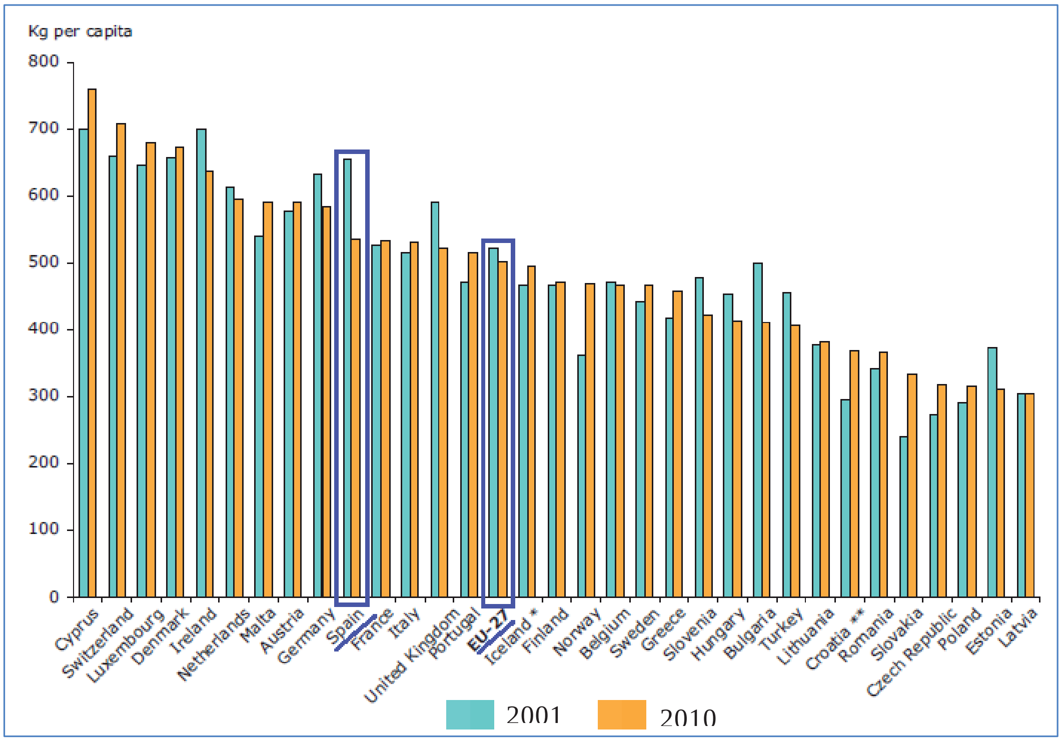


Figure 1.4 Municipal solid waste generation per capita in 32 European countries in 2001 and 2010

Source: European Environmental Agency (EEA report No 2/2013)
Note: The figure convers the EU-27 Members States, Croatia, Iceland, Norway, Switzerland and Turkey

1.5 Environmental sustainability in waste management

Environmental sustainability and waste management are associated with the welfare of human beings. Waste treatment and uses of by-products is an important issue in the management of waste. Therefore, as stated in Bonmatí (2001), solutions to environmental problems associated with organic waste require a global perspective and the development of integrated management plans including: actions to minimize waste generation, the establishment of specific soil-crop application programs, and treatment when required.

There are two main definitions in which environmental sustainability in waste management is supported. The first is *sustainable development* which was defined by the Brundtland commission as "Sustainable Development is the development that meets the needs of the present without comprising the ability of future generation to meet their own needs" (WCED, 1987). The second one is *environmental sustainability* which is defined as: "Environmental Sustainability itself seeks to improve human welfare by protecting the source of raw materials used for human needs, and ensuring that sinks for human waste are not exceed, in order to prevent harms to human" (Goodland, 2002). Thus, according to environmental sustainability, general objectives for any human activity can be summarized as an objective of rational resource consumption and reduction of environmental pollution. Hence, also environmental sustainability in waste management may be express through these two mayor objectives: conservation resources and pollution prevention. Therefore, the exploring of new waste management alternatives and improving of the existing ones are a key point to accomplish EU policies according to environmental sustainability principles.

1.6 Waste treatment

MSW are categorized in Europe according to the best treatment options in the "waste hierarchy" promoted by the EU on the basis of the Waste Framework Directive. Figure 1.5 indicates that for the period 2001-2010 for the EU-32 countries, landfilling of municipal waste decreased by almost 40 million tonnes, whereas incineration increased by 15 million tonnes and recycling grew by 29 million tonnes.

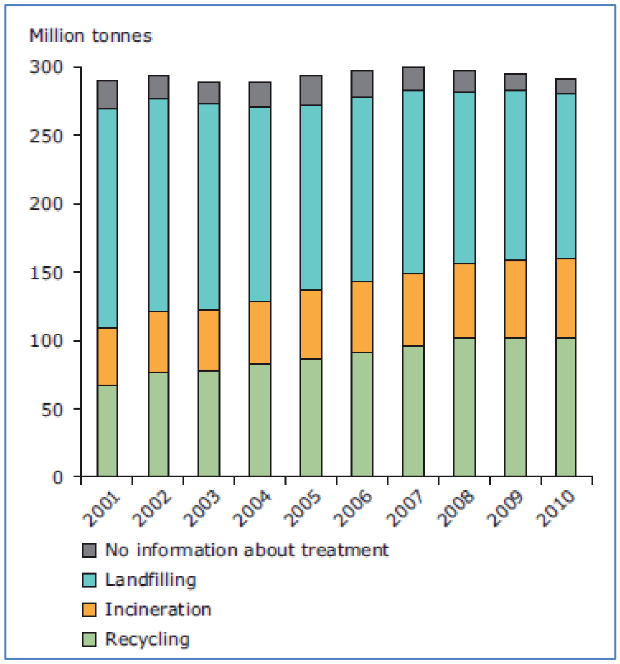


Figure 1.5 Municipal waste per treatment in 32 European countries in 2001-2010

Source: European Environmental Agency (EEA report No 2/2013)
Note: The figure covers the EU-27 Member States, Croatia, Iceland, Norway, Switzerland and Turkey

1.7 Waste treatment situation in Catalonia, Spain and European Union

Figure 1.6 shows the amount of waste in kg/inhabitant/year for different waste treatment for Catalonia, Spain and European Union for 2010 to 2012. In general the municipal waste treatment through the different alternatives available in Catalonia, Spain and European Union shows similar trends for the period 2010 to 2012. In the case of landfill, the municipal waste to landfill shows a decreasing trend in Catalonia, Spain and European Union countries for 2010 to 2012. The amount of waste send to landfill in Catalonia and Spain decreased in 9% and 8% from 2010 to 2012, respectively, and 13% for European Union. The efforts of the countries to reduce waste to landfill had been motivated by the EU Directive and local laws of the country members to achieve European targets. For the same period of analysis, the treatment of municipal waste through incineration technology decreased in Catalonia (7%), Spain had the same value and European Union had a slight decreased of 2%. For the case of recycling, both, Catalonia and Spain shown a decrease of 18% and

12%, respectively, but European Union grew about 6%. The amount of waste processed through composting alternative showed the same trend of recycling. Spain and Catalonia decreased the amount of municipal waste to composting in 7% and 20%; respectively, and European Union registered a slow increasing of 6%. In general it can conclude that only landfill showed a decreasing tendency regarding the other treatment alternatives, for the rest of technologies, only European Union registered increasing tendency but Catalonia and Spain showed a slight decreasing trend for the period compared.

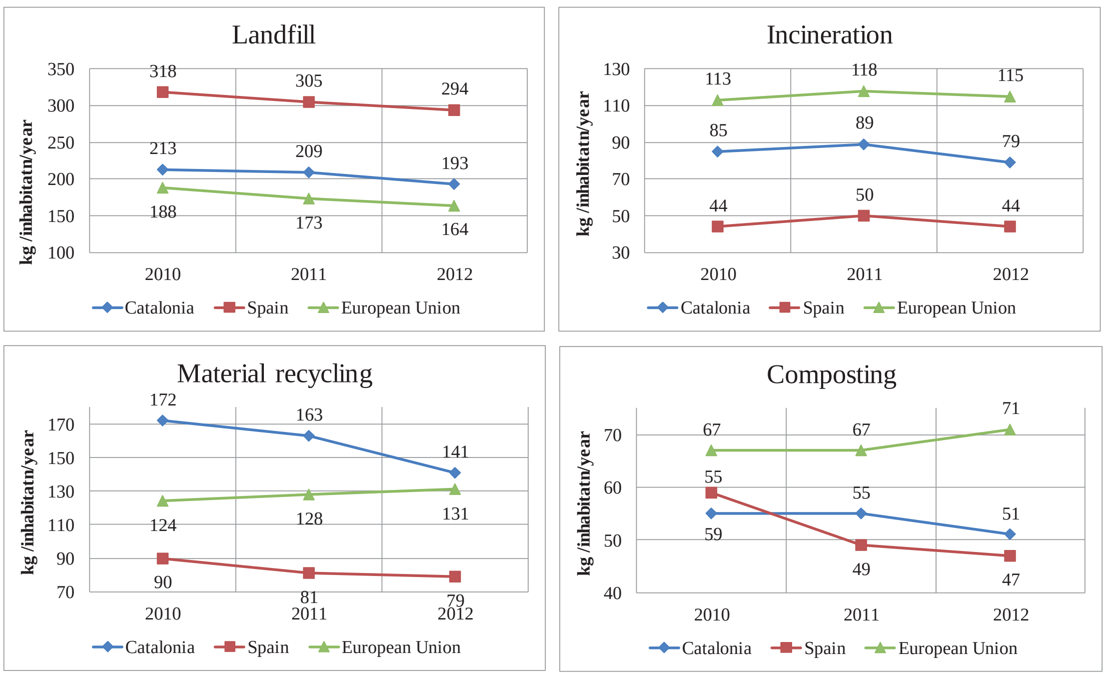


Figure 1.6 Waste treatment per capita in Catalonia, Spain and EU for 2010-2012
Units: kg/inhabitant/year
Source: Idescat, 2014; Eurostat, 2014

1.8 Technologies to treat unsorted MSW

In the following subsections an overview of the technologies to treat MSW used in the current dissertation is presented. The unsorted MSW was pretreated through the autoclaving technology to separate the biodegradable material from other fractions (plastics, metals, textiles, etc.) contained in the unsorted MSW. The environmental assessment results of the systems comprised of autoclaving + sorting + biological treatments (aerobic and anaerobic digestion process) were compared with incineration and landfill both with energy recovery. Incineration and landfill technologies were modelled and adapted to our case study from the ecoinvent database v2.2.

1.8.1 Autoclaving technology

Autoclaving is a process that is based on the principles used for the sterilization of medical and pharmaceutical equipment. Autoclaving is defined as a heat-based, non-combustion process that occurs in a moist environment under elevated temperatures and pressure (Papadimitriou, 2007). In the autoclaving process, waste is treated with saturated steam at high temperatures. The heating of the reactor requires the injection of saturated steam, so that the residue is eventually autoclaved. The main features of this treatment for recovering the value of municipal waste have already been described (Papadimitriou, 2007).

1.8.1.1 Benefits of autoclaving

The effect of the treatment and its subsequent mechanical separation system is that approximately 80% of the initial volume can be separated for recycling (Papadimitriou, 2007). At the same time, the sterilization of pathogens, the loss of fluids, the compaction of plastics, and the disintegration of labels on glass bottles, food packaging and cans is achieved. Also, all incoming *biodegradable fractions* are collected together in a single OF, which has been recently studied for biodegradability under composting and anaerobic digestion conditions (Stentiford, Hobbis, Barton, Wang, & Banks, 2010; Trémier, 2006). Figure 1.7 shows an autoclaving machine which was designed and built by private company located in Barcelona, Catalonia. Data of energy and resources consumption used in the case study was provided by the managers of this company.

Figure 1.7 Full-scale autoclaving machine
Source: Ambiensys

The autoclaving process can be applied directly to mixed or unsorted MSW in areas where source separation collection is not implemented. It may also be a good solution to treat the rejected fraction from the mechanical biological treatment (MBT) plants. This rejected flow mainly corresponds to the fraction refused in the first mechanical pretreatment with a characterisation similar to the MSW. The post-treatment of this MBT residual flow through an autoclaving process may maximise the recycled ratio (glass, plastic, metal and biodegradables) of MBT plants. However, there is still some lack of knowledge about the suitability of this technology for treating large amounts of MSW. The most important concern to be solved is the fate of the organic fiber (OF) obtained after autoclaving the MSW, which is the main constituent in the autoclaved material.

1.8.1.2 Overview of autoclaving process

In brief, in the *process of autoclaving*, the unsorted waste collected by the MSW system is introduced into a temporal storage chamber. The waste is then moved to size-reducing machinery by a crane operator. The ground-up waste is transported via conveyor belt to a reactor where the autoclaving process takes place. After the autoclaving process is finished, the OF is separated from the autoclaved waste stream and subsequently the recyclable fractions also are sorted by sorting machines. In the present study, the OF was treated through biological technologies (i.e. aerobic and anaerobic digestion), the sorted fractions (PET, ferrous and non-ferric material) were valorized as recyclable potential material and the mixed plastic fraction was valorized thru incineration with energy recovery. Figure 1.8 outlines the process of autoclaving since the moment the waste arrive to the facility up to separation of the OF and recyclable fractions.

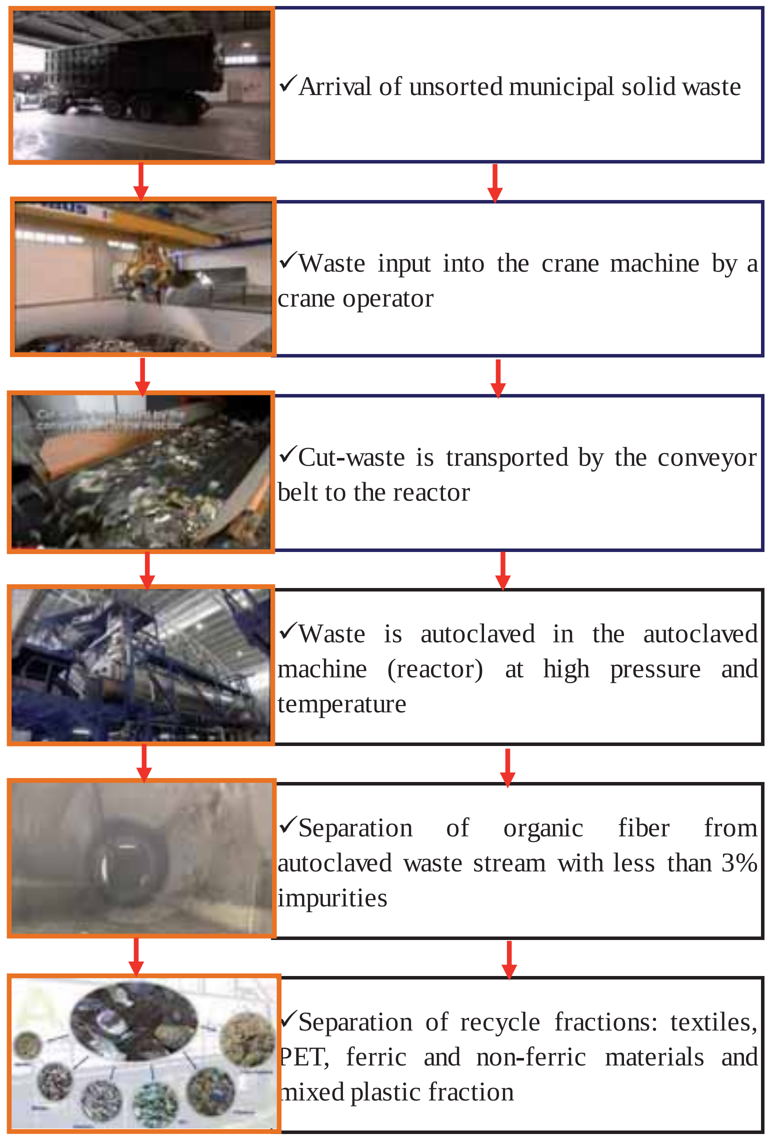


Figure 1.8 Autoclaving machine to treat unsorted waste
Source: Ambiensys SRL

1.8.1.3 Operational conditions of full-scale autoclaving machine

In this dissertation, an autoclaving process was carried out in a full-scale reactor with a capacity of 35 m^3, processing approximately 10-15 tonnes of unsorted MSW in a continuous mode of operation to avoid the problem of heterogeneity found in this kind of wastes. Working conditions were 600 kPa and 145 °C with a hydraulic retention time of 30 min. OF was obtained from the mechanical separation of this fraction from the rest of materials (glass, plastics, metals and stones) with a 10 mm sieving process and it was a highly homogeneous fibrous material as confirmed by transmission electron microscopy (TEM) images obtained with a JEOL electron microscope (model 1010, IZASA, Alcobendas, Spain) operating at an accelerating voltage of 15 kV (Figure 1.9) (García et al., 2013). This organic fraction represents 55% of the input material (in mass).

a. b.

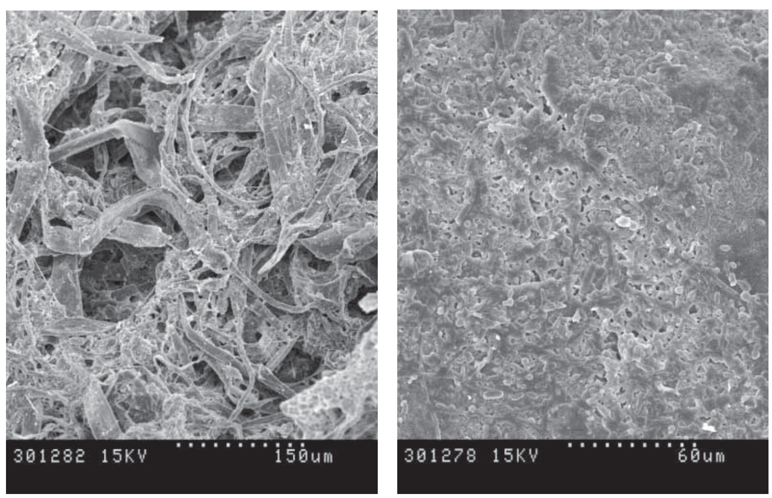


Figure 1.9 Transmission electron microscopy (TEM) images of the fiber a) and b) correspond to different resolutions.
Source: García et al. 2013

1.9 Biological treatments

Biological treatments processes (aerobic and anaerobic digestion) have been widely studied around the world (Ahring, 2003; Haug, 1993**)**. Biological processes are known to have several advantages over landfilling. These advantages include the reduction of waste volume, waste stabilization, pathogens elimination and production of biogas for energy use in the case of anaerobic digestion. Depending on its quality, the final product of these processes can be used as fertilizer and or soil amendment (Haug, 1993). Composting is an aerobic biological process, in which the organic fraction is stabilized. As results of the process, CO_2 will be released to the atmosphere. While, anaerobic digestion is a biological process in which microorganisms decompose the organic fraction of the MSW in the absence of oxygen, producing biogas. Methane and carbon dioxide form the major portion of the biogas, other gases such as non-methane organic compounds and sulfur gases also form in small amounts (Hanandeh and El-Zein, 2010).

1.9.1 Aerobic process (composting)

Composting refers to the purposeful and controlled decomposition of organic matter by microorganisms into a stable humus material known as compost. According to Haug (1993), composting is "the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land". This definition highlights the main characteristics of this process, which has been successfully applied to a lot of typologies of organic waste, including the organic fraction of MSW. The final production of a good end product is directly related to the quality of raw materials, which in the case of MSW, implies a separate collection of the organic fraction (European Commission, 2008).

1.9.2 Composting process

In the composting process it is important to maintain the biological, chemical and physical requirements of microorganisms to obtain the optimum degradation levels throughout the stages of the process. There are two phases in the composting process, a *decomposition* or high-rate phase and the *curin*g phase. The first stage is a high-rate phase because during this stage the decomposition activity of the feedstock into simpler compounds by microorganisms is intense and, as a result of the metabolic activities, heat is produced (Hang, 1993). This stage is also characterized by high oxygen uptake rates. Two ranges of temperatures are identified in the decomposition phase, the mesophilic in which microorganisms grows at temperatures between 23 and 45 °C. These organisms use available oxygen to transform carbon from the composting feedstock to obtain energy and organic materials to build new biomass and, in the process they expel carbon dioxide and water. When temperatures approaches 45 °C, mesophilic microorganisms die or become dormant. Over 45 °C star the thermophilic phase (between 45 to 70 °C). This phase is preferred than mesophilic for two reasons: it promotes rapid composting and it destroys pathogens and weed seeds. The activity of thermophilic microorganisms generates greater quantities of heat than that of mesophilic leading to higher temperatures in the composting mass.

The *curing* phase, also known as finished phase, is characterized by slow degradation because the nutrients available to microorganisms have been depleted **(Adani et al., 1997).** As a consequence of the slow activity during this phase, temperature decreases and the texture of the material becomes dry and powdery. At the end of this phase the material is considered stabilized or mature, which is the reason that this phase is also known as the maturation stage. The Figure 1.10 shows the range of temperatures of the composting process.

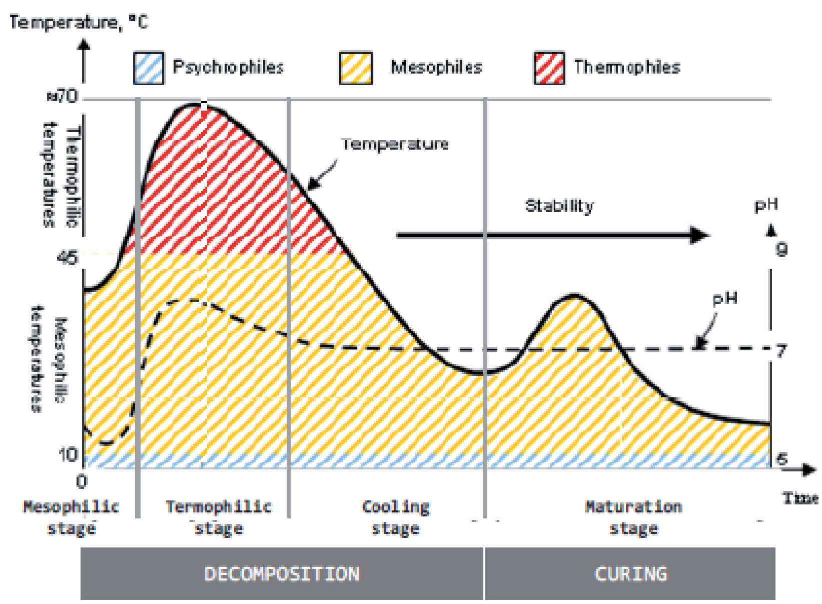


Figure 1.10 Phases of the composting process
Source: Adapted from Cadena (2009)

1.9.3 Physical, chemical and biological parameters of compost

Several parameters determine the chemical environment for composting, principally carbon and nutrient balance, moisture, oxygen, temperature, pH and particle size. Table 1.2 summarizes the main features of compost and reference parameters for each indicator.

Table 1.2 Parameters for final compost and reference values

Parameter	Features	Recommended value
Carbon balance and nutrients (C:N ratio)	Microorganisms require specific nutrient balance in an available form, proportion and proper concentration to perform the compostin efficiently. In compost systems C and N are usually the limiting factors for efficient decomposition. High C:N ratios (i.e. low C and high N) initially accelerates microbial growth and decomposition. Excess of N causes high release of ammonia and can cause result in a toxic environment for the microbial population, inhibiting the process.	15:30
Moisture	Microorganisms require moisture to absorb nutrients, metabolize and produce new cells because they can only use organic molecules if they are dissolved in water. Under constion of low humidity, the composting process slows down. High moisture conditions can reduce and even stop the transfer of oxygen air-filled process. Below 20% humidity, very few bacteria are active.	40-60%
Oxygen	The main functions of aereation in composting processes are to supply the oxygen needed by aerobic microorganisms, to facilitate the regulation of excess moisture by evaporation and to maintain the proper temperature. To support microbial activity, there must be many available pores in the material to serve as air chambers. Oxygen cab be provided throughout the turning and mixing of the material by using force aeration systems.	10-15%
Temperature	When aeration is controlled, the temperature in the compost pile is determined by the level of activity of the heat-generatiing microorgnanisms. The efective temperature in the process is between 45 and 59 °C. Temperatures below 20 ºC inhibit the activity of microorganisms lowering their decomposition capacity. Although composting ocurrs within a range of temperatures, the optimum temperature range of thermophilic microorganisms is preferred because it promotes rapid composting and it destroys pathogen and weed seeds.	45-59 ºC
pH	The optimal pH for biological process is normally in the range of 6 to 7.5 for bacteria and 5.5 to 8 for fungi. If the pH is below 6 microorganisms, particularly bacteria, die off and decomposition slows down. If the pH rises aove 9, ammonium becomes ammonia, which is toxic for microorganisms	6-7.5
Particule size and air filled porosity	The optimum particle size is that providing enough surface area for rapid microbial activity, but also enough void space to allow air to circulate for microbial respiration and material decomposition. The particles should be large enough to prevent compaction, thus excluding the oxyen in the voids.	25-30%

Microorganisms require specific nutrient balance in an available form, proportion and proper concentration to perform composting efficiently. The essential nutrients that microorganisms require in a large quantity include carbon (C), nitrogen (N), phosphorus (P) and potassium (K). In composting systems C and N are usually the limiting factors for efficient decomposition (Richard, 1992).

1.9.3.1 Full-scale biological treatments considered for the treatment of the organic fraction

Nowadays, the OFMSW (i.e. OF) treatment involves technologies such as composting or anaerobic digestion that result in the degradation and stabilization of organic matter and mass and volume reduction (Haug, 1993; Richard, 1992). For purposes of this dissertation, due to its physical-chemical and biological characteristics, OF from autoclaving unsorted MSW was assimilated to OFMSW. Therefore, OF was processed through biological processes (aerobic and anaerobic digestion). For the current case study, after the autoclaving process, the mixed waste is passed through sorting equipment that separates OFs from other sub-products (**Figure 1.8**). In this study, the OF produced through autoclaving was processed using aerobic and anaerobic digestion technologies. For this purpose, data from full-scale facilities that treat the OFMSW located in Barcelona, Catalonia, were adapted to the current case study. The full-scale facilities' technologies that were studied included composting in confined windrow (CCW), composting in tunnels (CT) and composting in turned windrow (TW) as well as anaerobic digestion for thermophilic and mesophilic ranges (ADC-T and ADC-M). Data on energy and emissions for these full-scale facilities were taken from previous studies carried out by Group d'Investigació en Compostatge at the Universidad Autónoma de Barcelona.

1.9.4 Technologies for aerobic treatments (composting)

The most common composting technologies at industrial or full-scale to treat the solid waste are: passive piles, turned windrows, aerated static piles and in-vessel technologies. These technologies differ mainly in the cost of the technology, space necessities, time required to obtain the compost and process emissions. A brief description of the biological technologies currently found at European level is shown in Figure 1.11. Consequently, the biological technologies to treat OF considered in the case study are the most common currently used in the area of Barcelona. Those technologies go from the complex ones (composting in vessel) with a high economical investment up to the simplest ones (passive piles) which are characterized by a low investment.

Complexity	Technology	Picture	Main features	Investment
High	In-vessel / tunnel composting		✓Process is carried out in fully enclosed structure ✓Aeration, moisture and temperature are automatically controled ✓Container composting system or tunnel composting systems ✓Composting duration between 2 to 4 months ✓High-cost technology	High
	Aeraged static piles		✓Forced aerated windrows ✓Forcing or pulling air through a trapezoidal compost pile ✓Average aerated piles are 2 to 2.6 mt in height ✓Composting duration between 3 to 6 months ✓Medium-cost technology	
	Turned windrow composting		✓Elongated piles are turned frecuently to maintain aerobic conditions ✓Material is frecuently turnned by mechanical methods ✓Composting duration 3 to 12 months ✓The windrow height is between 1.5 to 1.8 mt ✓The weigth of the windrows is twice of its height	
Low	Passive piles		✓Piles remain static without alteration ✓Piles have a delta or trapezoidal cross section ✓Ideal height of windrows 1.5 to 2 mt with a widht of 4.3 to 4.8 mt ✓Low investment technology ✓Composting time > 1 year	Low

Figure 1.11 Characteristics of full-scale aerobic technologies

An overview of the main features and operation conditions of the real full-scale facilities used in the case study are presented in Table 1.3. These characteristics and operation conditions were by the time the study was carried out. The data for energy and resources consumption was taken directly from facility managers. Data of energy and resources was adapted to OF stream. While compost production and biogas yield were determined at laboratory experimental scale by GICOM. A full description of data for energy and resources consumptions as well as the emissions of the composting process and other related data are presented in chapter 2.

Table 1.3 Main characteristics of the full-scale facilities

Facility	CT[1]	CCW[2]	TW[3]	ADC[4]
Main biological process	Composting	Composting	Composting	Anaerobic digestion plus composting
Decomposition phase	In-vessel composting	Aereated confined windrow composting	Turnned windrow composting	Anaerobic digestion (solid phase) + in vessel composting
Curing phase	Aereated windrow	Turned windrow	Turned windrow	Turned windrow
Type of facility	Closed except maturantion and storage zones	Completely open	Completely open	Completely closed
Exhaust gas treatment	Wet scrubber + biofilter	Not present	Not present	Wet scrubber + biofilters
Waste treated (tonnes/year)	7,435	91	3,000	17,715

[*]Data for the case study were taken from these full-scale facilities
[1]CT: Composting in tunnels
[2]CCW: Composting in confined windrows
[3]TW: Turned windrow composting
[4]ADC: Anaerobic digestion + composting

1.9.5 Home composting

The home compost represents an alternative for the sustainable use of the organic matter from MSW. Additionally to the aerobic technologies (full-scale composting facilities) explained in section 1.9.4, home composting is another option for the bio-waste treatment. Like full-scale composting facilities, home composting has some advantages such as the production of a nutrient-rich humus-like material for use on soil as a substitute for fertilizer and/or for peat in growth media (Andersen et al., 2010). One main advantage of home composting regarding large scale compositing facilities is that no external energy is required for transport or processing (Fisher, 2006).

The two home composts used for the case studies aforementioned were experimentally produced by GICOM. The first home compost quality with high gaseous emission during the composting process was applied to horticultural crops. A second kind of home compost with low emissions was produced and compared with home compost with high emissions. Results of this comparison are presented as case study broadly explained in chapter 4. The aim of this comparison was to study the consequences of the compost emissions in the environmental performance of horticultural crops. Figure 1.12 shows a composter used for the compost production. More details of experimental methodologies use for the production of these home composts, gaseous emissions measurements and resources consumption are explained in related chapter where they were used (i.e. chapters 3,4 and 5).

Figure 1.12 Composter used for the experimental composting production

1.9.6 Anaerobic digestion

Since the early 2000 the number of thermophilic anaerobic digestion plants treating organic wastes has increased significantly in Europe (Martín-Gonzalez et al., 2001). Anaerobic digestion is another biological process that has been used for over 100 years to stabilize materials such as wastewater sludge, MSW and other industrial refuses (Ferrer et al., 2008; Burke, 2001**).** Anaerobic digestion is a biological process in which the biodegradable matter is degraded or decomposed in the absence of oxygen using specific microorganisms that produces biogases than can be used for energy production (Adani et al., 2001; Chynoweth et al., 2001). As shown in Table

1.4 and Figure 1.13, in brief the anaerobic digestion consists of four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

Table 1.4 Anaerobic digestion process stages

Stage	Description	Reference
Hydrolysis	In this stage, the undissolved amd complex organic molecules are fragmented into simpler compounds (amino acids, fatty acids, alcohols and CO_2)	Ponsá et al., 2008); Pavlostathis and Giraldo-Gómez, 1991)
Acidogenesis	This stage involves the transformation of hidroglyzed compounds into volatile fatty acids (aminly acetate, propionate and butyrate), alcohols and other products including ammonia, hidrgoen and carbon dioxide. The bacteria in this stage are facultative and proteolytic bacteria (Clostridium, Bacillus, Pseudonomas and Micrococcus)	Madigan et al., 1998
Acetogenesis	In this stages alcohols, fatty acids, and aromatic compounds are degraded to produce acetic acid, carbon dioxide and hydrogen-substrates that will be used by methanogenic bacteria in the final abaerobic digestion stage	Archer, 19983
Methanogenesis	During this stage, anaerobic methanogenic microorganisms transform organic products in the earlies stages (acetate, carbon dioxide, methanol, hydrogen and some methylamine) into methane	Madigan et al.,1998

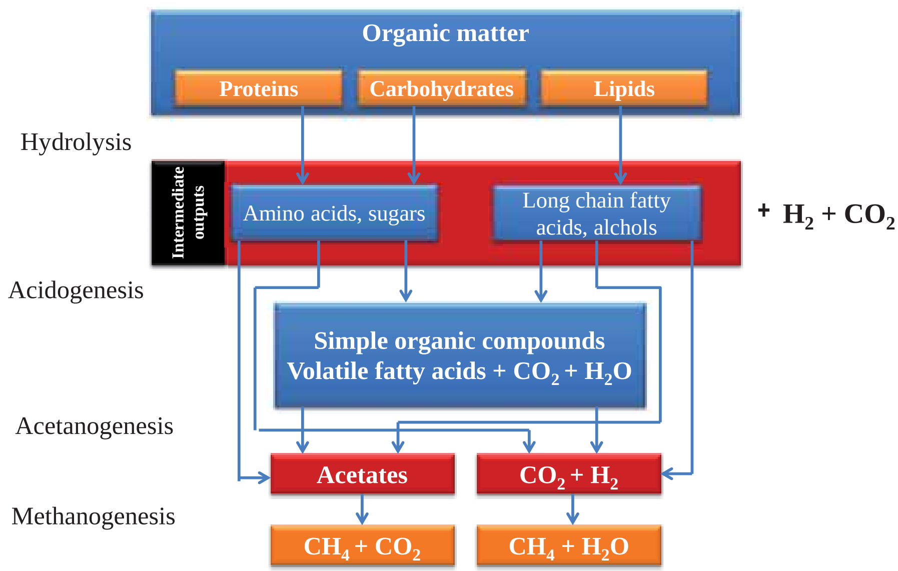


Figure 1.13 Anaerobic digestion process stages
Adapted from Colón (2012)

The full-scale anaerobic digestion process considered in this dissertation (chapter 2) as another technology to treat OF is based on DRANCO (DRy ANaerobic Composting, OWS, Belgium) technology (Figure 1.14). It is a dry process at thermophilic temperatures (50-55 °C). The digester mixing is provided by the recirculation of the digested material (digestate). The retention time is 22 days and the digester capacity is 1700 m^3.

Figure 1.14 Anaerobic digestor (DRANCO technology)
Source: Juniper Consultancy Service (2005)

1.10 Reference technologies (incineration and landfill)

In order to compare the environmental performance of the studied systems (autoclaving + sorting + biological treatment) two well-known technologies (i.e. incineration and landfill) were considered as reference. These technologies are used in EU and represent the two main management options for waste. Incineration and landfill are the only treatment methods that can handle mixed household waste (Erickson, 2005). In this dissertation, incineration and landfill were assumed as final fate of the entire unsorted MSW stream. Incineration and landfill technologies were just used as reference systems for comparison purposes with the systems (autoclaving + sorting + biological treatments) which considered the biological treatment of the OF. Both technologies were modeled according to the ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories, 2010). The processes of the ecoinvent database for those technologies were modified and adapted for the current case study. The modifications to data mainly were made in energy recovery in which efficiencies for electricity and heat conversion were changed for both alternative treatments (incineration and landfill).

1.10.1 Incineration

Incineration is the controlled process of combusting MSW in an oxygen rich environment. The heat generated from the process can be used to generate power and/or to heat water for the purpose of district heating (Hanandeh et al., 2010). Within the incineration process substances contained in waste are oxidized. Burnable waste is in this way transformed into gaseous substances, while inert waste fractions remain as a solid residue in form of incineration slag and ashes. Waste incineration has a number of environmental benefits: reduction of waste volume for final disposal, the recovery of energy from waste and reduction of emissions from final waste disposal. On other hand, several disadvantages are attributable to waste incineration. Incinerators are identified as mayor urban sources of heavy metals, dust, acid gases and $NO_{x,}$ and products of incomplete combustion, such as dioxins and other toxic organic micro-pollutants. Concern over public health impacts of these emissions led to the introduction of the 1989 incineration directives, the first community wide legislation to set minimum environmental standard for waste incineration.

The most common thermal treatment process for MSW is incineration by mass-burn technology. Fluidized bed incineration and refuse derived fuel systems are less common in MSW treatment. Fluidized bed systems and multi-hearth furnaces are also widely used for sewage sludge incineration, while major furnace types for hazardous wastes incineration are grateless systems such as a rotary kiln furnace, fluidized bed systems, combustion chamber and multi-hearth furnace (Sabbas et al., 2003).

The incineration process data used in the current study was taken from ecoinvent database v.2.2 (Swiss Centre for Life Cycle Inventories, 2010) which refers to the technology mix encountered in Switzerland but well applicable to modern practices for incineration applicable in Europe. The incineration technology was based on grate furnace incinerator with a wet flue gas cleaning system. The technology includes a waste-specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning, short-term emissions to river water and long-term emissions to ground water. In Annex 1.1 there is an overview of the incineration process, a full explanation of the incineration process can be seen in the reports of the ecoinvent database v.2.2.

1.10.2 Landfill

Landfilling is the most common practice of MSW management (Hanandeh, 2010). A landfill is a facility in which solid wastes are disposed in a manner which limits theirs impact on the environment. Landfills consists of a complex system of interrelated components and sub-systems that act together to break down and stabilize disposed waste over time (FCM, 2004). Modern landfills are highly engineered facilities that are specifically designed to stabilize the waste and minimize its hazards to the public (Rigamonti et al., 2010). Several countries around the world have issued directives to minimize the amount of waste sent to landfills. Nevertheless, it is impossible to eliminate the need of landfills because some materials are thermodynamically impossible to recycle (Dias and Warith, 2006).

In the case of landfilling of untreated waste, when MSW is landfilled directly, anaerobic biological degradation produces landfill gas and leachate. Over 90% of the converted organic carbon is release as CO_2 and CH_4 (Obersteiner et al., 2007), the remainder is release in the leachate (Binner, 2003).

In practice, several definitions of landfill can found in literature. Damgaard et al., 2011 in a LCA of landfill technologies define three archetypes: 1. the dump landfill; 2. the simple conventional landfill and 3.the energy-recovery conventional landfill. The *dump archetype* could be *open dump* or *covered dump.* The open dump represents the theoretical worst case of a landfill with no measures to control leachate or gas. The covered one is a dump that is supplied with a low quality soil cover and vegetation after filling section. This results in a reduced leachate generation since the soil cover can hold some water for evapotranspiration from the wet period to the dry period of the year. The *simple conventional landfill* has introduced a bottom liner, leachate collection and leachate treatment. The top cover is of higher quality than for the covered dump and therefore it is able to provide a superior oxidation of gas constituents. The gas may migrate through the top cover or be collected and managed by biofilters or by flares. The *energy-recovery conventional landfill* represents the most advanced conventional landfill, where the gas is collected and used for energy production. The design is similar to the simple conventional landfill, but the collected gas is here used for energy production**.** Figure 1.15 shows an engineered landfill gas with landfill gas (LFG) collection and energy recovery.

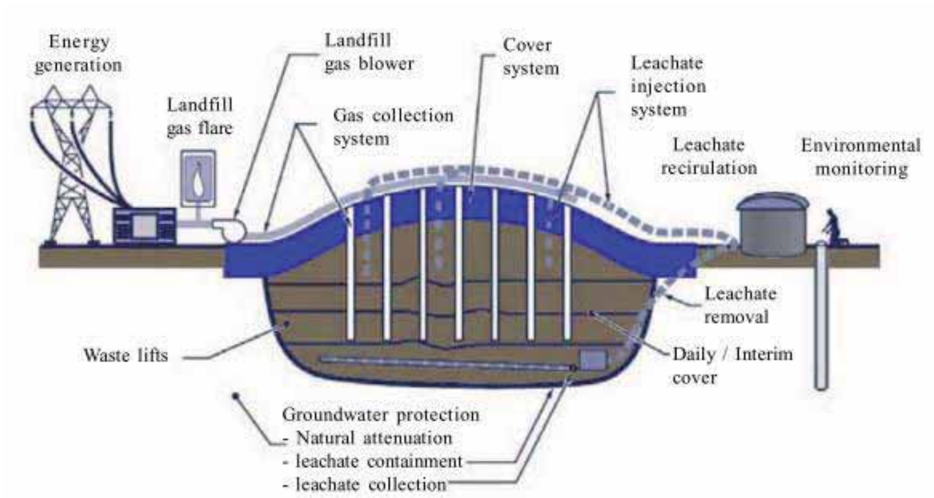


Figure 1.15 Conventional landfill with energy-recovery system
Source: FMC, 2004

Landfill was the second options considered as reference technology for the final fate of the unsorted MSW. Landfill as well as incineration, was considered as reference systems to compare the environmental results of the systems comprised of autoclaving, sorting and the biological treatment (i.e. aerobic and anaerobic digestion) in which OF resulting from the autoclaving unsorted MSW was processed.

1.10.2.1 Technical characteristics of the landfill technology

In the current case study, landfill data was taken and adapted from the ecoinvent database v 2.2 (Swiss Centre for life Cycle Inventory, 2010). According to ecoinvent database v2.2, landfill includes the processes of: waste-specific short-term emissions to air via landfill gas incineration and landfill leachate. Landfill includes base seal, leachate collection system and treatment of leachate in municipal wastewater treatment plant, and landfill gas collection system for energy recovery. Recultivation and monitoring for 150 years after closure also was considered. Ecoinvent database contains a full description of the landfill technology used in the dissertation.

1.11 Agricultural considerations

Agriculture currently accounts for 10-12% of the total global anthropogenic greenhouse gas (GHG) emissions generated worldwide (Smith, 2007) which is very close to the 13.5% considered in the IPCC (2007).

Traditional farming practices have been declining in the last years to spread intensive agriculture. The loss of traditional farming practices to spread intensive agriculture has led to many environmental problems, of which the European Environmental Agency (EEA, 2012) highlights soil erosion, water pollution, over-exploitation of water resources, loss of biodiversity, pesticide-born damage and risk for human health.

Furthermore, agricultural intensification involves increased fertilization; in most cases there is a large response to nitrogen fertilization measured as crop yield (Martínez, 2012). As the cost of fertilizers is often small compared of the cost of lost yield, farmers prefer over-fertilization of crops with nitrogen rather than risking under-fertilization and consequent loss of revenue (Del amor, 2007). However, excess nitrogen may result in lodging, greater weed competition and pest attacks, with substantial losses of production.

1.12 Shortage of organic matter in soil: a relevant issue

There is an increasing concern about soil interrelated environmental problems such as soil degradation, desertification, erosion, and loss of fertility (European Commission, 2006c). These problems are partially consequences of the decline in organic matter content in soils. Van-Camp et al. 2004 considers that a level of 2% of soil organic carbon (SOC) is commonly considered desirable for maintaining good soil structure for organic activities. According to European Soil Bureau (2012) it is estimated that 45% of European soils have low (<2%) soil organic matter content, principally in southern Europe, i.e. in the Mediterranean regions, but also in others areas of UK, France, Sweden and Germany (European Commission, 2006c)

In Spain, the situation is more critical due to it is estimated that 50% of agricultural land and pastures have less than 1.7% of organic matter in soil. Therefore, there is a real risk of desertification by 50% of agricultural land and pastures in Spain (European Commission, 2006).

The European Commission adopted the Soil Thematic Strategy (European Commission, 2006a) with the objective to protect soils across the EU. The draft Soil Framework Directive (European Commission, 2006b) imposes the obligation for member states to design programmes of measures to prevent organic matter decline (Martínez, 2012).

1.13 Sustainable agriculture

In simplest terms, sustainable agriculture is the production of food, fiber, or other plants or animal products using farming techniques that protect the environment, public health, human communities, and animal welfare. This form of agriculture enables us to produce healthful food without compromising future generations' ability to do the same. Organic farming can be defined as a method of production which places the highest emphasis on environmental protection and, with regard to livestock production, on animal welfare considerations. Organic farming is considered by EU as a main driver to promote sustainability in agriculture. It avoids or largely reduces the use of synthetic chemical inputs such as fertilizers, pesticides, additives and medicinal products. The production of genetically modified organisms (GMOs) and their use in animal feed are forbidden (Eurostat, 2014c). Farming is only considered to be organic at the EU level if it complies with Council Regulation (EC) No 834/2007 (EU, 2014) and Commission Regulation (EC) No 889-2008, which has set up a comprehensive framework for the organic production of crops and livestock and for the labelling, processing and marketing of organic products, while also governing imports of organic products into the EU. The detailed rules for the implementation of this Regulation are laid down in Commission Regulation (EC) No 889/2008. According with this regulation, organic farming should primarily rely on renewable resources within locally organised agricultural systems. In order to minimise the use of non-renewable resources, wastes and by-products of plant and animal origin should be recycled to return nutrients to the land (EU, 2014).

In the last years, EU countries have been changing from conventional agriculture to organic, although this trend has been very slow for the last decade. The Figure 1.16

shows that area under organic farming for EU-27 countries was of 5.2%, 5.5% and 5.8% for 2010, 2011 and 2012, respectively. Likewise, Austria, Estonia, Check Republic and Sweden are the countries having the largest land cover as organic farming (above of 12% of total cultivated areas) in EU.

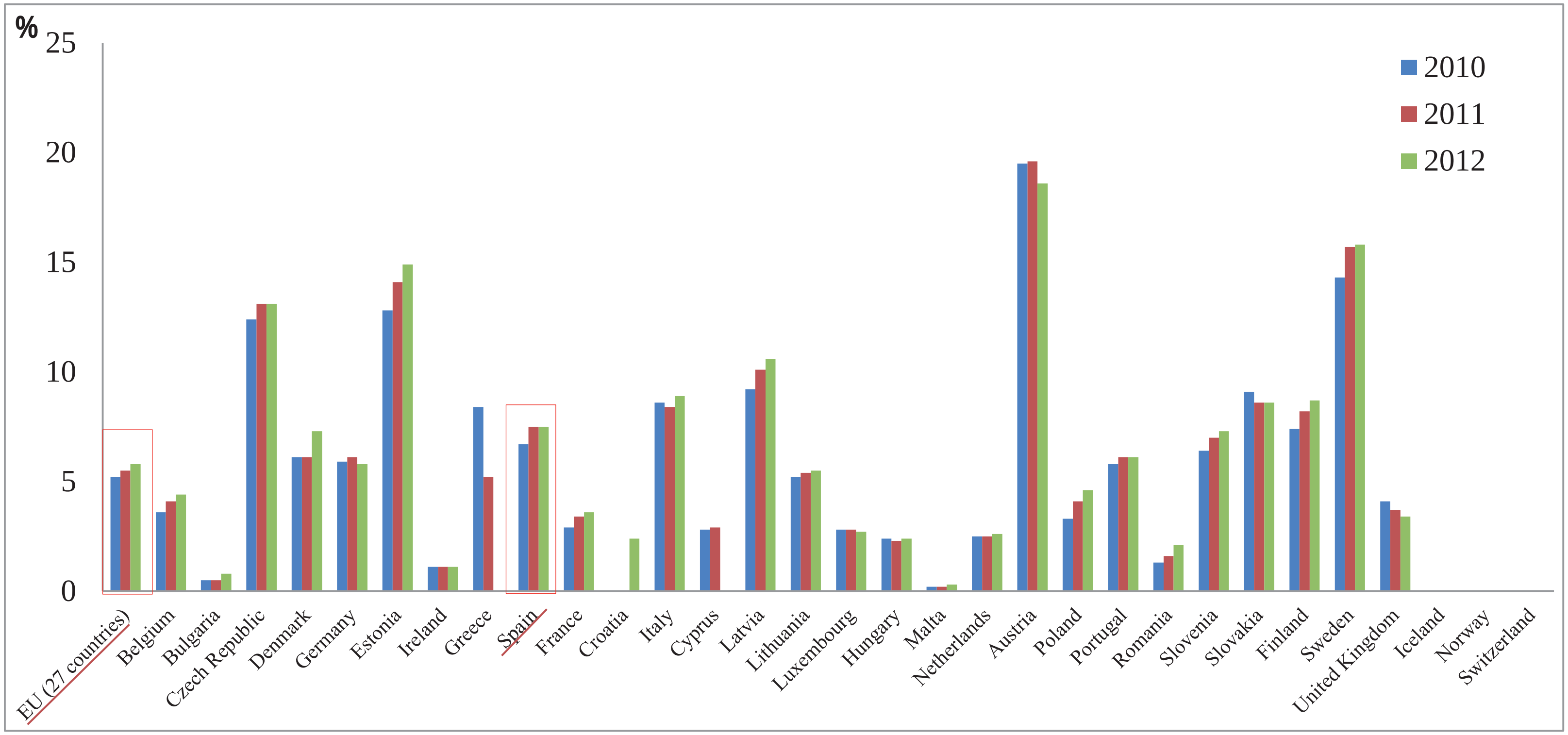


Figure 1.16 Percentage of area regarding total cultivated area under organic farming in EU-27
Period: 2010-2012
Source: Eurostat 2014

1.14 Sustainable use of organic waste in agriculture

The increase in waste generation due to a massive growth of industrial activities, population and urban planning, is becoming a global problem in developed countries due the rapid collapse of landfills and the high impacts related to biowaste dumping (Martínez-Blanco, 2012) (Figure 1.17).

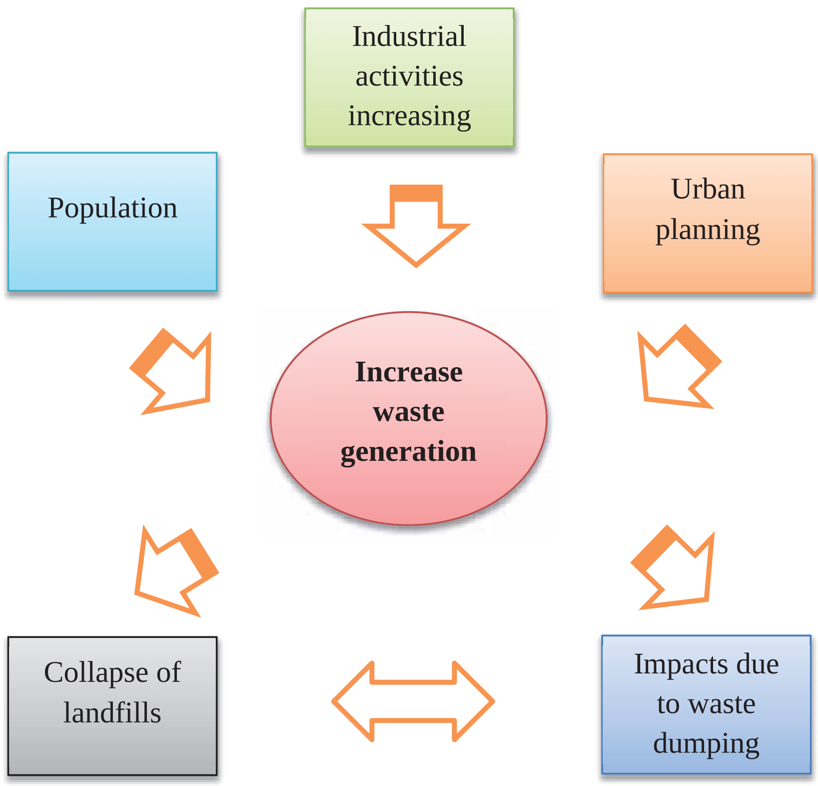


Figure 1.17 Causes and effects of waste generation

Furthermore of the mentioned problems related to waste generation (i.e. collapse of landfills and impacts), the shortage of organic matter in soils and the prices increasing of fertilizers[1] make compost a suitable option for the treatment of organic fraction from municipal solid waste.

[1] The average prices of mineral fertilizers increased about 91% from 2005 to 2011 (Martínez-Blanco, 2012).

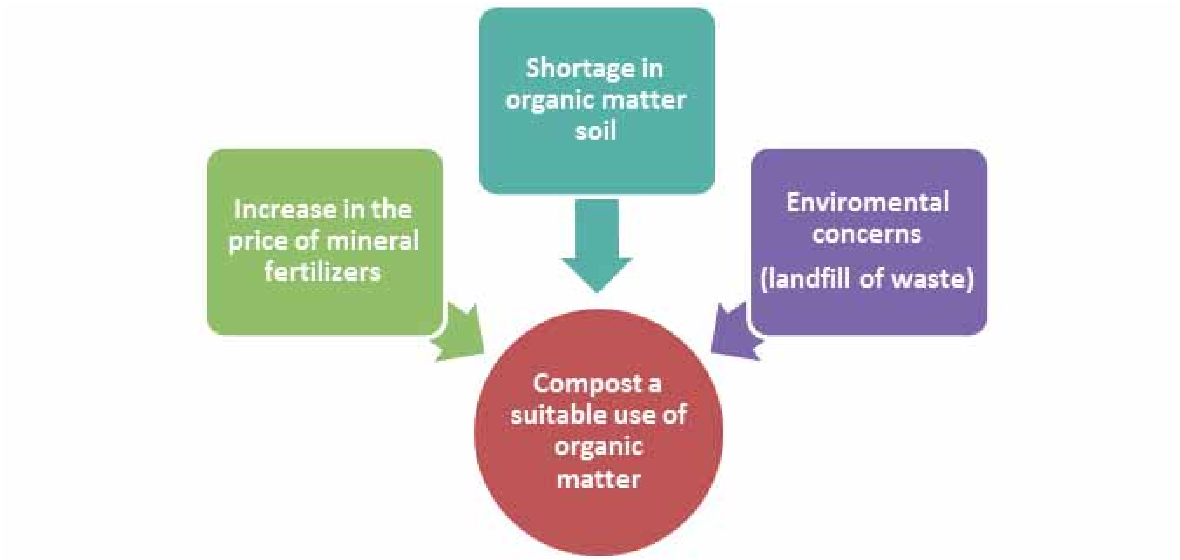


Figure 1.18 Compost a suitable alternative for the organic waste treatment

1.15 Objectives of the thesis

The main two objectives of this dissertation are the environmental assessment of a new technology for the treatment of unsorted municipal solid waste, and the environmental assessment of the organic matter cycle to produce compost which was applied in horticultural crops. In order to achieve those objectives, the following specific aims were addressed:

1. To assess the environmental performance of new technology for the treatment of the organic fiber resulting from unsorted municipal solid waste.

2. To assess the environmental and agronomical performance of three fertilization treatments (organic and mineral) applied in horticultural open field crops.

3. To compare the environmental performance of two home composts with low and high gaseous emissions of the composting process applied in horticultural crops.

4. To determine the environmental assessment of a crop sequence of tomato and cauliflower and to close an entire horticultural cycle.

In Table 1.5 are shown the main actions developed to achieve the general and specific objectives.

Table 1.5 Actions to achieve the general and specific objectives

Objectives	Actions
1. To assess the environmental performance of new technology for the treatment of the organic fiber resulting from unsorted municipal solid waste.	1.1 To study operational conditions of the new autoclaving technology for the pretreatment of unsorted municipal solid waste. 1.2 To quantify the energy requirement and resources consumption of autoclaving process. 1.3 To prepare a full mass balance of material and energy from the entire system comprised of autoclaving, sorting and biological treatment. 1.4 To evaluate through biological treatments (i.e. aerobic and anaerobic) the organic fiber resulting from the autoclaving unsorted municipal solid waste. 1.5 To compare using LCA methodology the environmental performance of the systems (autoclaving + sorting + biological treatment) with two of the most traditional waste management options: landfill and incineration. 1.6 To assess through a sensitivity analysis the variables the most affected the environmental performance of the systems (i.e. the lower heating value of waste and conversion efficiencies for energy (electricity and heat) recovery from the waste combustion process.
2. To assess the environmental and agronomical performance of three fertilization treatments (organic and mineral) applied in horticultural open field crops:	2.1 To study the entire organic matter cycle since collection, transportation, compost production and its application in horticultural crops, and also the cycle of mineral fertilizers. 2.2 To quantity the yield and quality parameters (weight and fruit diameters) of crops fertilized with organic (industrial and home compost) and mineral fertilizers. 2.3 To determine the bioactive substance content in cauliflower crops fertilized with organic and mineral fertilizers 2.4 To determine the best fertilization option in agronomical and environmental terms. 2.5 To demonstrate the suitability of compost as mineral fertilizer substitute in crop.
3. To compare the environmental performance of two home composts with low and high	3.1 To determine the consequences of different values of the gaseous emissions of the composting process in the environmental performance of agricultural systems.

Objectives	Actions
gaseous emissions of the composting process applied in horticultural crops.	3.2 To highlight the relevance of the management compost production stage in the environmental assessment of horticultural crops. 3.3 To identify the critical variables of the composting process that most affect the gaseous emissions emitted during the compost production.
4. To determine the environmental assessment of a crop sequence of tomato and cauliflower and to close an entire horticultural cycle.	4.1 To close organic matter cycle in a crop sequence of cauliflower and tomato through the collection, transportation production, waste management and application of fertilizers in crops. 4.2 To compare the environmental assessment of individual crops (cauliflower and tomato) with the entire crop sequence (sum of impacts of both crops). 4.3 To assess the impact in horticultural systems of two methodologies to allocate organic fertilizers (compost) to crops. 4.4 To calculate a nitrogen balance taking into consideration the different nitrogen inputs and the nitrogen uptake by crops.

1.16 Methodology

This section presents the main methodology aspects included in the dissertation. First, an overview of the general methodology applied is described. As second part, it was included the theoretical elements that comprise the Life Cycle Assessment methodology (LCA). Then, an overview of the main analytical methods used to obtained data used in the case study is presented. The methodology was structured as follows:

- General methodology
- Environmental and sustainability assessment tools
- Life cycle assessment methodology and related subjects
- Experimental methodology for data collection

1.17 General methodology

As shown in Figure 1.19, the general methodology applied for the case studies was based on the LCA methodology. The thesis was structured in four main case studies following the LCA methodology in accordance with the ISO 14040 and 14044. For the first three case studies (chapter 2, 3 and 4) the CML 2001 (Centre of Environmental Science of Leiden University) methodology was used for the environmental impacts calculations and the fourth was made with ReCipe 2008. ReCipe emerged as new methodology, in the year of 2000 after a SETAC meeting in order to harmonize the CML midpoint and the Pré endpoint approach into a single and consistent methodology. The software SimaPro v 7.3.2 and 7.3.3 developed by Pré Consultants was used for the calculation of the environmental impacts and the data were processed with the Excel spreadsheet for the graphics modules and for the calculations. As presented in Figure 1.19 the LCA's (i.e. case studies) were developed from the period of 2011 to 2014 which corresponds to the thesis duration period.

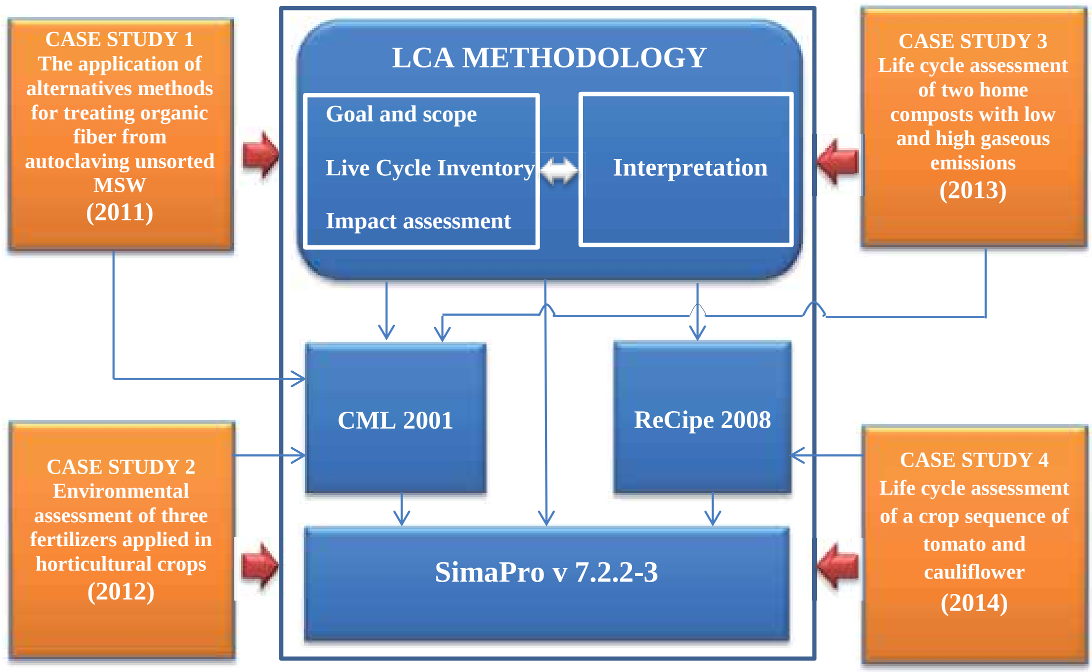


Figure 1.19 General methodology applied to the case studies

*Note: Case studies correspond to thesis chapters presented as articles published or in process to be published in scientific journals.

Furthermore apart from the LCA used as core for the environmental assessment, several analytical methods were used for data collection for the inventories to do the environmental assessments.

1.18 Life cycle assessment methodology

LCA is a tool for evaluating environmental effects of a product, process, or activity throughout its life cycle or lifetime, which is known as a ‘from cradle to grave’ analysis. LCA is a robust-scientific tool nowadays broadly used for several purposes such as comparison of alternative products, processes or services; comparison of alternative life cycles for a certain product or service and identification of parts of the life cycle where the greatest improvements can be made.

1.18.1 Definitions

LCA is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. LCA provides an adequate instrument for environmental decision support. The International Organisation for Standardisation (ISO), a world-wide federation of national standards bodies, has standardised this framework within the series ISO 14040 and 14044 on LCA. LCA takes into account a products full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste.

The two most known definitions found in literature are from SETAC and the ISO 14044. Therefore, according to the Society for Environmental Toxicology and Chemistry (SETAC, 1993): "Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal." According to ISO 14044, **"**LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use, end of life treatment, and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided".

1.18.2 Phases of life cycle assessment

As shown in Figure 1.20, ISO 14040-14044 states the four main phases in an LCA study:

a. The goal and scope definition phase

b. The inventory analysis phase

c. The impact assessment phase

d. The interpretation phase

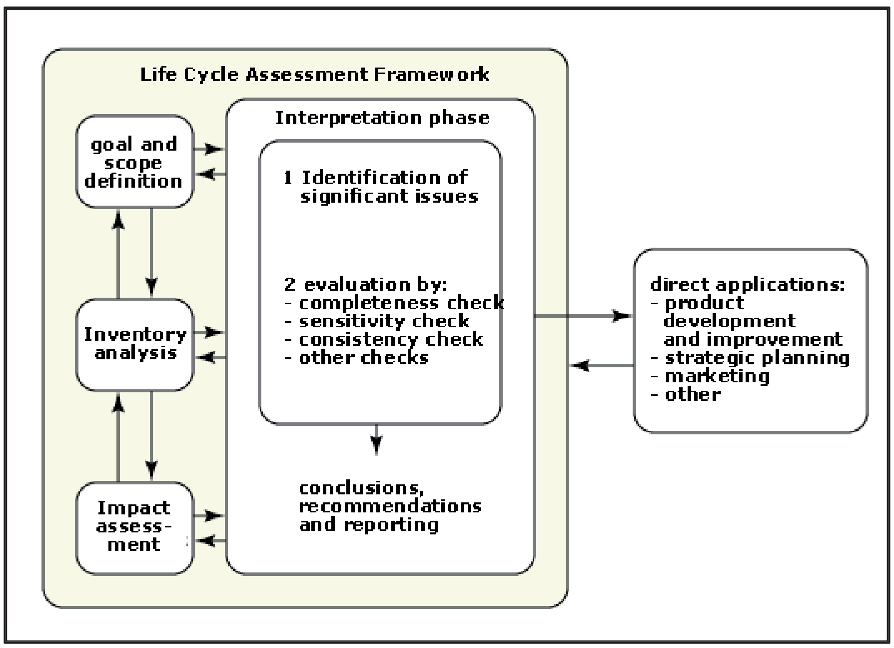


Figure 1.20 Life cycle assessment phases
Source: ISO 14044

1.18.3 Goal and scope definition

Goal definition and scoping is perhaps the most important component of an LCA because the study is carried out according to the statements made in this phase, which defines the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions. Furthermore, the goal of an LCA states the intended application, the reasons, the intended audience – i.e. to whom the results of the study are intended to be communicated -, and whether the results are intended to be used in comparative assertions (ISO, 2006).

The scope of an LCA should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. The scope includes (a) the description of the system under study, (b) its functions, (c) the functional units, (d) the system boundaries, (e) the allocation procedures rules, (f) the methodology of impact assessment and the selected impact categories, (g) data requirements, (h) assumptions established and limitations, and other requirements (ISO, 2006).

The system boundary of a system is often illustrated by a general input and output flow diagram. All operations that contribute to the life cycle of the product, process, or activity fall within the system boundaries. The purpose of FU is to provide a reference unit to which the inventory data are normalized. The definition of FU depends on the environmental impact category and aims of the investigation. The functional unit is often based on the mass of the product under study.

1.18.4 Life cycle inventory analysis (LCI)

In this phase all emissions released into the environment and resources extracted from the environment along the whole life cycle of a product are grouped in an inventory. Energy and raw materials consumed, emissions to air, water, soil and solid waste produced by the system under study are split up into several subsystems and unit process, and the data obtained is grouped in different categories in a LCI table. The main steps identified in LCIA phase are data collection, the identification of relevant and non-relevant elements, mass and energy balance, and allocation of the system burdens. The data should include all inputs and outputs from the processes. Inputs are energy (renewable and non-renewable), water, raw materials, etc. Outputs are the products and co-products, and emission (CO_2, CH_4, SO_2, NO_x and CO) to air, water and soil (total suspended solids: TSS, biological oxygen demand: BOD, chemical oxygen demand: COD and chlorinated organic compounds: AOXs) and solid waste generation (municipal solid waste: MSW and landfills).

Data sources for inventory are indicated in each chapter. Data were from several research groups: Group d'Investigació en Compostatge (GICOM), Sostenipra

Research Group at the Universidad Autónoma de Barcelona; Institut of Research in Agrifood (IRTA) and external laboratories.

1.18.5 Impact assessment

The life cycle impact assessment (LCIA) aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO, 2006). The LCIA phase shall include the following mandatory elements: selection of impact categories, category indicators and characterization models; assignment of LCI results to the selected impact categories (classification) and calculation of category indicator results (characterization). The classification is the process of grouping the different elements (e.g. energy, water and materials consumed) of an LCI into a common impact groups (e.g. CO_2, N_2O, SO_2, etc.). In waste management systems, for example, the gaseous emissions of the composting process are classified according the main pollutant element (i.e. CH_4, N_2O, NH_3 and VOc's). Now, characterization is the process of assignment of the magnitude of potential impacts of each inventory flow into its corresponding environmental impact (e.g. modelling the potential impacts of carbon dioxide and methane in global warming potential). The characterization provides a way to directly compare the LCI results within each category. In our case studies, biological treatments can be compared by its contribution to global warming potential category due to methane and nitrous oxides emissions from its production process. Figure 1.21 shows the different steps for the impact assessment for the general case and for an example based on biological treatment.

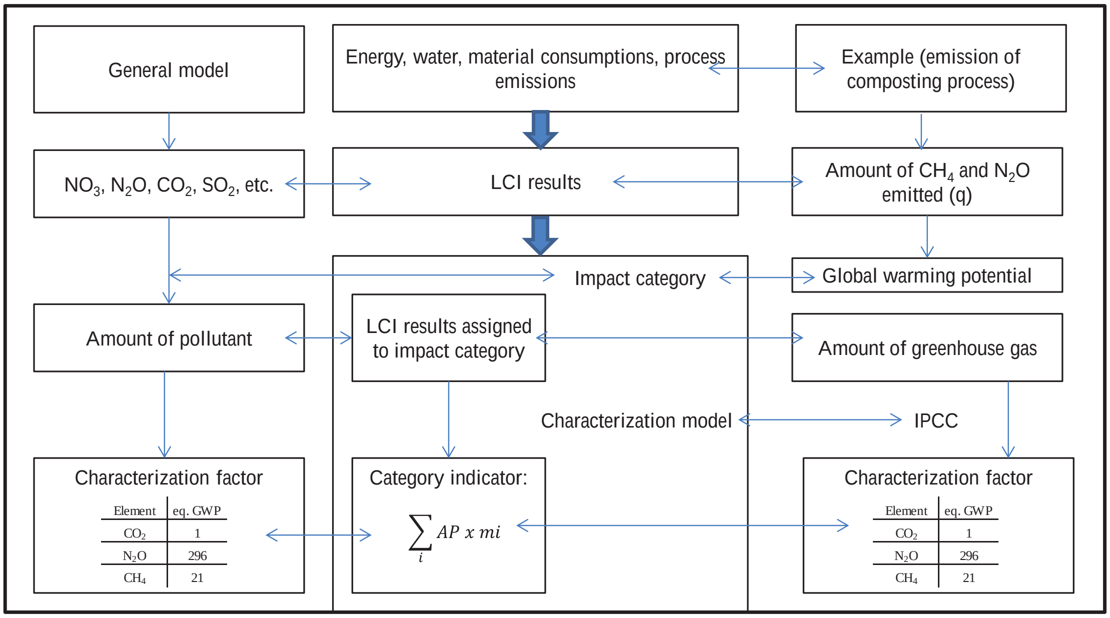


Figure 1.21 Phases of LCIA with a biological treatment example

1.18.6 Interpretation

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

This phase may also involve the reviewing and revising of the goal and scope, as well as the nature and quality of the data collected. As depicted in Figure 1.22 and in accordance with ISO 14044, the life cycle interpretation phase of an LCA or LCI study comprises several elements:

- Identification of the significant issues based on the results of the LCI and LCIA phases of LCA.
- Evaluation that considers completeness, sensitivity and consistency checks.
- Conclusions, limitations, and recommendations

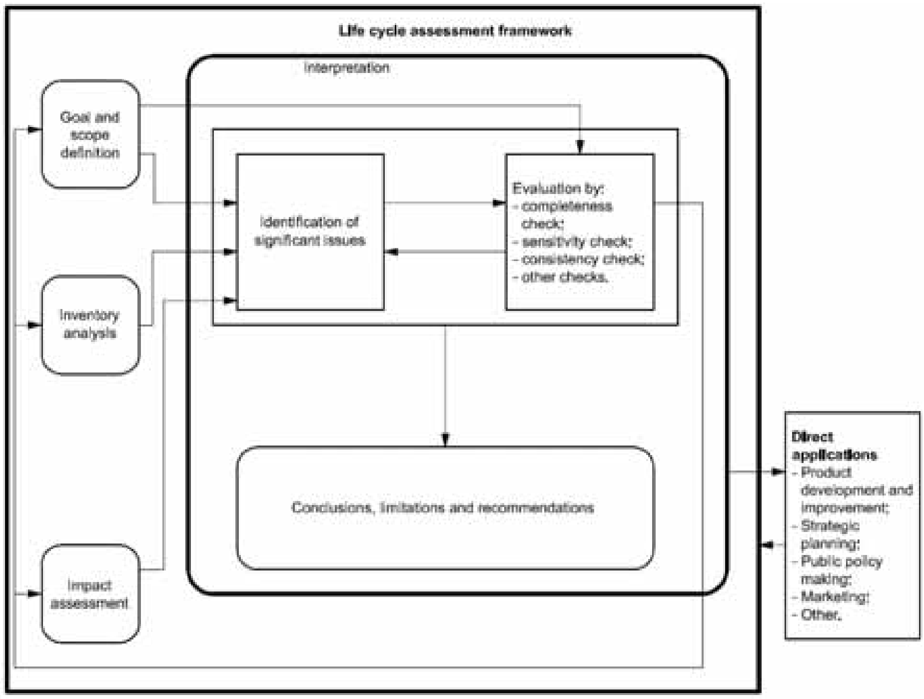


Figure 1.22 Interpretation phases and its interrelation with the other phases of LCIA
Source: ISO 14044

1.19 Selection of methods and impact categories

In the current dissertation, the impact categories selected for the characterization factors applied to each impact category are those proposed by the CML 2001 methodology, which was based on CML Leiden 2000 developed by the Centre of Environmental Science of Leiden University (Guinée et al. 2001) and ReCipe 2008 methodology. CML 2001 was used for the three first case studies (chapters 2, 3 and 4) and ReCipe 2008 was used for the fourth case study. In practice, there are minimum differences between CML and ReCipe for midpoint categories, however, in order to have an updated methodology for the impact assessment and per journal reviewer recommendations it was decided to develop the last research (i.e. case study 4) with ReCipe 2008 instead of CML 2001. The Cumulative Energy Demand – CED (Jungbluth and Frischknecht, 2004) as energy flow indicator was also calculated in the environmental assessment for the four case studies. Table 1.6 presents the categories selected for the environmental assessment for the two mentioned methodologies.

Table 1.6 Impact categories considered for CML 2001 and ReCipe methodologies

	Acronym	Category	Description	Geographic Scope	Units
CML 2001	ADP	Abiotic Depletion Potential	It is concerned with the protection of human welfare, human health and ecosystem health. It is related to the extraction of minerals and fossils fuels due to imputs into the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels based on concentration reserves an the rate of deaccumulation.	Global scale	kg Sb eq.
CML 2001	AP	Acidification Potential	Acydifying substances cause a wide range range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). AP factor emissions into the aire are calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances.	Local and continental scale	kg SO_2 eq.
CML 2001	EP	Eutrophication Potential	Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by the emission of nutrients into the air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (1992).	Local and continental scale	kg PO_4 eq.
CML 2001	GWP	Global Warming Potential	It can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100).	Global scale	kg CO_2 eq.
CML 2001	OLDP	Ozone Layer Depletion Potential	Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterization model is developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gasses.	Global scale	kg CF eq.
CML 2001	POP	Photochemical Oxidation Potential	Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and cosystems and which also may damage crops. This problem is also indicated with "summer smog". Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate).	Local and continental scale	kg C_2H_4 eq.
ReCipe 2008	CC	Climate Change	It can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100).	Global scale	kg CO2 eq.
ReCipe 2008	POF	Photochemical Oxidation Formation	The characterization factor of photochemical oxidant formation is defined as the marginal change in the 24h-average European concentration of ozone (dCO3 in kg·m–3) due to a marginal change in emission of substance x (dMx in kg·year–1).	Local and continental scale	kg NMVOC
ReCipe 2008	TA	Terrestrial Acidification	Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates, cause a change in acidity in the soil. For almost all plant species there is a clearly defined optimum of acidity. A serious deviation from this optimum is harmful for that specific kind of species and is referred to as acidification. As a result, changes in levels of acidity will cause shifts in species occurrence (Goedkoop and Spriensma, 1999, Hayashi et al. 2004). Major acidifying emissions are NOx, NH3, and SO2 (Udo de Haes et al., 2002; Hayashi et al., 2004).	Local and continental scale	kg SO_2 eq.
ReCipe 2008	FEW	Freshwater Eutrophication	Aquatic eutrophication can be defined as nutrient enrichment of the aquatic environment. Eutrophication in inland waters as a result of human activities is one of the major factors that determine its ecological quality. On the European continent it generally ranks higher in severity of water pollution than the emission of toxic substances. The long-range character of nutrient enrichment, either through air or rivers, implies that both inland and marine waters are subject to this form of water pollution, although due to different sources and substances and with varying impacts.	Local and continental scale	kg P eq.
ReCipe 2008	ME	Marine Eutrophication			kg N eq.
ReCipe 2008	FD	Fossil Depletion	The term fossil fuel refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials (like methane), to liquid petrol, to non-volatile materials (like coal).	Global scale	MJ eq.
CED	CED	Cumulative Energy Demand	It aims to investigate the energy use throughout the life cycle of a good or a service. This includes the direct as well as the indirect uses. Characterization factors were given for the energy resources divided in: non renewable, fossil and nuclear, renewable, biomass, wind, solar, geothermal and water.	Local scale	MJ eq.

Source CML 2001 (Goedkoop et al., 2009) and ReCipe 2008 (Pré Consultant 2010)

1.20 Allocation procedures in LCA applied in horticultural

ISO 14044:2006 defines allocation as the procedure that consist in the partitioning the input or output flows of a process or a product system between the product system under study and one or more other products systems. Therefore, many processes usually perform more than one function or output. The environmental load of that process needs to be allocated over the different functions and outputs. There are different ways to make such an allocation. According to ISO 14044:2006 (ISO, 2006)**,** wherever possible, allocation should be avoided by either dividing the unit process to be allocated into two or more sub-processes or, in second place, by expanding the product system to include the additional functions related to the co-products. Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions according to physical relationships.

1.21 Allocation methodology for compost production and organic waste management

Multifunctional systems are those who consider two or more functions simultaneously. The waste management is a typical issue of multi-functionality due to a sub-product (i.e. compost) and energy can be obtained from its treatment. This allocation problem can be avoided through an expansion of the systems boundaries, so the system is transformed in a single function (Finnveden 1999; Ekvall and Weidema 2004**).** The compost production is considered a multifunctional system due to it imply the waste management treatment and a technology to produce a fertilizer. On the other hand, mineral fertilizer is a single functional system which considers only the fertilizer production (Figure 1.23). Then, according to the proposed methodology, the systems boundaries are expanded to take into consideration the dumping of the organic waste in landfills. The environmental burdens of organic waste to landfill are subtracted to the compost production stage (Figure 1.23).

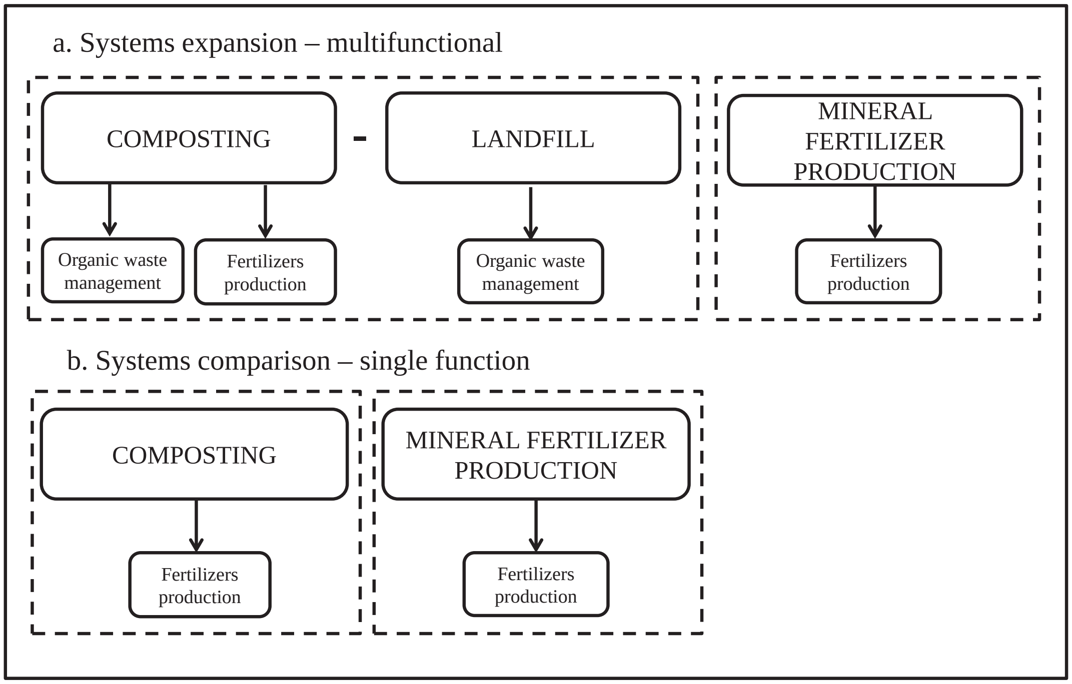


Figure 1.23 System expansion for organic waste management and fertilizer production

1.22 Experimental details (methods and materials)

This section refers to some issues related to experimental field conditions that were used for chapters 3 to 6. Most of the methods are broadly explained in cited chapters.

1.22.1 Crop plots location and soil characteristics

The plots where cauliflower and tomato were grown are located in Santa Susana in the Maresme County in the North East Part of Catalunya, Spain (41°38’27’’N, 2°43’00’’E) Figure 1.24 shows the field location. The soil was Typic Xerothent with a loamy sand texture in the first 20 cm and sandy loan at greater depth.

Figure 1.24 Crop plots location

1.22.2 Crops plots design

As shown in **Figure 1.25**, data of the cultivation phase were obtained in experimental plot of Institu de Recerca i Technología Agroalimentaries (IRTA) located in Santa Susana, Maresme county. The plot had a total area of 414 m^2. The plot was divided in three sub-plots of 138 m^2, for the three fertilization treatments. Similarly, each sub-plot was divided in a block design with three replicates for each sub-plot. The plot was used for the crop sequence of cauliflower and tomato (chapter 6).

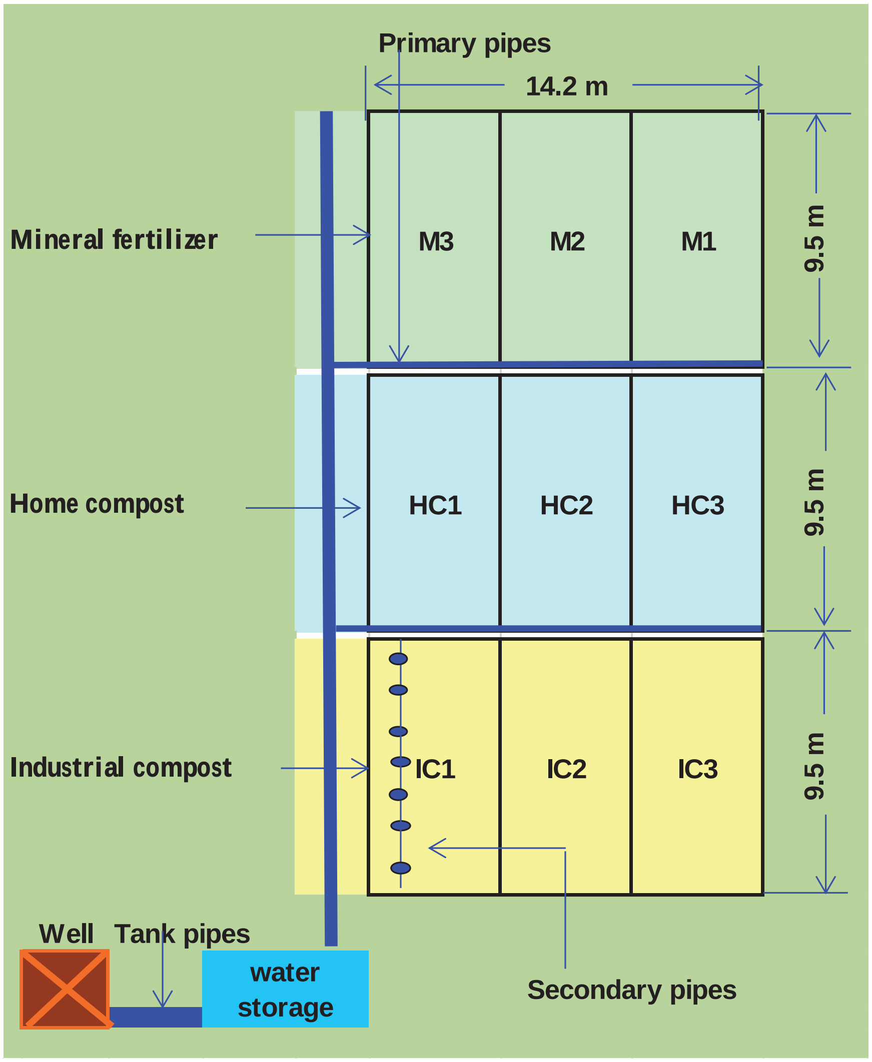


Figure 1.25 Experimental plots design

1.23 Other experimental methodologies used

In order to obtain the data used in the different case studies several methodologies where designed and applied for a full-scale and laboratory-scale. The methodologies were rigorously developed by the research groups involved in the studies. Furthermore, some parameters such as metals content for the OF and compost were determined by certificated external laboratories. The main methodologies were designed for the autoclaved OF produced from the unsorted MSW and the composts production (industrial and home) which were applied to crops. Likewise, several methodologies for the application of compost to crops were developed for the research groups. Mostly of methodologies are broadly explained in the relevant chapters for each case study. Table 1.7 summarizes some methodologies used in the case studies. Annex 1.2 shows a brief of the analytical methods used for gaseous emissions measurement of the composting process.

Table 1.1 Other experimental methodologies used in the case studies

Chapter	Case study	Methodologies*	Notes
2	The application of LCA to alternative methods for treating the organic fiber resulting from autoclaving unsorted municipal solid waste	Determination of the gaseouss emissions of the composting process for full-scale facilities for aerobic and anaerobic digestion	This methodologies included methods for compost sampling in facilities. Equipment and methods for $CH_{4,}$ NH_3, N_2O and VOC's emission
		Physico, chemical and biological charateristics of compost produced in full-scale facilites	This methodologies included organic moisture, electritical conductivity, pH, N-kjendal, dinamic respiration index, among others.
		Physico, chemical and biological charateristics of organic fiber for aerobic and anaerobic digestion processes	This methods were designed for a laboratory scale-reactor for aerobic digestion (composting) of the OF. This methodologies included organic moisture, electritical conductivity, N-kjendahl, among other
		Biogas production from autoclaved organic fiber	A laboratory scale reactor waste for anaerobic digestion for the meshophilic and termophic ranges used. The biogas production was used for methane and dioxide carbon calculations
3	Environmental agronomical assessment of three fertilization treatments applied in horticultural open field crops	Since compost production was considered within the LCA of the horticultural systems, so the same methodological aspects before explained (case study 2) were used in this stage. Furtehermore, several methodologies related to management of horticultural crops were applied such as: fertirrigation, irrigation, nursery, carbon sequestration, emission post-cultivation to air (NH_3, N_2O, NO_x) and to water (NO_3). Likewise, other specific methodologies, such as determination of bioactive substances of fruits were applied in this case study.	For this case in furthersThis magament practice was made in real trials developed in the crop field. Some specif methods were: machinery application for land preparation and compost application, calculation of emissions with literature references, etc.
4	Environmental assessment of two home composts with low and high gaseous emissions of the composting process	This chapter is based the same methodologies used in chapter 2 for compost production and application in crops.	The methodological procedures emphasizes about the management of compost production
5	Life cycle assessment of a crop sequence of cauliflower and tomato	This chapter included the same methods used in chapter 2 for compost production and cultivation stages. However, this chapter also include other methodologies such as the nitrogen cycle (input source and plant uptake) and methodologies for compost allocation to crops	The methodolgies included are based on experimental trials and literature references which were used in cases where was difficult to obtain data

*Methodologies used with its respective references are broadly analysed in the case studies

Chapter 2

Technologies to treat municipal solid waste

Chapter 2

2 The application of LCA to alternative methods for treating the organic fiber produced from autoclaving unsorted municipal solid waste: Case study of Catalonia

This chapter is based on the following paper:

Quirós, R., Gabarrell, X., Villalba, G., Barrena, R., García, A., Torrente, J., Font, X., 2014. The application of LCA to alternative methods for treating the organic fiber from autoclaving unsorted municipal solid waste: Case study of Catalonia. Published in Journal of Cleanner Production, 2014.

Abstract

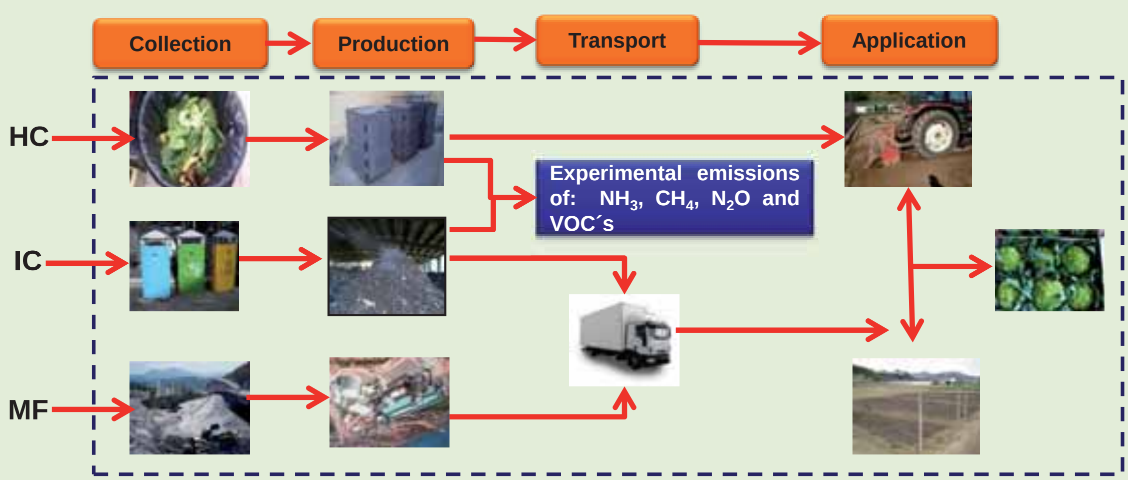
Despite efforts to increase the selective collection of municipal solid waste (MSW) in developed countries, the amount of unsorted waste remains high, with the consequent difficulty of material recovery and recycling. In 2010, 61% of the MSW generated in the European Union (EU) ended up in landfill and incineration facilities. Autoclaving is a novel technology that can be used to treat unsorted MSW, producing organic fibers that can be composted. The life cycle analysis (LCA) was used to assess the effectiveness of autoclaving unsorted MSW and various alternative methods for treating organic fibers produced through this process. The alternative methods that were considered included composting in tunnels, composting in confined windrow and composting in turning windrow as well as anaerobic digestion. The environmental assessment results were compared to those associated with incineration and landfill. The results of this study showed that autoclaving, sorting, digesting anaerobically and composting had the lowest impact values for eutrophication and the global warming potential. It was also found that autoclaving is justified only if the products of the process, that is, polyethylene terephthalate, ferrous and non-ferrous metals, are recycled to avoid virgin material production and if the remaining mixed plastic wastes are incinerated for energy recovery.

DOI: 10.1016/ j.jclepro.2014.04.018

Reference link

Chapter 3

Environmental and agronomical assessment of three fertilization treatments



Chapter 3

3 Environmental and agronomical assessment of three fertilization treatments applied in horticultural open fields crops.

This chapter is based on the following paper:

Quirós, R., Villalba, G., Muñoz, P., Font, X., Gabarrell, X., 2014. The application of LCA to alternative methods for treating the organic fiber from autoclaving unsorted municipal solid waste: Case study of Catalonia. Published in Journal of Cleanner Production, 2014.

Abstract

In 2010, the generation of municipal solid waste (MSW) by the European Unión (EU-27) was 252 million tonnes, with an estimated organic content of 30-40% by weight. We present a Life Cycle Analysis (LCA) and agronomical assessment of the following three fertilization treatments: industrial compost (IC), home compost (HC) and mineral fertilizer (MF), applied to horticultural cauliflower crops. For the IC and HC treatments, we evaluated the entire cycle of the organic matter, starting from the moment it becomes MSW and including collection, production of compost, transportation and application in open field cauliflower crops. For the MF treatment, the analysis includes the raw material extraction, production, transportation and the application to crops via irrigation.

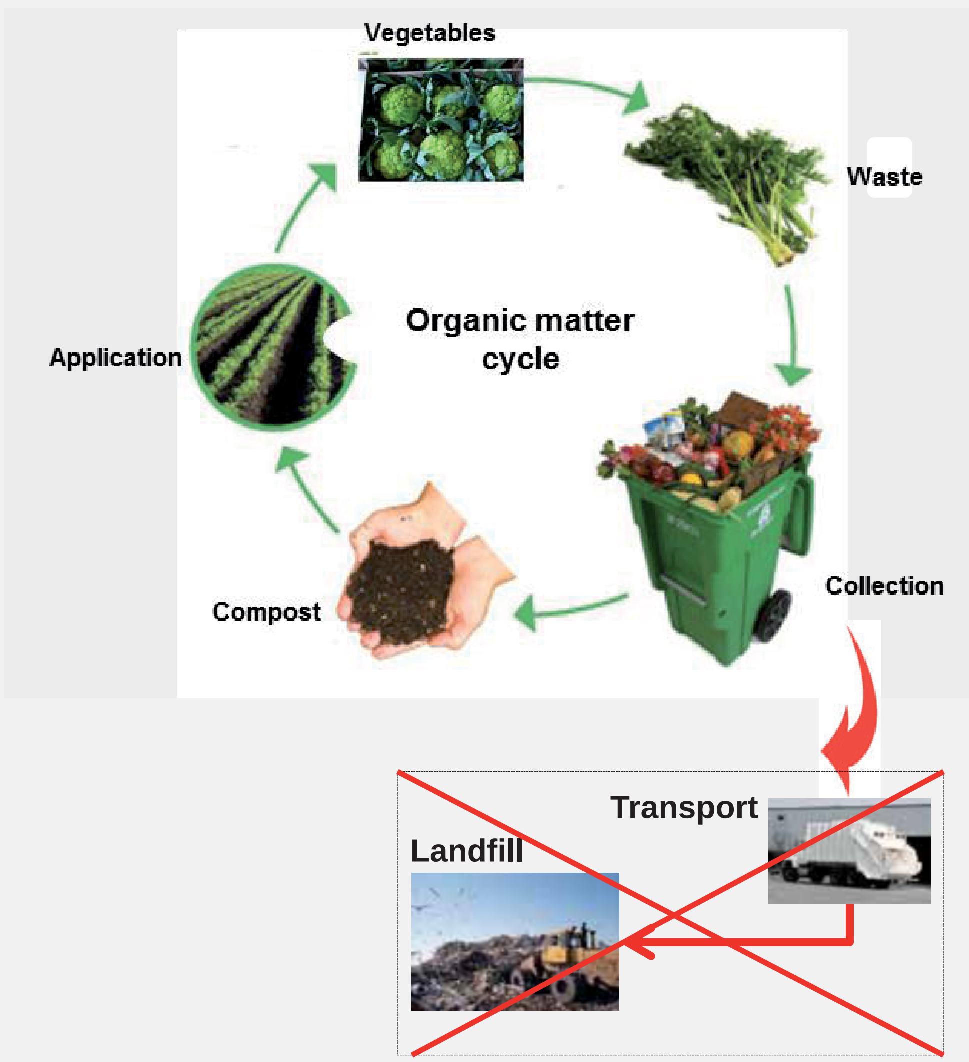
A higher crop yield was achieved with MF treatment, which was 26% and 91% higher than HC and IC treatment, respectively. However, the application of HC treatment resulted in larger, heavier cauliflowers. No significant differences were found in the nutritional analysis, which included the quantification of the total phenols, glucosilonates and flavonoids. The HC treatment had the best environmental performance with the lowest impact in all categories assessed except for its abiotic depletion potential and eutrophication potential (which was the lowest for IC). The IC treatment had the highest environmental impact in five of the seven categories assessed, whereas the MF treatment had the highest eutrophication and global warming potentials.

DOI: 10.1016/j.jclepro.2013.12.039

Reference link

Chapter 4

Environmental assessment of two home composts



Chapter 4

4 Environmental assessment of two home composts with high and low gaseous emissions of the composting process

This chapter is based on the following paper:

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. Published in Resource, Conservation and Recycling. 2014.

Abstract

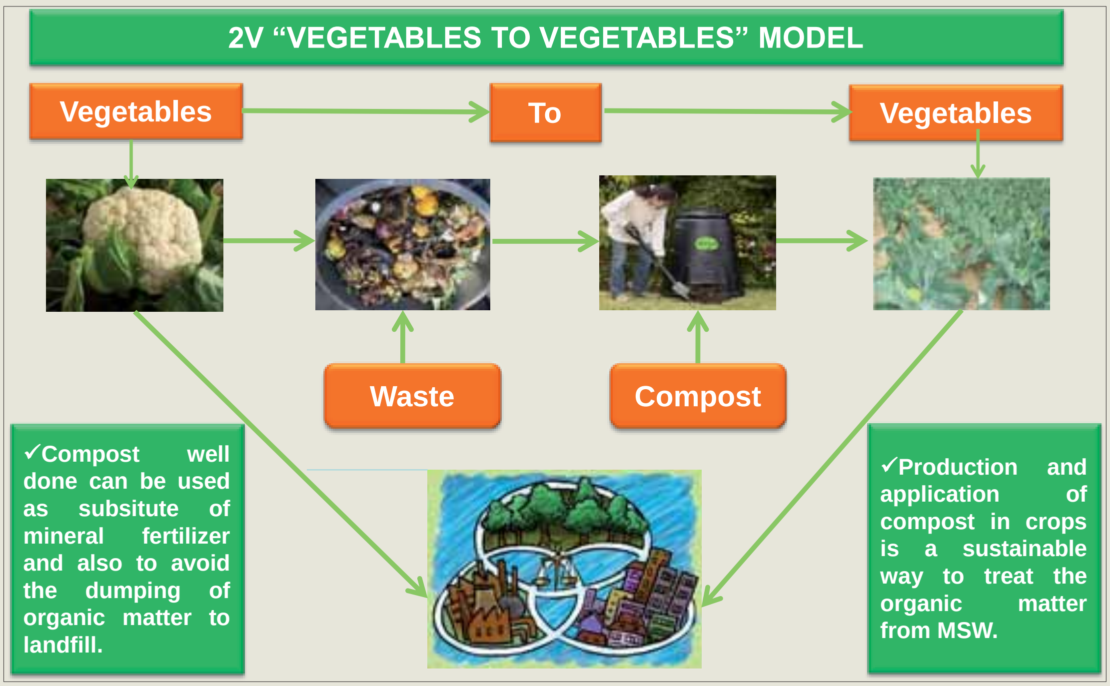
A Life Cycle Assessment (LCA) of two home composts with low and high gaseous emissions of the composting process is presented. The study focused on the gaseous emissions of the composting process. Gaseous emissions of methane, nitrous oxides, ammonia and volatic organic compounds of the composting process were experimentally measured in field real trials. The results showed that the differences in gaseous emissions between the two home composts were 4.5, 5.8 and 52 for methane, nitrous oxides and ammonia, respectively. Higher emissions of nitrous oxides and methane affected significantly the category of global warming potential, while higher emissions of ammonia affected mainly the categories of acidification potential, eutrophication potential and photochemical oxidation. The differences found in the compost emissions were attributable to the composting production management (quality and composition of waste stream, frequency mixing of waste, humidity and temperature monitoring, among others) as well as weather conditions (temperature and humidity).

DOI 10.1016/j.jclepro.2014.04.018

Reference link

Chapter 5

Guidelines for organic waste management



Chapter 5

5 Guidelines for organic waste management focused on domestic compost and its application in horticulture

These guidelines are based on the published document in http://ecotechsudoe.eu/es, developed on the frame of ECPTECH SUDOE SOE2/P1/E377 project.

5.1 Introduction

This chapter was developed under the Ecotech Sudoe Project with the participation of different partners from Catalonia, Spain, France and Portugal. Several experiments were developed by research groups for home compost production and its application in open-field of cauliflower crops.

The different case studies presented in the dissertation served as the basis for the current manual. All experiments were experimentally carried out and analyzed from agronomical and environmental standpoint to study the viability and performance of home composting.

The research was based on field work done by the following research groups: Group d'Investigació en Compostatge (GICOM) for the production of home compost, Institut of Reserca (IRTA) for the application of compost in crops and Sostenipra Research for the methodological aspects and for the environmental assessment.

The aim of the manual of is to leave a guideline to different audiences related with the compost production and its application on crops. The study considers the entire cycle of the organic matter from the V2V "vegetables to vegetables" model**.**

Potential users of the manual:

- **Composters:** It refers to users who produce the compost by different technologies (i.e. home or industrial compost)
- **Farmers:** It refers to users who apply the compost on farms.
- **Technicians:** It refers to public or private users such as municipal technicians in charge with the compost production and monitoring.

5.2 Food and waste

The waste from food has a significant impact on organic matter portion that is landfilled. From agricultural production and in all stages of the food cycle about 1,300 million tons of food fit for human consumption is lost. This accounts for one third of the edible parts of food produced for human consumption (Gustavsson J., et al., 2011).

The generation and management of waste has become a major problem in modern society (Figure 5.1). In EU-27 countries, in 2010, an average of 37% of municipal waste was landfilled (Eurostat, 2010**),** while Municipal Solid Waste (MSW) generation for 2010 was 252 million tons in EU-27 (Eurostat, 2012). This MSW has an organic matter content of approximately 30-40%. Meanwhile mineral fertilizers consumption was 18 million tons in 2010 (Eurostat, 2012). Potential quality compost in the EU is about 30-40 million tons which represent 131,000 tons of nitrogen available. Moreover, good quality compost can be used as mineral fertilizer substitute.

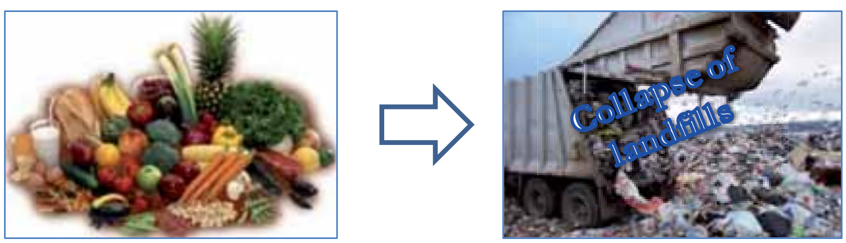


Figure 5.1 Food waste to landfill

5.3 An overview of composting production

5.3.1 Definition of compost

Composting is a natural aerobic process by which microorganisms transform putrescible organic matter into CO_2, H_2O and complex metastable compounds (e.g. humic substances) (Barrena et al., 2005). The final product, compost is a stable, sanitized and humus-like material. Compost is defined as the end product of the biological decomposition of the organic matter from municipal solid waste **(Figure 5.2).**

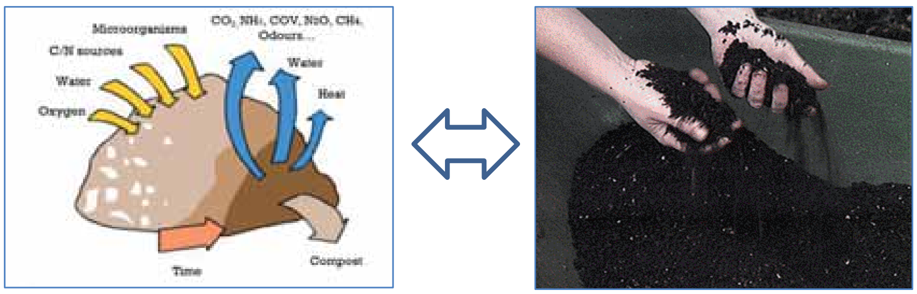


Figure 5.2 Compost process and the final product

5.3.2 Home composting

Home composting or backyard composting which refers to the self-composting of the bio-waste as well as the use of compost in a garden belonging to a private household (European Commission, 2009). Figure 5.3 shows self-composting.

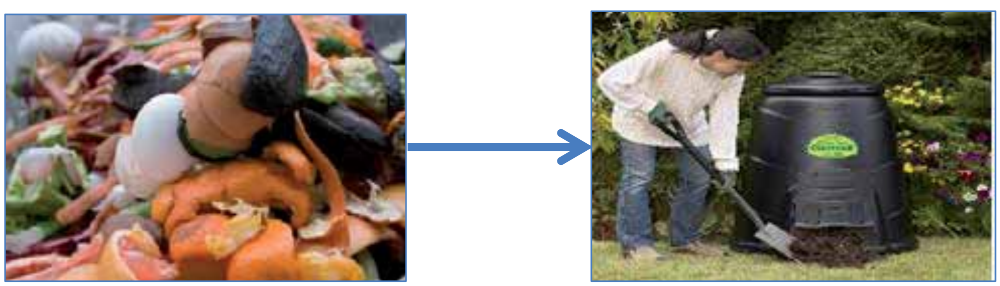


Figure 5.3 Self-composting

Home composting can be a good alternative to industrial composting in low density urban areas were a large investment in transport is required for the separate collection of OFMSW (organic fraction of municipal solid waste).

5.4 V2V "vegetable to vegetable" model

This model considers the entire cycle of organic matter from the generation of waste in households to the cultivation of vegetables (Figure 5.4). The model considers all stages of the organic fraction of MSW: the collection and transportation of waste, compost production, transportation from production sites to crops, and its application to obtain final products (i.e. vegetables).

The V2V "vegetable to vegetable" model for vegetables and compost production avoids the transportation of waste, organic fertilizers and vegetables to retailers. This new conception of horticultural production represents a sustainable way to treat household waste with the consequent benefits for society in accordance with the sustainable development (economic, social and environmental).

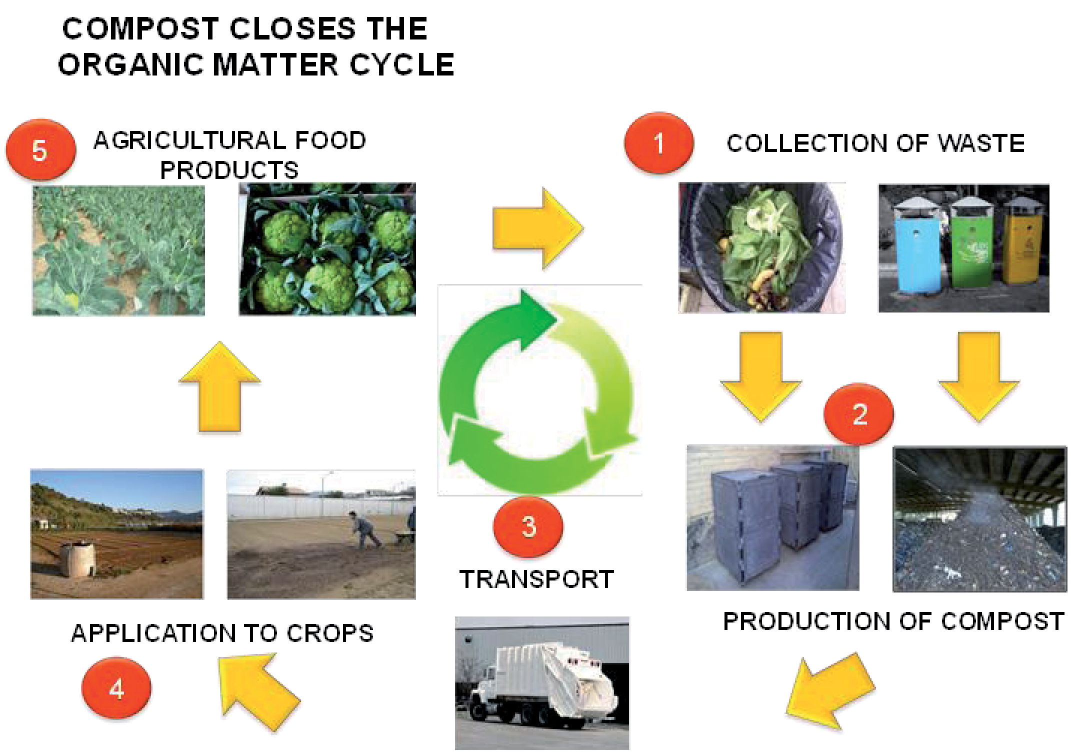


Figure 5.4 Organic matter and 2V2 "vegetable to vegetable" model

5.5 Organic material to be composted

In general material suitable for composting includes: garden waste, kitchen scraps (meat, fish, eggshells), leftover of fruit and vegetables, manure, leaves, grass clippings, straw, etc. (Figure 5.5).

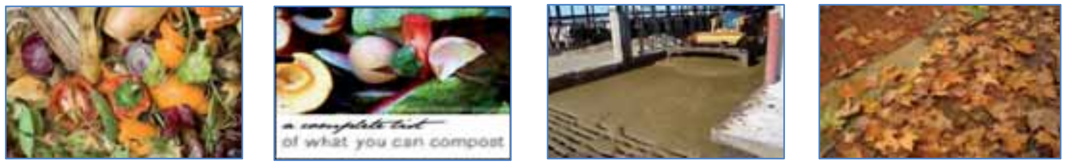


Figure 5.5 Type of organic matter suitable for composting

5.5.1 Materials from municipal solid waste

- The organic fraction of municipal household waste.
- Green material (tree branches, hedgerows, grass, etc.)
- Agricultural residues, such as plant residues (cotton ginning, rice processing, etc.).

5.5.2 Materials which include a "Gate fee"

- Expired food from supermarkets, restaurants, etc.
- Biodegradable organic waste from regional industries.
- Sludge from Waste Water Treatment Plants.
- Animal waste from livestock operations.
- Wine residues and processing industries, standardization (juice, citrus fruit), waste extraction.
- Organic waste from slaughterhouses or mills.
- Other possible types of biodegradable organic material.

5.6 Principal compost parameters

In order to guarantee good quality compost specific criteria should be used for both incoming material (waste) and the final product (compost). For incoming waste should be considered: the content of biodegradable material (leftover of raw fruit and vegetables, food and scrap yard) and improper material content such: plastics, glass, metals, textile etc. In the case of the final product (i.e. compost) some parameters should be controlled: temperature, pH, moisture, organic matter content (C), nitrogen (N), biological stability and heavy metals content, among others, should be controlled. The periodic characterization of main parameters and field studies are recommended for both products (incoming waste and compost) to guarantee the quality of the final product.

In a real case study of compost parameters experimental measures for home composting were carried out by the Group d'Investigació en Compostatge (GICOM) of Universitat Autònoma de Barcelona within the frame of Ecotech Sudoe project. For the case study, 18 samples were analyzed, 7 for household compost, 7 for school compost and 4 for community compost (Table 5.1).

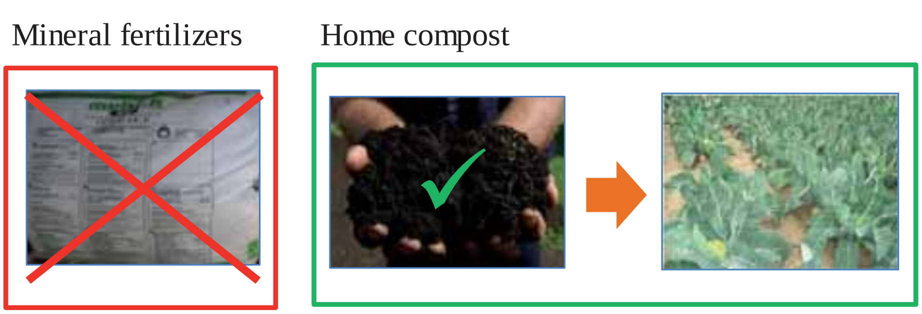
Table 5.1 Physical-chemical characterization for samples of compost

Parameter	Units	References[a]	Average	Deviation (%)
pH			7.65	7
Conductivity	mS/cm		4.29	73
Density	g/cm^3		0.59	32
Moisture	%	30-40	42.89	36
Organic matter	% dmb	≥ 35	57.85	27
NTK	% dmb		2.21	40
N-ammonia	% dmb		0.17	45
Phosphorus	% dmb		0.89	40
Potassium	% dmb		1.63	40

dmb: Dry matter basis
Reference: http://ecotech.cat/zerowaste/workshopUAB2012/

5.7 The benefits of compost

- Compost can be used as a mineral fertilizer substitute in horticultural crops



- Reduction of waste to landfills
- In regards to mineral fertilizers, compost production avoids greenhouse gases emissions and other contaminants to air, water and soil.

- Economic benefits (energy savings for producers).

5.7.1 Other benefits of compost and cares during compost production

Compost avoids the collection of the Organic Fraction of Municipal Solid Waste (OFMSW). This practice significantly reduces the economic, material and energetic requirements of management and treatment. Furthermore, compost reduces the amount of impurities present in OFMSW by means of direct control on waste being treated.

In addition, home composting contributes to environmental awareness by involving people in the correct management of their own waste and by highlighting the importance of a number of factors influencing the treatment process.

However, as with for all human activities, home composting has also negative impacts on the environment such as uncontrolled gaseous emissions with a high global warming potential or acidic character. The use of materials (composter and tools) and energy (mixing and chipping) when home composting is performed in an uncontrolled manner may also be harmful. Furthermore, odor generation, the possible presence of rodents and insects and a final product of low quality are the main drawbacks of this practice that make it unattractive to some potential practitioners.

Despite efforts to obtain good quality compost, it can observe some problems in compost production for example: compost obtained often is not homogenous; odors and other pollutants such as methane, ammonia and nitrous oxide emitted directly to the atmosphere during the decomposition process (Amlinger et al., 2008; Ansorena, 2008).

5.8 Good manufacturing practices for home composting

Some practices and recommendations are listed below in order to avoid in some extend the negative aspects of home composting:

5.8.1 The choosing a suitable composting bin

There are several commercial models of different sizes and shapes available on the market. The following aspects should be considered when choosing the most suitable:

- When deciding on bin-capacity, a bin with enough capacity is required, the daily-weekly generation of OFMSW of a particular home should be estimated for a correct election. The inclusion of garden waste should also be taken into account as well as the use of bulking material to give enough porosity to the waste under composting (a volumetric ratio of 1:1 is recommended).
- Aeration should be ensured through the composting bin walls by means of regularly distributed holes.
- The composting bin should be rainproof. This will help to reduce leachate production and to keep the moisture content of the material under control.
- An easy way for the removal of the composted material should be provided minimizing the disturbance to the material still under composting.

5.8.2 Adecuate material mixing and handling

- Organic fraction of municipal solid waste (OFMSW) can be fully fed to the home composter but avoiding fish and meat leftovers. These wastes can promote the presence of insects if the composter is not correctly managed.
- Adequate porosity should be provided to the composting material by using a bulking agent.
- Porosity is needed for material aeration, which is crucial as the composting process is aerobic in nature. A volumetric ratio of 1 part of OFMSW to 1 part of bulking agent is recommended.
- As bulking agent also serves to moisture content regulation. If the OFMSW is mainly vegetal and/or weather conditions do not promote water evaporation, the amount of bulking agent needed may increase. Bulking agent and waste should be mixed appropriately by hand. Moisture content of the mixture can be determined by using a “fist test”. Preventing rainfall from entering the bin will also help to maintain correct moisture levels.
- The material used as bulking agent should provide structure and porosity to the waste as well as absorb excess humidity. Wood chips are the most commonly used bulking material. Wood chips can be obtained from private

gardens or provided by local environmental agents from the maintenance of public parks and gardens.

- Material in the composting bin should be mixed periodically to ensure correct moisture distribution and aeration care should be taken to avoid the lower part of the bin, where compost is in curing phase.

5.8.3 Leachate and gaseous emission

- Leachates are generated due to the excessive moisture of material or rainfall entering in the composter bin. Leachates should be prevented because they lead a loss of nutrients. Prevention can be achieved through moisture control and by preventing rainfall entering the bin, as stated above.
- If the composting bin is placed on unpaved soil, this will absorb the leachates. Therefore, if the bin is placed on paved soil, a system for leachate collection should be present.
- Most harmful gaseous emissions are those related to odors, mainly volatile organic compounds and ammonia emissions. The correct management (correct mixing of the material, enough porosity, moisture level control, etc.) of the composting process will help to prevent these emissions. The prevention of anaerobic zones is very important to reduce greenhouse gases.

5.9 Quality of the final compost

- A highly stable product (compost) can be obtained if the composting process is managed properly. However, as the temperature of the material during the process will not probably be high enough to ensure sanitation.
- The separation of bulking agent may not be necessary depending on the use intended for the compost obtained. However, if the bulking agent is scarce in the local area, separation is recommended by using a commercial or homemade screen.

5.10 Good management practices for compost use in crops

When compost is applied to crops, some considerations should be taken into consideration to guarantee the effective use of the product:

- Before the application of compost in soil, a soil-study is recommended to discover which nutritional substances (nitrogen, potassium and phosphorus) are present in soil.
- Compost doses according to crop type and soil.
- A rigorous control of leachate and emissions.
- Precise irrigation considering rainfall, well or other water sources.
- Control and monitoring of weather conditions.
- Good conditions for compost storage (i.e. humidity, temperature, aeration, no insect presence, etc.).

5.11 Other consideration

This manual for home compost production and its application in horticultural crops includes a brief description of theoretical elements related to Life cycle assessment methodology that was presented in the introduction (i.e. chapter 1). Furthermore, the manual includes the main results of the cases studies developed (i.e. chapter 3 and 4) in the thesis. As well as list of reference were included for home compost practitioners or interested in these subjects.

5.12 References

Links to papers of interest:

- ✓ A methodology to determine gaseous emissions in a composting plant. Erasmo Cadena, Joan Colón, Antoni Sánchez, Xavier Font, Adriana Artola. Waste Management, 29 (11), 2009, 2799-2807. http://www.sciencedirect.com/science/article/pii/S0956053X09002797
- ✓ Composting from a sustainable point of view: respirometric indices as key parameter. A Artola, R Barrena, X Font, D Gabriel, T Gea, A Mudhoo, A Sánchez, J Martín-Gil. Dynamic Soil, Dynamic Plant 3 (Special Issue 1), 1-16 http://www.cabdirect.org/abstracts/20113223007.html
- ✓ Environmental assessment of home composting. Joan Colón, Julia Martínez-Blanco, Xavier Gabarrell, Adriana Artola, Antoni Sánchez, Joan Rieradevall, Xavier Font. Resources, Conservation and Recycling, 54 (11), 2010, 893-904. http://www.sciencedirect.com/science/article/pii/S0921344910000261
- ✓ Environmental impact of two aerobic composting technologies using life cycle assessment. Erasmo Cadena, Joan Colon, Adriana Artola, Antoni Sánchez, Xavier Font. International Journal of Life Cycle Assessment, 14 (5), 2009, 401-410.

http://www.springerlink.com/content/mn27tt3044326346/

- ✓ The use of life cycle assessment for the comparison of bio-waste composting at home and full scale. Júlia Martínez-Blanco, Joan Colon, Xavier Gabarrell, Xavier Font, Antoni Sánchez, Adriana Artola, Joan Rieradevall. Waste Management, 30 (6), 2010, 983-994. http://www.sciencedirect.com/science/article/pii/S0956053X10001091

Other documents of interest

- ✓ Handbook. Ecotech Sudoe Project. http://ecotechsudoe.eu/es

Web sites to visit:

- ✓ http://ecotechsudoe.eu/es
- ✓ http://ecotech.cat/zerowaste/workshopUAB2012/

Chapter 6

Life cycle assessment fertilizers in a crop sequence

Chapter 6

6 Life cycle assessment of fertilizers in a crop sequence

The following paper submitted to a journal review is based on current chapter 6.

Quirós, R., Villalba, G., Gabarrell, X., Muñoz, P. (2014). Life cycle assessment of organic and mineral fertilizers for a crop sequence. Submitted to Resource, Conservation and Recycling. 2014.

Abstract

Fertilizers are commonly applied to an entire crop sequence which can be made up of two or more crops. This study presents a LCA of a crop sequence of cauliflower and tomato in a Mediterranean region subject to three different fertilization treatments (industrial compost, home compost and mineral fertilizer). The crop sequence lasted one calendar year from cauliflower plantation (October 2011) until tomato harvesting (October 2012). Two allocation procedures based on the crop cultivation time and the degree of nitrogen mineralization were used to allocate compost burdens to crops. Regardless of the allocation methods used, the crops fertilized with home compost had the best environmental performance in all impact categories considered, except in marine eutrophication and terrestrial acidification. When comparing the impacts (kg eq. of pollutant/day) of the entire horticultural cycle with the individual crops, the former had the lower impacts in the most categories assessed. The crops fertilized with the home compost, the allocation method based on the degree of nitrogen in soil had the least impact value in all categories studied. In this case study, the allocation procedure based on the cultivation duration was considered as the better attributional method given the high degree of uncertainty in the nitrogen degradation. This uncertainty is related to complex interactions between variables to metabolize the nutrients content in fertilizers such as: variety of crop, crop management, soil type, weather conditions, fertilizer, among others.

6.1 Introduction

Agriculture is considered a major contributor to some present environmental impacts such as those of water pollution given the intensive use of fertilizers and pesticides (Mueller et al., 1995; Ongley et al., 1996; European Commission, 1999; Laegreid et al., 1999). Fertilizers and pesticides applications affect not only the target crop but in also subsequent ones.

Crop sequence is a farming practice in which different crops are grown in the same field at different times over several years. This practice aims to promote soil fertility and minimize the development of pests, weeds, while ensuring, better nutrient management. The timing and crops of a rotation depend on the type of farming employed (arable-mixed, organic/conventional), local climate conditions, soil type, water availability, irrigation, crop and potential market opportunities. They are key factors in determining not only the yield and the quality of the crops, but also their environmental impacts. The essential mineral nutrient must be provided by the soil, or by organic and mineral fertilizers. The risk of nutrient depletion is latent when the amount of nutrient added to crop is less than the amount of nutrients removed from the soil in the form of crop yields and residues, and losses of nutrient in the form of volatilization, leaching, and erosion. The consequences of nutrient depletion are that soil fertility declines, crop growth and inputs of carbon to the soil decline, and the soil is left open to the negative effects of erosion. On the other hand, the mineral fertilizers are usually used in great quantities by farmers to increase crop yield. Over-supply of nutrients is the main environmental problem related to fertilizer use. However, application of N fertilizer will have little effect on increasing yields if other factor limiting growth.

The analysis included in this study was performed on the entire life cycle of a crop sequence of cauliflower and tomato, which includes the production, transport and application of compost and mineral fertilizer.

The crop sequence of cauliflower and tomato was fertilized with industrial compost (IC), home compost (HC) and mineral fertilizer (MF). The IC was produced from the organic fraction of municipal solid waste (OFMSW). The IC was taken from full-scale facility that manages the waste of the twelve municipalities that make up

Mancomunitat La Plana, located in Catalonia. The HC was produced from leftover of raw fruit and vegetables (LFRV) and pruning waste (PW) as bulking agent. The organic material for HC was collected from a single-family home in a neighborhood of the city of Barcelona, Catalonia (Quirós et al., 2014). The fertilization treatment with MF consisted in the application to crop of nitrogen fertilizers (KNO_3) mixed with water.

The environmental assessment of this study was carried out with the Life Cycle Assessment (LCA) methodology which was proven to be a valuable tool for the comparison of farming systems at crop level (Audsley et al., 1997; Gaillard et al., 1996; Martínez et al., 2009; Martínez et al., 2011). The LCA was lead following the guidelines of the ISO 14044 (ISO, 2006) and the ReCipe 2008 v1.05 methodology was used to calculate the environmental impacts. To our knowledge, no evidence of previous studies was found in literature review of environmental assessment of home compost application in a crop sequence neither environmental comparison between home compost with industrial compost and mineral fertilizers.

The first aim of this research is the environmental comparision of three fertilization treatments in a crop sequence using LCA methodology. The second objective is to study the environmental performance of the system with two allocation procedures for the compost applied to crops. The life cycle impacts of compost were allocated to the two crops following the physical causality principles as stated in the ISO 14044 (ISO, 2006). Two procedures of allocation were implemented to quantify the compost burdens, the first one was based on the cultivation time (Ta) and the second one considered the degree of N mineralization (NMa) in soil.

6.1.1 Description of the systems

Three fertilization treatments (IC, HC and MF) applied to a crop sequence of cauliflower and tomato were compared to observe the environmental performance of single crops and the entire sequence. The three cropping systems were compared between them and individually with the entire crop sequence. Annexes 6.1-6.3 show the stages and sub-stages for each fertilization treatment. The stages considered in the LCA were: compost and mineral fertilizer production, compost transport for IC and

MF fertilizers; and the cultivation stage. The cultivation stage included: fertirrigation infrastructure and equipment, irrigation, emissions of fertirrigation, machinery used in cultivation (i.e. field preparation and harvesting); carbon sequestration, nursery and phytosanitary substances.

Compost production stage considered: the collection and transport of the OFMSW (collection bin and transport); electricity, diesel and water consumed in the process; gaseous emissions of the process (CH_4, NH_3, N_2O and COV's); the building and machinery used and waste management of infrastructure. Compost transportation for IC accounted the transport from the production plant to the plots which included: the fuel, the truck and its maintenance and the road build and maintenance. MF production comprised the extraction of raw material and fertilizer production at plant including infrastructure, transport of raw materials, synthesis of the chemical components required, dosages and the deposition or treatment of waste generated. MF transport accounted the distance from the plant to the plots. The transportation of MF was split in two portions, the sea transport portion from Israel to Barcelona Port and the transport by road from the port to the crop plots. Process for the production and transport of MF were taken and adapted from the ecoinvent database (Swiss Centre for Life Cycle Inventories, 2010**)**.

Fertirrigation considered infrastructure and equipment to irrigate the crops, transport and the waste management. Irrigation sub-stage incorporated the irrigation water and electricity consumed by the well pump and the irrigation pump. Emissions post application of fertilizers and water included the emissions to air of NH_3, N_2O, NO_x and $N_{2;}$ and emissions of NO_3 to water. Fertirrigation phase considered the machinery and tools to prepare the land, mixing and spreading the fertilizers (IC and HC), hours of operation and fuel consumption. The stage of phytosanitary substances was based on the type of substance needed according to crop; doses and its production process.

6.2 Methodology

6.2.1 Life cycle assessment (LCA)

Life cycle assessment was used to calculate the environmental impacts of the crop sequence of cauliflower and tomato considering the entire life cycle (production, transport and application on crops) for one year horticultural cycle, including resources extraction and waste disposal. The inventories were built following the guidelines as stated in the ISO 14040-14044 (ISO, 2006).

6.2.2 Functional unit and scope

The functional unit is the basis for comparisons between different systems in LCA (ISO, 2006). The functional unit used for the LCA was resources and elements consumed (energy, water, equipment and machinery) in all stages and sub-stages per area cultivated (m^2) for one year cycle. The scope of the study was limited to compost and mineral fertilizer production, transport and its application on crops. The limits were set taking into account all the input and output flows of material and energy according to the systems definition.

6.2.3 Systems boundaries

The system boundaries included the production of the organic and mineral fertilizers, the transport between the production site until the cultivation plots, and all activities related with the cultivation such as: fertilization equipment, machinery and tools, pesticides, irrigation and nursery (Annexes 6.1-6.3).

6.2.4 Categories of impact and software used

In this research, ReCipe 2008 v1.05 (midpoint method, hierarchist version) methodology was used to calculate the environmental impact. ReCipe emerged as new methodology, in the year of 2000 after a SETAC meeting to harmonize the CML midpoint and the Pré endpoint approach into a single and consistent methodology. Since this a relative new methodology, nowadays a few studies used this methodology for the assessment of agricultural systems. In our case study, according to ReCipe methodology, six impact categories were selected to do the environmental assessment of the crop sequence for the three fertilization treatments. The categories selected were as follows: climate change (CC), photochemical oxidation formation (POF), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil depletion (FD). Furthermore, the cumulative energy demand (CED) as an energy flow indicator was considered (Frischkenecht and Jungbluth, 2003). The SimaPro v 7.3.3 program (Pré Consultants, 2013) was used for the impact analysis, with the obligatory classification and characterization phases defined by the ISO 14044 (ISO, 2006).

6.2.5 Method for avoided burdens of dumping OFMSW and VF in landfill

The method of cut-off proposed by Ekvall and Tillman (1997) was used to allocate the burdens of dumping OFMSW and VF (vegetal fraction) which is in accordance with the ISO 14044. This method sets that each system is charged with the burdens for which it was directly responsible. In this study, environmental burdens for dumping the same amount of OFMSW and VF were used in the calculation of total burdens for IC and HC fertilization treatment. These burdens were subtracted from the total impact of the compost production stage. The process used to calculate the environmental charges of dumping compostable material to landfill was taken and adapted from the ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories, 2010). The collection and transport of organic waste, including the production of the bin to collect the organic fraction in houses was considered too. Furthermore, the construction of the landfill and road access, the machinery operation, the combustion of methane without energy recovery, and the land used, were all considered with a time limit of impact of 100 years (Doka, 2007).

6.2.6 Quality and origin of the data in the inventory

Most of data for compost (IC and HC) production were locally and experimentally obtained from a full scale industrial facility for IC from Mancomunitat La Plana, Barcelona and from homes of Barcelona city for HC. Annex 6.4 shows the origin of data for IC and HC. In the case of the cultivation stages, as explained elsewhere, the data were experimentally obtained from real essays in plots located in Santa Susana, Maresme county (Catalonia, Spain). When local information was not available, bibliographical sources and the ecoinvent database 2.2 (Swiss Centre for life cycle

Inventories, 2010) were used and adapted to our systems conditions. Data sources used for the cultivation phase, stages and sub-stages are shown in Annex 6.4**.**

6.2.7 Life cycle inventory

The inventories for the production of compost (IC and HC) included the energy (electricity and diesel), water and the different elements used in the process such as building, tools and machinery. Also, the inventory considered the waste management of those elements (i.e. building, tools and machinery). The different stages and sub-stages for the three fertilization treatments (IC, HC and MF) are presented in Annexes 6.1-6.3. Likewise, the inventories for the cultivation stage which included the energy, water, and resources (machinery and tools, pesticides, etc.) consumed according to the functional unit are presented in Annex 6.5. The processes used for the cultivation stage inventory were similar for the two crops which only differed in the water irrigation system. The cauliflower used a micro-sprinkler, and the tomato a dripping system. A full description of the inventories for the cauliflower crop which was used as base to calculate the inventories of the crop sequence can be found in Quirós et al. (2014).

6.2.8 Irrigation water

Irrigation water was pumped from a nearby well (depth, 10-15 m) to the fields using two pumps, one to pump the water out the wells (4 kW) and the other one to spread it over the plots (2.7 kW). Irrigation water measurements depended on the evapotranspiration demands. The irrigation water was very similar per fertilization treatment for each crop (Table 6.1). The final consumption of water was taken from meters placed in the plots. Cauliflower was an average of irrigation water of 109 $L \cdot m^{-2}$ for IC, 108 $L \cdot m^{-2}$ for HC and 94 $L \cdot m^{-2}$ for MF. In the case of tomato crop the irrigation water was of 304 $L \cdot m^{-2}$, 296 $L \cdot m^{-2}$ and 287 $L \cdot m^{-2}$ for IC, HC and MF, respectively. In this case study, the differences between both crops were due to cauliflower is a winter crop and tomato was cultivated in the summer season. Furthermore, the irrigation water for cauliflower was lower than the scheduled due to the high quantity of rainfall registered at the beginning of the cultivation. Although the irrigation water was very similar for a same crop, the small differences registered were attributable to random causes of the experiment. The irrigation water stage also considered the electricity consumed by the pump used for pumping water from well located nearby the plots and the electricity consumed by the pump to irrigate the plots (Annex 6.5). As expected, the electricity consumption in tomato crop was higher than cauliflower crop due to a greater amount of irrigation water applied to the crop.

Table 6.1 Total nitrogen provided to crops per fertilization treatment*

				Crop sequence[1]		Cauliflower			Horticultural inactivity GAP		Tomato		
		L	Units	IC	HC	IC[2]	HC[3]	MF[4]	IC	HC	IC	HC	MF
		a	N organic content in compost applied (dwb)[5]		2.5%	1.7%								
		b	Humidity of compos[6]		39.7%	50.3%								
		c	N content in well water[7]	$g·m^{-3}$	26.052									
		d	Irrigation water	$l·m^{-2}$			108	109	94	-	-	304	296	287
		e	**N provided by irrigation water[8]**	**$g·m^{-2}$**			**2.8**	**2.8**	**2.4**	**-**	**-**	**7.9**	**7.7**	**7.5**
		f	N content in rainfall	g·l	0.00076									
		g	Rainfall	$l·m^{-2}$			529	529	529	220	220	133	133	133
		h	**N provided by rainfall[9]**	**$g N·m^{-2}$**			**0.40**	**0.40**	**0.40**	**0.17**	**0.17**	**0.10**	**0.10**	**0.10**
Allocation procedures	Ta[a]	i	Compost allocated to crops[10]	$g·m^{-2}$			188	274	-	158	230	203	296	-
Allocation procedures	Ta[a]	j	**N organic provided by the compost allocated[11]**	**$g N·m^{-2}$**			**2.8**	**2.3**	**-**	**2.4**	**1.9**	**3.0**	**2.5**	**-**
Allocation procedures	Ta[a]	k	**N total provided to crop[12]**	**$g N·m^{-2}$**			**6.0**	**5.6**	**-**	**2.5**	**2.1**	**11.1**	**10.3**	**-**
Allocation procedures	NM[b]	l	Compost allocated to crops[13]	$g·m^{-2}$			151	219	-	127	184	163	237	-
Allocation procedures	NM[b]	m	**N organic provided by the compost allocated[14]**	**$g N·m^{-2}$**			**2.2**	**1.9**	**-**	**1.9**	**1.6**	**2.4**	**2.0**	**-**
Allocation procedures	NM[b]	n	**N total provided to crop[15]**	**$g N·m^{-2}$**			**5.5**	**5.1**	**-**	**2.1**	**1.7**	**10.4**	**9.8**	**-**
	MF	o	Dose of mineral fertilizer applied (KNO_3)[16]	$g * m^{-2}$			-	-	6.92	-	-	-	-	74.3
	MF	p	N mineral[17]	$g N·m^{-2}$			-	-	0.96	-	-	-	-	10.30
	MF	q	**N total provide to crop[18]**	**$g N·m^{-2}$**			**-**	**-**	**3.8**	**-**	**-**	**-**	**-**	**17.9**

*Three fertilization treatment and two allocation procedures were considered
[a]Ta: This procedure allocates the compost applied to crops according to the crop duration (since plant cultivation date until fruit harvesting).
[b]NMa: This procedure allocates the compost applied to crops according to the degree of N mineralization in soil
[1]Crop sequence column refers to data that are common for the two crops
[2]IC: Industrial compost
[3]HC: Home compost
[4]MF: Mineral fertilizer
[5,6]Experimentally determined (compost characterization)
The letters in the left side of the table (column L) were used for the calculations
[7]The N content in ground water was 1.86 miliequivalent ($26.052\ gN·m^{-2}$)
[8,11]e = c·d (conversion factor)
[9]h = f·g
[10,13]See calculation in Table 2
[11]j = a · (1-b) · i
[12]k = e + h + j
[14]m = a · (1-b)· l
[15]n = e + h + m
[16]Experimentally determined in crop fields
[17]Experimentally determined according to N molecular weight
[18]q = e + h + p

6.2.9 Compost characterization

The organic fertilizers (IC and HC) were physically and chemically characterized in order to know their quality to be used as mineral fertilizer substitutes. Physico-chemical characteristics such as moisture, organic matter, pH, electrical conductivity, N-Kjedhal, dynamic respiration index, quality parameters of salmonella and escherichia coli were experimentally measured in field for IC and HC (Annex 6.6). Also, the gaseous emissions of CH_4, NH_3, N_2O and VOC's emitted during the composting process were experimentally studied for IC and HC. The experimental procedures for the characterization and gaseous emissions quantification can be seen in Colón et al. (2012) and Lleó et al. (2012) for IC and HC, respectively. All values found were compared with international and local standards (Spanish legislation) and references, such as the European Commission for bio-waste management (2008) and the Spanish Royal Decree 506/2013 (Ministerio de la Presidencia, 2013). This decree sets the limits permitted for heavy metal content in compost in order to be used as mineral fertilizer substitute (Annex 6.6). According to Spanish Royal Decree 506/2013, the compost (IC and HC) comply the quality conditions to be used as soil amendment and as a mineral fertilizer substitute.

6.2.10 Experimental conditions

This crop sequence was part of an experimental crop rotation fertilized with organic and mineral fertilizers since 2006. The experimental plots were located at the SELMAR research fields in the Maresme county in Santa Susana (Norwest part of Catalonia). This site is an experimental open-field of the Institut de Recerca i Tecnologia Agroalimentàries (IRTA). The Maresme county is a region characterized by an intensive crop rotation of several horticultural products (i.e. vegetables).

The region has a typic Xerothent soil and Mediterranean climate. The land have been used in an intensive crop rotation since 2006 (i.e. chard (2006), tomato and cauliflower (2007), onion (2008) and endive (2010). In our case, a crop sequence of cauliflower and tomato crop was considered to study the environmental impacts for a one-year cycle. Figure 6.1 shows an overview of the crop sequence.

	Compost application[1]			
Date →	10-sep-11	06-oct-11 → 08-feb-12	09-feb-12 → 10-jun-12	11-jun-12 → 24-oct-12
Crop		Cauliflower		Tomato
Horticultural stage		Planting – Harvesting	Horticultural inactivity GAP[2]	Planting – Harvesting
Crop duration (days)		125	122	135
Specie		Brassica oleracea	-	Lycopersicon esculentum
Irrigation system		Micro-sprinkler	-	Dripping
Density (pl · m^{-2})		2.01		0.5
Yields (ton · ha^{-1})				
IC[3]		4.5	-	35.7
HC[4]		6.8	-	28.0
MF[5]		8.6	-	27.9

Figure 6.1 Summary of the main features of the crop sequence

[1]The composts applied to plot crops were industrial and home compost
[2]There was not cultivation between cauliflower and tomato crops
[3]IC: Industrial compost
[4]HC: Home compost
[5]MF: Mineral fertilizer
Note: the entire horticultural activity lasted 384 days, a one year cycle of 365 days was considered for the crop sequence. The impacts of the horticultural inactivity gap were allocated to the last crop (tomato).

The experimental field design (one plot of 414 m^2) consisted in three blocks of 138 m^2 (IC, HC and MF) with three replicates for each fertilization treatment . A total of 9 blocks of 46 m^2 each were designed for the entire crop sequence.

6.2.10.1 Crop varieties: Cauliflower and tomato

The plants of cauliflower *(Brassica oleracea* L. var. botrytis, commercialized as Trevi) were transplanted on October 06th, 2011 at a density of 2.1 plants·m^{-2}. The cauliflower was harvested in February 08th, 2012, for a cultivation period of 125 days (Figure 6.1). In the case of tomato crops, the plants (*Lycopersicon esculentum* Var. Punxa) were transplanted in June 11th, 2012 at a density of 0.5 plants·m^{-2}. The tomato was harvested in October 24th, 2012 for a cultivation period of 135 days (Figure 6.1).

6.2.10.2 Horticultural inactivity gap

There was a horticultural inactivity gap (HIG) during the crop sequence in which no cultivation was made in the plots. The HIG was from February 09th 2012 until June 10th 2012 (Figure 6.1). Some experimental conditions (i.e. weather) and agricultural management operations (land preparation and resources) prevented cultivation during this period. In a crop sequence, the environmental burdens of the inactivity horticultural periods or any period between the harvesting of a crop and soil tillage should be attributable to the following crop (Hayer et al. 2010 and Martínez et al. 2014). Therefore, in our case of study, the environmental burdens of HIG were allocated to the tomato crop. The environmental burdens charged to tomato crop were basically the emissions to air (NH_3, N_2O and N_xO) due to the biological activity; and to water by the leachate of the NO_3 that remains in soil during the period of horticultural inactivity.

6.2.10.3 Weather conditions

Different weather conditions were observed during the cropping time for each crop. Climate data were obtained from a weather station next to crop fields (Santa Susana). In the case of the cauliflower that was planted and harvesting in the winter season of 2011, the average of temperature was of 12.9 °C with a rainfall of 200 $L{\cdot}m^{-2}$ for October 2011and 120 $L{\cdot}m^{-2}$ for the first two week of November 2011 (RuralCat, 2013). These weather conditions were considered atypical compared with the same period for previous years which recorded an average of 11 °C (RuralCat, 2013). These weather conditions affected mainly the nitrogen mineralization and the leachate of fertilizers. In fact, these weather conditions delayed the application of mineral fertilizer and affected negatively the yield of fruits for the three fertilization treatments. For tomato crop that was cultivated in summer season of 2012, an average temperature of 22 °C and a rainfall of 122 $L{\cdot}m^{-2}$ were recorded during the cultivation period (RuralCat, 2013). The weather conditions for this crop were similar regarding previous years for the same period.

6.2.11 Water and fertilizers applied

The cauliflower was irrigated 3-4 times per week and the tomato daily. The water dose was based on the tensiometer reading and the evapotranspiration. For the irrigation of crops, we use the most common practices in the region. Cauliflower was irrigated using micro-sprinkler system and tomato with dripping system (Figure 6.1). The IC and HC were applied directly to land with agricultural machinery at the beginning of the cauliflower crop (September 2011). The mineral fertilizer was mixed and applied with the irrigation water. Table 6.1 shows the dose of organic fertilizer applied to crops for the two compost allocation procedures (Ta and NMa), the dose of mineral fertilizer and the irrigation water applied to each crop.

The doses of fertilizers were experimentally calculated by taking into account the soil nutrient content and the nutrient needs of the crops. Similar quantities of fertilizer were applied to each fertilization treatment (Table 6.1), except for cauliflower crop which the quantity of MF was considerably lower than tomato crop. The fact of a lower application of mineral fertilizer to cauliflower crop was due to the great quantity of rainfall at the beginning of the cultivation.

The organic fertilizer (compost) generally is applied to cover the nutrient needs of several crops in cycles of 1-2 years. In this research, it was assumed that the compost was applied to meet the nutrient needs of two calendar years (720 days). The total compost applied to land for the crop sequence was of 1.1 $kg \cdot m^{-2}$ for IC and 1.6 $kg \cdot m^{-2}$ for HC (Table 6.2). As explained, in this study two procedures of compost allocation to crop (Ta and NMa) were evaluated to know the environmental performance of the systems.

Table 6.2 Compost allocated to crop for the two allocation procedures

	L	Fertilization treatment	Units	Crop sequence[1] IC[3]	Crop sequence[1] HC[4]	Cauliflower IC	Cauliflower HC	Horticural inactivity GAP[2] IC	Horticural inactivity GAP[2] HC	Tomato IC	Tomato HC
	a	Total compost applied to plots[5]	tons · ha^{-1}	11	16						
	b	Cultivation period[6]	days			125		105		135	
Allocation procedures – Ta[a]	c	Lifetime of compost application[7]	days	730							
Allocation procedures – Ta[a]	d	Allocation factor[8]	-			17%		14%		18%	
Allocation procedures – Ta[a]	e	**Compost allocated to crops[9]**	**tons · ha^{-1}**			**1.88**	**2.74**	**1.58**	**2.30**	**2.03**	**2.96**
Allocation procedures – NMa[b]	f	N mineralization for the first year[10]	days	365							
Allocation procedures – NMa[b]	g	N mineralization rate for the first year[11]		40%							
Allocation procedures – NMa[b]	h	Time factor[12]				34%		29%		37%	
Allocation procedures – NMa[b]	i	Allocation factor [13]				14%		12%		15%	
Allocation procedures – NMa[b]	j	**Compost allocated to crops[14]**	**tons · ha^{-1}**			**1.51**	**2.19**	**1.27**	**1.84**	**1.63**	**2.37**

[a]Ta: This procedure allocates the compost applied to crops according to the crop duration (since plant cultivation date until fruit harvesting).
[b]NMa: This procedure allocates the compost applied to crops according to the degree of N mineralization in soil.
[1]Crop sequence column refers to data that is common for the two crops
[2] There was not crop during the period from February 16, 2012 to June 10, 2012.
[3]IC: Industrial compost
[4]HC: Home compost
[5]The composts were applied to plots at the beginning of the crop sequence
[6]Cultivation period refers to the duration of crop since plantation to harvesting. A horticultural inactivity GAP of 105 days was considered between the two crops
[7]It was considered for the Ta (allocation procedure) that the compost is applied to plots every two years
The letters in the left side of the table (column L) were used for the calculations
[8]d = b / c
[9]e = a · d
[10]The period considered for the N mineralization for the APB procedure was one calendar year
[11]It was considered a constant degree of N mineralization of 40% for the first year (365 days)
[12]h = b / f
[13]i = g · h
[14]j = a · i

The irrigation water applied to each crop was similar for the three fertilization treatments (IC, HC and MF), Table 6.1. According to Directive 91/676 (European Economic Community 1991), the high content of nitrogen found in the ground water (1.86 miliequivalents of NO_3^- = 115.32 g $NO_3^- \cdot m^{-3}$) nearby of the experimental plots was out of limit permissible (50 g $NO_3^- \cdot m^{-3}$). Therefore, the nitrogen content in the ground water was accounted as a contribution of nutrient to crops (Table 6.1).

6.2.12 Degree of nitrogen mineralization

The compost is characterized as a slow release-nutrient fertilizer, which is normally applied to fulfill an entire cropping plan (van Zeijts et al., 1999). The degree of N mineralization after the application of compost can vary significantly. Several causes affect then mineralization in soil: the fact of the nitrogen depends primarily on the composition and maturity of the compost, as well as climatic conditions and management practices, among others. Several rates of mineralization of nitrogen have been determined by researchers such as Martínez-Blanco et al. 2013 who considered rates between 5-22% for the first year of compost application, and 40-50% for the following 3rd-5th years. Experts on compost production and its application in the Catalonia region reported rates of 60% of the nitrogen available in the soil during the first year and 40% for the second year (Bernat et al., 2000; Martínez et al., 2013). For this study, a rate of 40% was used to calculate the mineralization of the N available in the compost (IC and HC). This consideration in the degree of N mineralization in soil was for the first year of compost application and it is assumed a constant degradation rate over the time. The remainder N in soil will mineralize at a constant rate of 20% for the second year and so on until complete the entire mineralization cycle over the time.

6.2.13 Nitrogen provided to crops

The N provided to crops (Table 6.1) was from three sources: a. from irrigation water, b. from rainfall and c. from organic (IC and HC) and mineral fertilizers (MF). The N content in the irrigation water (1.86 miliequivalents of N = 26.1 $gN \cdot m^{-3}$) was experimentally measured from the ground water taken from a well located near the plots. As well as, the N in rainfall was of 0.00076 $L \cdot m^{-2}$. In the case of the N content in the organic fertilizer (IC and HC), they were experimentally measured from samples (Annex 6.6). Furthermore, the N supplied by the organic fertilizer varied according to the allocation method. As explained before, the first allocation method was based on the cultivation time (from plantation to harvesting) and the second one took into account the degree of N mineralization (i.e. 40% for the first year). In the case of organic fertilizer, the doses applied of KNO_3 were also experimentally calculated taking into consideration the type of crop and the nitrogen available in soil.

6.2.14 Nitrogen uptake by crops

The N uptake by the fruits was experimentally measured from biomass samples per m^{-2} and per plant for the three fertilization treatments. Determinations of NO_3^- N content were done following the method Keeney and Nelson (1982). Total and marketable yield in the whole plot area were determined at harvest time. The plants, sampled in the harvest period, were dried at 65 ºC until constant weight and its N content analyzed in fruits, leaves and stems by the Kjldahl method (Doltra and Muñoz, 2010). The N uptake by m^2 and plant is presented in Table 6.3.

Table 6.3 Nitrogen uptake by crops per m^2 and plant

		Crop sequence					
		Cauliflower			Tomato		
	Units	IC[1]	HC[2]	MF[3]	IC	HC	MF
Yield[4]	g dry matter·m^{-2}	342	353	319	709	619	836
N uptake	g N·m^{-2}	28	26	27	22	16	21
Plantation density	pl·m^{-2}	2.1	2.1	2.1	0.5	0.5	0.5
Yield	g dry matter·pl^{-1}	164	169	153	1,418	1,239	1,672
N uptake	g N· pl^{-2}	13	12	13	44	31	43

[1]IC: Industrial compost
[2]HC: Home compost
[3]MF: Mineral fertilizer
[4]Samples of plants were analyzed to determine N content in the biomass (fruit, leaves and stem)

6.2.15 Carbon sequestration

Sequestration of C into soil can be seen as removal of C from atmosphere and translated to saved CO_2 emissions, being directly related to the category of "Global warming" (Martínez et al., 2013). As presented by Smith et al. (2001), the carbon sequestration has been recognized by the Intergovernmental Panel on Climate Change (IPCC, 2006) as one of the possible measures through which greenhouse gas emissions can be mitigated.

Carbon sequestration is calculated as a percentage of the added carbon in the treated organic waste permanently bound in the soil (Hansen, 2006). After the compost is produced and applied to the land, it continues to degrade, releasing carbon dioxide and forming humic compounds. We assumed that only 8.2% of C content in compost remains in soil 100 years after its application and the remaining 91.8% will be mineralised to CO_2 over the time (Handsen et al., 2006; Smith et al., 2001; Martínez et al., 2010a; Martínez et al., 2010b). The carbon sequestration calculated for each crop was considered as a negative contribution to the total greenhouse gas emission.

Table 6.4 shows the carbon sequestration per crop for the two compost allocation procedures (Ta and NMa).

Table 6.4 Carbon sequestration per crop and fertilization treatment

Allocation procedures		L	Fertilization treatment	Units	Crop sequence[1]		Cauliflower		Horticural inactivity GAP[2]		Tomato	
					IC[3]	HC[4]	IC	HC	IC	HC	IC	HC
		a	C content in compost[5]	$g \cdot kg$ of compost^{-1}	161	344						
Allocation procedures	Ta[a]	b	Compost allocated to crops[6]	$g \cdot m^{-2}$			188	274	158	230	203	296
		c	C content in compost applied[7]	$g \cdot m^{-2}$			30	94	25	79	33	102
		d	**C sequestration[8]**	$g \cdot m^{-2}$			**2.4**	**7.5**	**2.0**	**6.3**	**2.6**	**8.1**
	NMa[b]	e	Compost allocated to crop[9]	$g \cdot m^{-2}$			151	219	127	184	163	237
		f	C content in compost applied[10]	$g \cdot m^{-3}$			24	75	20	63	26	81
		g	**C sequestration[11]**	$g \cdot m^{-4}$			**1.9**	**6.0**	**1.6**	**5.1**	**2.1**	**6.5**

[a]Ta: Time allocation procedure allocates compost applied according to cultivation time
[b]NMa: N mineralization procedure allocates compost applied according to the N mineralization in soil
[1]Crop sequence column refers to data that are common for the crops
[2]There was not crop during the period from February 16, 2012 to June 10, 2012. The carbon sequestered was allocated in the environmental assessment proportionally to crop according to the allocation procedure
[3]IC: Industrial compost
[4]HC: Home compost
[5]The C content in compost was experimentally determined (compost characterization)
[6,9]The compost was allocated according to the two allocation procedures (Table 2)
The letters in the left side of the table (column L) were used for the calculations
[7]c = a·b/1000 (conversion factor kg / g)
[8]d = c·8%, it was considered that 8% of C contained in the compost applied is retained in soil after 100 years
[10]g = a·f /1000 (conversion factor kg / g)
[11]h = g·8%

6.3 Results and discussion

This section presents the analysis of results for the agricultural parameters experimentally measured and the environmental assessment of the systems. The agricultural parameters measured were the yield, nitrogen uptake by the crops, the degree of N mineralization in soil and the carbon sequestration. The environmental assessment was leaded by stages and sub-stages and for the total impacts. Likewise, the analysis for the total impacts were split by crops, fertilization treatments and the allocation procedure used to allocate the compost applied to plots.

6.3.1 Agricultural parameters

6.3.1.1 Yield

The total yield varied according to crops and fertilization treatments. As shown in Figure 6.1, the crops (cauliflower and tomato) fertilized with MF had the best agronomical performance. The yield for cauliflower fertilized with MF was 26% and

91% higher than cauliflower fertilized with IC and HC, respectively. While, the yield for tomato fertilized with MF and HC was the same for both but tomato fertilized with IC was 22% lower than MF and HC. The weather condition affected negatively the yield of cauliflower. A lot of rainfall at the beginning of the cultivation surely caused fertilizers leachate and consequently nutrients loss (nitrogen). Also, the rain delayed the MF application with the consequent reduction of the quantity applied. Due to the compost was applied to cover the nutrient needs for a cycle of two years until the next application; therefore, the nutrient loss by the high rainfall also affected negatively the yield of tomato. Furthermore, it is important to highlight that the quantity and availability of the fertilizers are crucial for the crop yield, for example, the fact of the nutrients in MF are already mineralized in form of NO_3; so, they are almost immediately available to be assimilated by the crops for its metabolic processes. On the other hand, the organic fertilizers (compost) are characterized by a slow nutrient release in which the conversion process are highly dependent on several variables such as nutrient content, maturity and stability of compost, cultivation management and the weather conditions.

A literature review showed a lacking of data for yields of tomato and cauliflower under similar cultivation management. Although, in different condition (i.e. different dose of fertilizer and weather conditions), Martínez et al. (2011) reported commercial yields of 1 and 10 times higher for cauliflower and tomato fertilized with MF. It is presumed that the higher yields applied in those crop were favored by the weather conditions and a higher dose of MF applied to crops, among others. In the case of tomato, this was a traditional variety (*Lycopersicom esculemtum* Var. Punxa) which normally presents inferiors yields than the variety cultivated (*Lycopersicom esculemtum* Var. Elvirado) in Martínez et al. (2011) essays. However, the yields found in the current essay (2-4 $kg \cdot m^{-2}$ for a density of 0.5 $pl \cdot m^{-2}$) were similar of those reported in Casals et al. (2011) (2-3 $kg \cdot m^{-2}$ for a density of 0.5 $pl \cdot m^{-2}$) for the same variety (*Lycopersicom esculemtum* Var. Punxa).

6.3.1.2 Nitrogen applied and uptake by crops

As shown in Table 6.1 the total N supplied to crops through the compost applied was similar regarding the fertilization treatments (IC and HC) for a same crop and compost allocation procedure. For the cauliflower crop, the total N supplied through MF was lower than IC and HC. The differences between MF and IC and HC ranged from 25-37%, depending on the fertilization treatment and compost allocation procedure. Meanwhile, the N total supplied through MF for tomato crop was higher than IC and HC. For this case, the differences varied between 62-73% depending on the fertilization treatment and compost allocation procedure.

In general, as seen in Table 6.1 the quantity of MF supplied to tomato was 4 folds higher than cauliflower. This result is explained because tomato is a more demanding-nutrient crop than cauliflower. Furthermore, the great quantity of rainfall at the beginning of the cultivation delayed the application and quantity of MF for cauliflower crop.

Regarding, the N uptake was similar for a same crop regardless the fertilization treatment (Table 6.3). The results shows that the N uptake ($gN \cdot pl^{-1}$) was considerable higher in the tomato crop. Depending on the fertilization treatment, the N uptake ($gN \cdot pl^{-1}$) for tomato was about 2-3 fold higher than cauliflower. The low quantity of N uptake by tomato crop for the case of HC (31 $gN \cdot pl^{-1}$) was considered a special case attributable to random conditions of the experiment.

The rough balance of N between the N uptake (Table 6.3) and the N provided (Table 6.1) indicated that great part of the N uptake was supplied by the soil in both crops. The N uptake for cauliflower was in an average of 27 $gN \cdot m^{-2}$ for the three fertilization treatments (IC, HC and MF), meanwhile the average of N supplied to crop was of 5 $gN \cdot m^{-2}$. Thereby, almost 22 $gN \cdot m^{-2}$ (440%) of N uptake was sourced by the N storage in soil. Similarly for tomato crop but in less proportion, the N uptake (average of 19 $gN \cdot m^2$) for IC and HC against the N supplied (average of 11 $gN \cdot m^2$). In the case of MF for tomato the N uptake (21 $gN \cdot m^2$) was 3 $gN \cdot m^2$ higher than the N supplied (18 $gN \cdot m^2$). The result indicated that the soil of the experimental plot operated as reservoir of N which surely was applied with the fertilizers (organics or minerals) to crops previously cultivated.

6.3.1.3 Carbon sequestration

The carbon sequestration accounted was decreased to the total impact for the CC category. As seen in Figure 6.2, the carbon sequestration represented a great contribution (i.e. 3-18% of the total impact) in the environmental performance of the systems for the global warming potential. The results of carbon sequestration varied depending on the crop and fertilization treatment, the highest values for carbon sequestration were for the crops fertilized with HC. Now, regardless the allocation procedure for the compost applied to crops, the carbon sequestration was approximately three times higher for the systems fertilized with HC than IC (Table 6.4**).** As seen in the Table 6.4, the higher quantity of carbon sequestration for HC systems was due to a great quantity of compost applied and its high content of C which was two times higher than IC. Meanwhile, regardless the fertilization treatments (IC and HC), the carbon sequestered was 25% higher for the time allocation procedure (Ta) than the allocation procedure based on the degree of N mineralization (NMa) in soil. The differences found between allocation procedures were due to Ta allocated a higher quantity of compost than NMa procedure. Likewise, Ta procedure had an allocation factor a little higher (2-3%) than the calculated for NMa (Table 6.2).

6.3.2 Environmental assessment

6.3.2.1 Environmental assessment by stages and sub-stages

Figure 6.2 presents the environmental impacts of the different stages and sub-stages per crop type, category and per fertilization treatment. Figure 6.2 (a, b) show that the compost production stage which considers element such as: energy, water, building and process emissions, was the greatest impact contributor for POF and TA. These results were for both crops (cauliflower and tomato) fertilized with IC. The impacts for these categories were mainly produced by the NH_3 emitted during the composting process. For the remainder categories (CC, FE, ME, FD and CED), the impacts for both crops varied mainly with the stages related to the cultivation phase. For example in the cauliflower crop fertilized with IC the fertirrigation stage (i.e. primary pipe) was the highest impact contributor for CC, FE, FD and CED categories. Whilst the tomato crop which had a higher irrigation than the cauliflower, the irrigation stage showed the greatest impacts in CC, FD and CED. In those categories the impacts were due to the electricity consumed for the two pumps used to pump the water from well and to irrigate the crops.

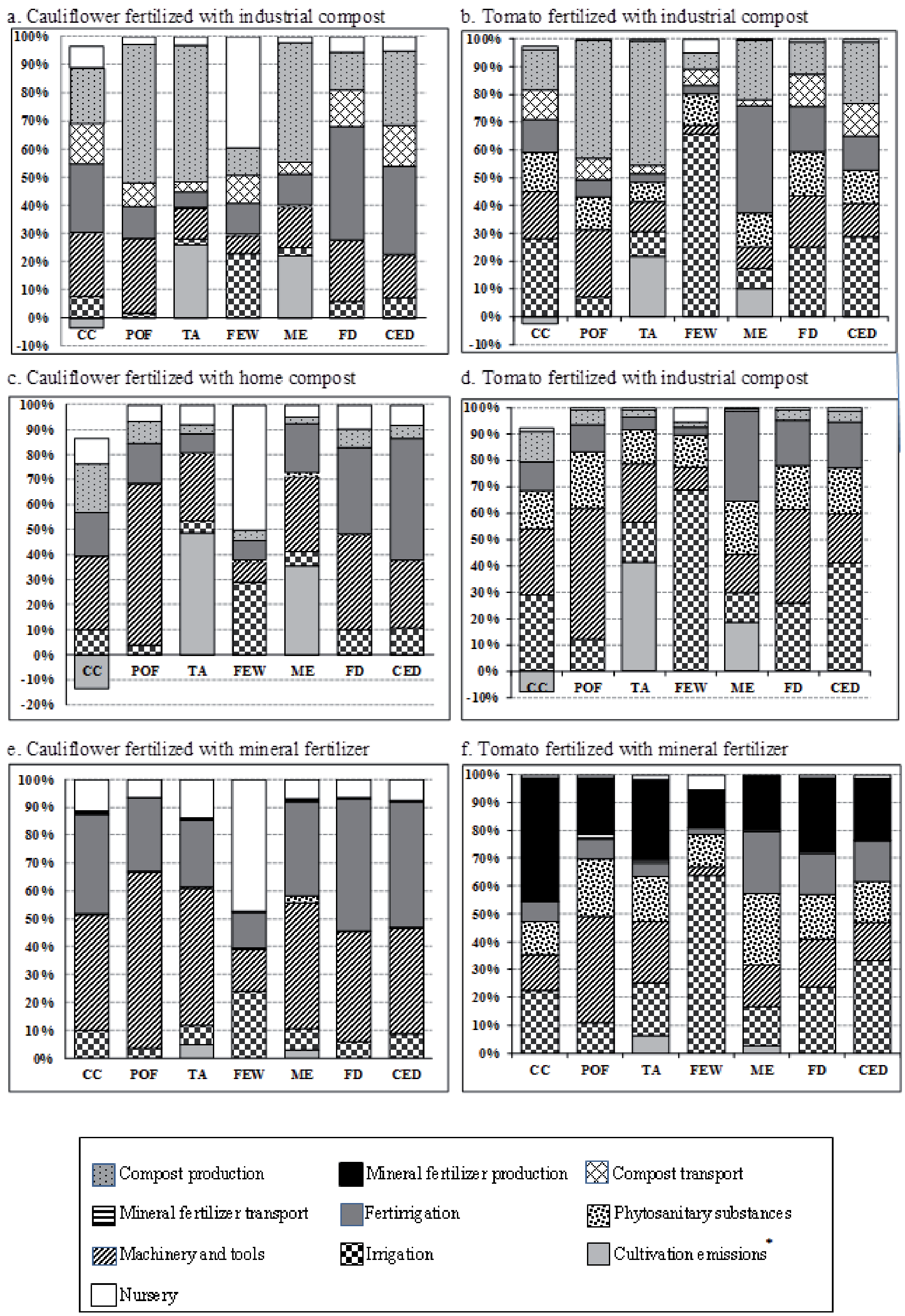


Figure 6.2 Impacts by fertilization treatment, stages and impact category

*This stage considers emissions to air (NH_3, N_2O and NO_x) and water (NO_3^-) from fertilizer applied.
**In this figure, the impacts are accounted for the NMa allocation procedure

Figure 6.2 (c, d) shows the impacts for cauliflower and tomato fertilized with HC, respectively. The machinery and tools used in the tillage operations (i.e. soil preparation, compost application, etc.) represented the highest impacts for cauliflower in the most categories assessed (CC, POF and FD), Figure 6.2c. While, in the case of tomato crop, the stages of machinery and tools and the irrigation were the greatest contributors for the most categories (CC, POF, FE, FD and CED). It is remarkable (Figures 6.2c and 6.2d) the amount of the carbon sequestration for both crops which represented a negative contribution in the CC category. The results showed that the carbon sequestration was two folds higher for crops fertilized with HC than IC which is explained due to a greater content of C (344 g · kg of compost^{-1}) (Table 6.4) in HC and the high quantity of HC (16 tons · ha^{-1}) applied to crops (Table 6.2).

Now comparing MF with IC and HC, we can see significant difference in the environmental assessment of the systems (Figures 6.2d and 6.2e). The machinery and tools and fertirrigation were the stages that most affected the environmental performance of the cauliflower crop. Meanwhile, mineral fertilizer production, the phytosanitary substances and irrigation were the stages that most contributed in the environmental performance of the tomato crop. Two reasons explain the impact differences between the two systems, the high quantity of MF (KNO_3) applied to tomato that was eleven times greater than cauliflower (Table 6.1). Furthermore, as explained in the methods section, the high quantity of irrigation water applied to tomato which was almost three times higher than cauliflower. While, the high quantity of water applied to tomato considerably affected other stages (i.e. irrigation) due to the electricity consumption by the two pumps used to pump water from well and to irrigate the crop plots.

6.3.2.2 Total environmental assessment

As shown in Figure 6.3, the systems were classified according to crop type (cauliflower and tomato), fertilization treatment (IC, HC and MF) and the allocation procedure used to allocate the compost applied to crops (Ta and NMa). Regardless the fertilization treatment and the compost allocation procedure, the cauliflower crop had a better environmental performance than tomato for all impact categories. The high quantity of irrigation water as well as the fertilizer applied was the main elements that affected the performance of the tomato crop. On the one hand, for tomato crop, the irrigation implied the use of more pump-hours, so a mayor electricity consumption by the use of pumps to pump water from well and to irrigate the plots. Furthermore, the application of greater quantity of compost applied to tomato meant a mayor use of machinery in soil due to the tillage operations to apply and prepare the soil for the cultivations steps.

The fertilization treatment with HC had the best results than IC and MF in all impact categories except in TA in which MF had the lowest impact. Although, the differences for TA were not as significant between HC and MF, it is known that the organic fertilizers have emissions of NH_3 and NOx (a great contributor of TA.

In regards to allocation procedure, as shown in Figure 6.3, the crops (cauliflower and tomato) fertilized with IC and Ta (i.e. allocation procedure based on the cultivation time) had the greatest environmental impact in all categories except in CC and ME where the highest impact was for NMA (i.e. allocation procedure based on the degree of N mineralization). The impacts values ranged between 7-14% depending on the crop and the category considered. While, the crops fertilized with HC, the NMa procedure showed the highest impacts in all categories assessed. For this case, the impacts were between 1-14% depending on the crop and the category. For our case of study, an opposite trend was observed when analyzing the results according to the allocation procedure. The compost production stages for HC had low contribution in the total impacts (<10%), while in IC the contribution of those stages (i.e. compost production plus transportation) the impacts ranged between 12-50%. Thereby, a greater contribution in the compost production stage, so a lower contribution in the cultivation stages. Therefore, Ta showed better results in such cases with low incidence in the compost production (HC) and NMa in those cases with high contribution of the production process (IC).

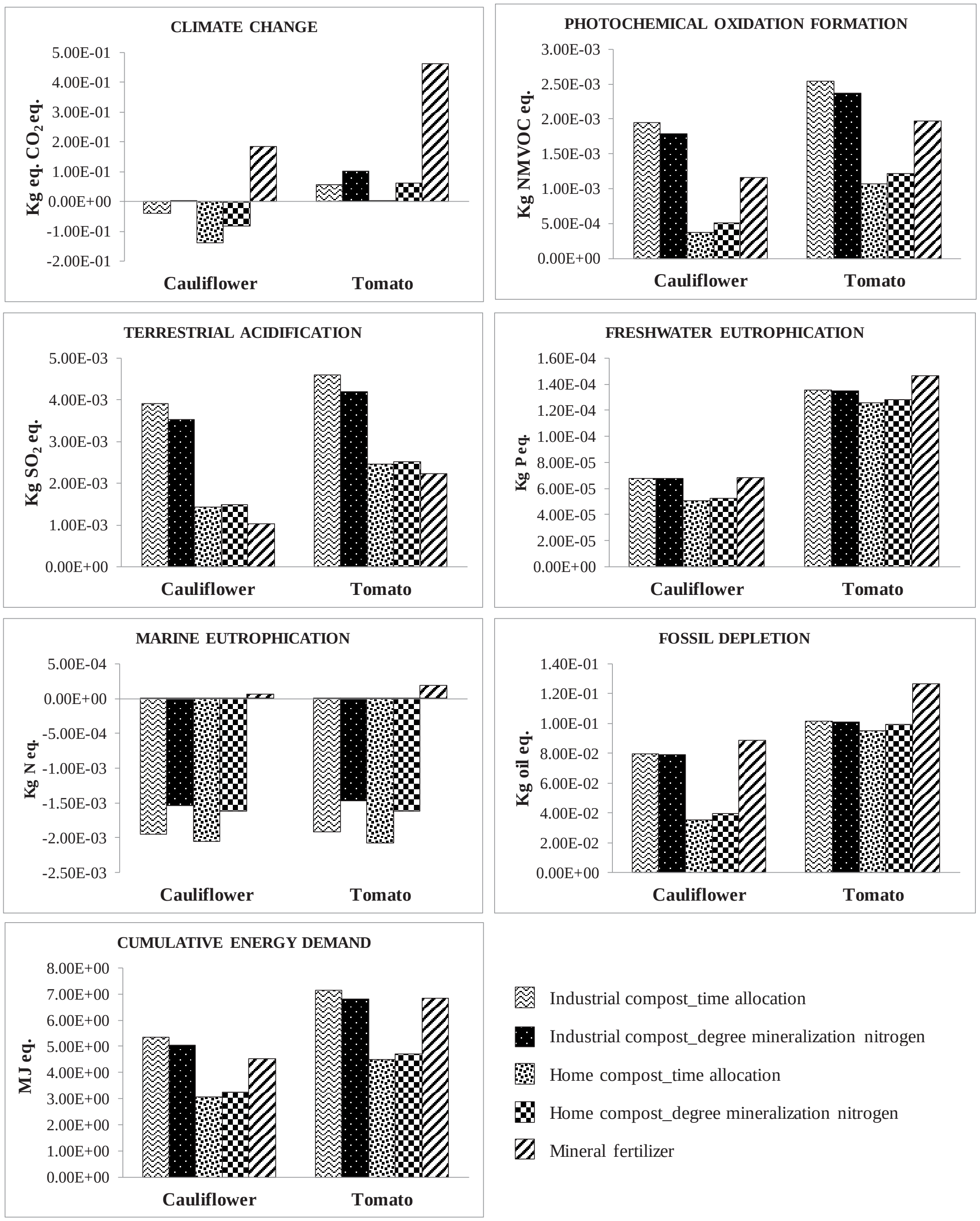


Figure 6.3 Total impacts per fertilization treatment, impact category and allocation procedure

In order to study the potential environmental benefits of the entire crop cycle regarding the individual crops, the impacts were calculated per day for the two crops and for each fertilization treatment, and for the entire crop cycle (i.e. sum of impacts of both crop), Figure 6.4. In general it was observed that the impacts of the entire horticultural cycle were lower than the individual crop in the most categories assessed. Although, the differences were higher between the cycle and tomato crop due to in general this crop had greater impacts than cauliflower. As explained in others sections, the tomato crop was more irrigated and more quantity of mineral fertilizer was applied.

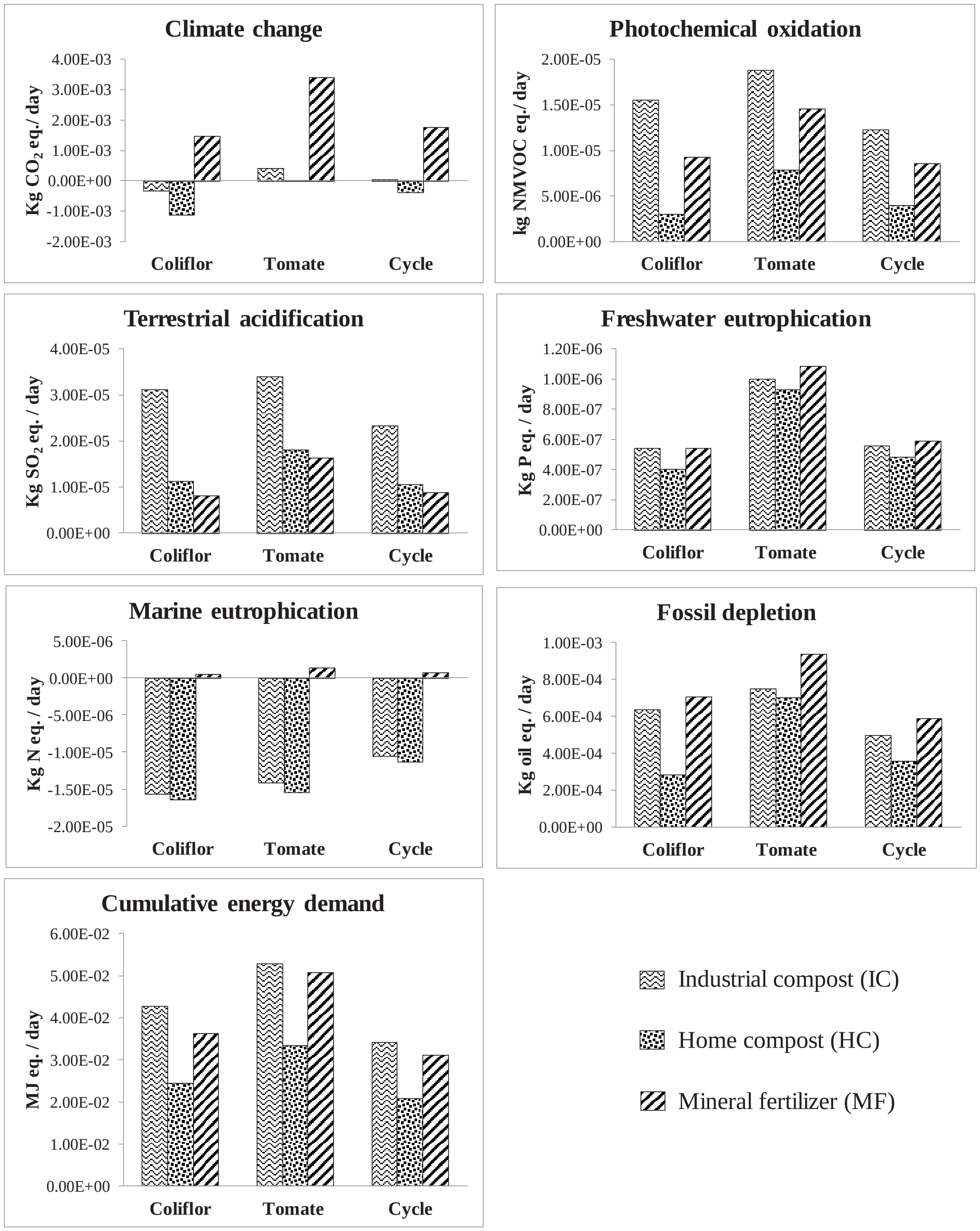


Figure 6.4 Environmental comparision (unit eq. of pollutant element/day) between single crops and the entire crop cycle

6.3.2.3 Discussion

The agronomical and environmental performance of cropping systems is the result of a complex interrelation of variables such as crop type, weather conditions, fertilizer type and crop management. The interrelation in the variables is key factor for a sustainable crop sequence. By one side we observed that the fertilization with MF for both crops (cauliflower and tomato) was much better than the fertilization with organic matter (IC and HC). However, on the other hand, the environmental performance of the crop fertilized with organic fertilizer (HC) was better than MF. From this research we observed that the yield of crops is highly depended on the nutrient supplied to crops and the grade of N mineralization in soil. The nutrient supply depends on several variables, weather conditions (rainfall), irrigation water, the nutrient content (nitrogen) in fertilizers, allocation methods of compost to crop and horticultural management practices. For our case of study no literature references under similar production and application of fertilizer in crops were found to compare results. Martínez et al. (2011) reported higher yields for cauliflower and tomato cultivated in the same plots were our study was made. Although, the horticultural results found by Martínez el al. (2011) were for crops cultivated in different conditions such as: crop management, cycles and varieties; sourcing of compost; nutrient concentration in compost; irrigation, doses and weather conditions.

Even though N content in IC was 47% higher than HC (Table 6.1), the final N applied to crops was very similar for both fertilization treatments (IC and HC) due to the quantity of compost applied to HC compensate the N concentration registered for IC.

The total N provided to crops varied according to the fertilization treatment, crop and allocation procedure for compost applied (Table 6.1). Furthermore, the quantity of N applied varied considerably with the crop type (i.e. the N applied to tomato crop was two folds higher than cauliflower except for mineral fertilizer).

In horticultural crops, it is very important the balance between the nutrients need by the crop and the N content in soil because not necessarily great quantities of N applied to crop will guarantee a greater crop yield. As was observed in this study, the N uptake was very similar in a same crop with an average for the three fertilization treatment (IC, HC and MF) of 27 $gN \cdot m^2$ for cauliflower and 21 $gN \cdot m^{-2}$ for tomato (Table 6.3). Then, regardless the allocation procedure, the N supplied was in the order of 7.5 $gN \cdot m^{-2}$ and 16 $gN \cdot m^{-2}$ for cauliflower and tomato, respectively. Therefore, a rough balance shows that almost 20 $gN \cdot m^{-2}$ and 4 $gN \cdot m^{-2}$ for cauliflower and tomato, respectively, were supplied from the N storage in soil. While, the situation was a little different with MF, the N uptake by the cauliflower was 27 $gN \cdot m^{-2}$ and 21 $gN \cdot m^2$ for cauliflower and tomato, respectively, while the total N supplied to crops was 5 $gN \cdot m^{-2}$ for cauliflower and 23 $gN \cdot m^{-2}$ tomato, respectively. The net balance showed that in the case of cauliflower 21 $gN \cdot m^{-2}$ was taken from soil and the tomato crop exceeded N requirements in about 2 $gN \cdot m^{-2}$ which surely will remain in ground for future crops. This great provision of N from soil in the case of mineral fertilizer for the cauliflower crop should be considered as a negative environmental effect because the soil lost an important source of nutrients.

Despite of the range of benefits of the compost applied to crops; it enhances soil aggregate stability and reduces risk of erosion (Annabi et al., 2011); increases soil porosity (Hargreaves et al., 2008); and releases nutrients including C and N (Benitez et al., 2003). However, the levels of N in the compost applied (1-2.5% N-Kjedhal) which are considerably lower than the inorganic fertilized (14% of N in KNO_3) required high quantity of compost to compensate the N differences. As in our study case, Thangarajan et al. (2013) reported low levels of N content in compost between 1-2%; and 46% for inorganic fertilizers (Urea). Though beneficial, compost production and application are associated with some risk and problems such as contamination by heavy metals, salts, weed seeds, and pathogens (Chan et al., 2007). In addition the mayor concern of composting is C and N-losses which decrease the agronomic value of compost and also contribute to GHG (Hao et al., 2004) and other environmental impacts such eutrophication (freshwater and marine) and terrestrial acidification.

6.3.3 Conclusions

The present research was carried out using the LCA methodology for the evaluation of a crop sequence of tomato and cauliflower for one year cycle. Organic and mineral fertilizer can be used as mineral substitute in crops. The home compost showed the best environmental performance than industrial compost and mineral fertilizer in the most impact categories, except in terrestrial acidification and marine eutrophication. Emissions occurred due to compost degradation in soil by the biological activity are the main contributor for those categories. The environmental performance of the horticultural systems was better for the allocation procedure based on the cultivation time than the degree mineralization in soil. Crops fertilized with IC had a better environmental result (less impact per category) than HC when considering the allocation procedure based on the degree of N mineralization in soil. This trend was observed since for this fertilizer the compost production stage had a great contribution in the total environmental impacts. The environmental analysis showed a better result of the entire cycle of the crop sequence than the individual crops in the most categories considered. In terms of the agronomical results, the mineral fertilizer gave higher yields than the crop fertilized with home and industrial compost. This yield is due to in part the prompt availability of nutrient to plants due to the nutrient is already mineralized as KNO_3 at the time of application. While, in the case of organic fertilizer, the mineralization of nitrogen is slow and gradually in time, so it is no prompt availability of nutrients to crops. Likewise, the mineralization process depends on some other conditions such as maturity and stability of the compost, weather conditions, soil type, horticultural management; and the nutrient content in the compostable material.

Future research should be recommended in the same field plots where the current experiment was conducted to evaluate and validate results of the current work such as the degree of N mineralization in soil. As well as, future research in the same fields should be needed in a crop rotation by varying and testing some variables such as, weather condition, year season, organic fertilizers compositions and horticultural management.

CHAPTER 7

Discussion, conclusions and future perspectives

Chapter 7

7 Discussion, conclusions and future perspectives

7.1 Discussion

This chapter presents a discussion of the main highlights found from the case studies developed in the dissertation. The outcomes of the thesis and its related discussion are directly linked with the proposed objectives for each case study. In general, the thesis focused in technologies for a sustainable management of municipal solid waste. Specifically, a new technology to treat unsorted municipal solid waste was studied to observe its environmental performance which was compared with two well-known traditional technologies: incineration and landfill. Secondly, it was considered the treatment of the organic matter from municipal solid waste (MSW) to produce compost which was applied in horticultural crops. Regarding the transformation of the organic matter to produce compost, a case study was developed to observe the environmental and agronomical performance of industrial and home compost versus mineral fertilizers. Another case study was developed to compare the environmental impacts of two home composts with low and high gaseous emissions of the home composting process. Finally, a case study was carried out to analyze the environmental behavior of a crop sequence of cauliflower and tomato for one-year horticultural cycle. Thereby, as stated in the dissertation, the cornerstone for a sustainable management of waste is based on the use technologies to avoid or at least to reduce environmental pollution.

7.1.1 Environmental assessment of technologies to treat municipal solid waste

The European Union countries set goals to reduce the quantity of waste to landfill (Directive 1999/31/CE). Autoclaving technology is seen as an alternative to achieve in part EU goals. This new technology combined with biological treatments technologies presents several advantages regarding traditional ones (incineration and landfill) such as the separation of recyclables (i.e. metals and plastics) in single fractions (PET, metals, mixed plastics, etc.) and the formation of an organic fiber (OF) from the biodegradable material content in the waste stream. However, autoclaving presents several disadvantages mainly by the great quantity of energy consumed to carry out the process. It is clearly observed in the environmental assessment that the energy consumption was the main contributor in the most categories assessed, and autoclaving was the main energy consumer regarding other processes (e.g. sorting and biological treatments). As stated in the case study, autoclaving should always be seen as part of an integrated system along with sorting process and biological technologies for the treatment of the OF resulting from its process. Autoclaving has a total energy consumption of 287 kWh / tonne of unsorted municipal solid waste processed, which 120 kWh corresponds to electricity and 167 kWh for thermal energy (heat). In fact, it can be observed that autoclaving represented between 98% and 59% of the total energy (electricity + heat) consumed in the entire system (autoclaving + sorting + biological treatments). This energy consumption was related to the technologies considered, e.g. composting in tunnels (CT) and turning windrows (TW) which ranked as the higher (216 kWh / tonne OFMSW) and the lowest (5 kWh / tonne OFMWS) energy consumption, respectively. However, part of the energy and resources consumed by autoclaving, the sorting process and the biological treatments was greatly compensated by the energy recovery with the incineration of the mixed plastic fraction (300 kg) resulting from autoclaving process. For this fraction, a lower heating value (LHV) of 31,000 MJ / tonne of mixed plastic was considered which means a high calorific power. Although, in less proportion, the results were also favored by the recyclable fractions (PET and metals) resulting from autoclaving which were credited by the sorting process, and N, P and K content in compost produced from the autoclaved OF. N, P and K content in compost were credited to the biological treatments. Due to its physical, chemical and biological characteristic the compost produced from OF was comparable with the compost obtained from OFMSW.

It was observed that the results of autoclaving can be improved by increasing efficiencies of other processes (i.e. recycling and biological treatments). Furthermore, the results can be improved by looking for better technologies (i.e. high process efficiencies) to treat the resulting products from autoclaving and a better quality of final products: OF's and the compost obtained from this. Likewise, different compositions (organic matter, paper & cardboard, glass, metals, .etc.) for the entry waste stream can considerably change the results found in this dissertation. For example, a high content of plastics in the waste stream would contribute to a great benefit to systems due to the high calorific power of this fraction. As well as, a waste stream composition with high quantity of PET and metals will do autoclaving more attractive technology than others (e.g. incineration).

The incineration of mixed plastic fraction was credited to systems (autoclaving + sorting + biological treatments). Likewise, as seen in the sensitivity analysis, higher efficiencies for energy recovery (electricity and heat) will be directly proportional to the improvement of the environmental performance of the systems.

The systems integrated by autoclaving, sorting and biological treatments represent an option for unsorted municipal solid waste when compared with landfill and incineration. The anaerobic digestion, both thermophilic and mesophilic ranges, showed the best environmental performance in eutrophication potential (EP) and global warming potential (GWP). In the remainder categories incineration had the best environmental performance except in photochemical oxidation potential where the best result was for turning windrow composting (TW). Although, incineration had a better result in four of the seven impact categories considered, the differences against anaerobic technologies were relatively low (8% to 25%); differences varied depending on the category considered. Due to uncertanties associated to systems, differences of around 10% are considered negligible. Even so, despite the energy recovery (i.e. electricity) from the biogas collect in landfill which was credited to this technology, this alternative showed the worst environmental performance for the management of unsorted MSW.

The autoclaving technology could be considered as a controversial technology in those countries which are promoting the selective waste collection. However, the most of those countries still have a high volume of unsorted waste from its mechanical biological treatments that generally is landfilled. Therefore, according to the scope of this dissertation, autoclaving represents an alternative for those countries without a selective waste collection or those who still have high unsorted fraction. Despite autoclaving technology represents an option for the treatment of unsorted municipal solid waste. This technology should be studied by taking into consideration economic and social indicators.

7.1.2 Environmental assessment of organic and mineral fertilizers

In this contest three main subjects arise for a discussion in this dissertation: 1. the application of compost (industrial and home) to cauliflower crops and its environmental and agronomical comparison with mineral fertilizers; 2. the environmental assessment of two home composts with high and low gaseous emissions of the composting process, applied in horticultural crop; and 3. the environmental assessments of a crop sequence of tomato and cauliflower.

Life cycle methodology (LCA) is a robust tool to study the environmental impacts for an entire life cycle of a product, process or activity. The life cycle for organic matter from municipal solid waste was studied for real case studies, from the collection of organic waste, transformation to compost, its transportation, for those cases in which it applies, its application to crops and waste management. This typical LCA is an approach "from cradle to grave " defined by ISO 14044. Mineral fertilizer (i.e. KNO_3 for our case study) which is the most common fertilizer (i.e. nutrient) used in crops by farmers was also considered for the environmental comparison with the two organic fertilizers (industrial compost and home compost). As well as for organic fertilizer, the entire life cycle was considered for the mineral fertilizer according to ecoinvent database.

As a main finding of this research was the suitability of compost (industrial and home) to be used as mineral fertilizer substitute. This condition was experimentally revealed by its physical, chemical and biological characteristics presented in the final composts which were applied to crops. The compost were according to Spanish legislation (Royal Decree 506/2013) which set the parameters for moisture, organic matter and heavy metals content in compost in order to be used in soil applications (i.e. as soil amendment or as substitute of mineral fertilizer). Likewise, both compost (industrial and home compost) were considered as stable material with a Dynamic

Respiration Index (DRI) of 0.89 mg O_2·g^{-1} OM h^{-1} and 0.43 mg O_2·g^{-1} OM h^{-1} for industrial compost and home compost, respectively. These DRI were according to European Commission for bio-waste management (2008). This European Commission sets a DRI of 1 mg O_2·g^{-1} OM h^{-1} to consider compost as stable material suitable to be used in soil applications.

The agronomical results showed a better yield for mineral fertilizers regarding the organic fertilizers. However, the home compost presented a better performance than industrial compost and mineral fertilizers in some quality parameters such weight and diameter of fruits (i.e. cauliflowers). The high yield of fruits obtained with mineral fertilizer can be explained by two main factors: the slow mineralization rate of the nutrient content in compost and the atypical weather conditions observed during the harvesting. The nutrients (N) applied to crop were experimentally calculated in order to have the same nutrient quantity for the three fertilization treatments (industrial compost, home compost and mineral fertilizer). Atypical weather condition (temperature and rain) affected the application of fertilizers. The excessive rainfall at the begging of the crop may cause leachate of nutrients contained in the organic fertilizers. This weather situation delayed mineral fertilizer application. Therefore, the availability of nutrients (N) to plants affected the crop yields. Organic fertilizer has a slow mineralization rate of N in soil, in contrast with the mineral fertilizer in which N is already mineralized and almost immediately available to be used by plants. On the other hand, the high temperature registered for the harvesting period (1.9 ºC compared with other periods) affected the floral induction and ultimately affected the cauliflower yield for the three fertilization treatments.

Then, when comparing the environmental assessment of the three fertilizer treatments (industrial compost, home compost and mineral fertilizers) it was observed that home compost showed the best environmental performance regarding industrial compost and mineral fertilizers. Therefore, considering not only the agronomical results but the environmental performance, home compost is a good alternative for management the organic fraction from MSW. For example, regarding industrial compost, the home compost avoids the collection of waste, the transport to industrial facilities and to crop areas. Moreover, this alternative avoids CO_2 emissions and other environmental pollutants, and it also represents economical saving for farmers.

7.1.3 Environmental assessment of gaseous emissions of the composting process

The environmental sustainability in waste management considers two mayor objectives: conservation resources and pollution prevention. As seen before, the home compost is a suitable alternative to be used as mineral fertilizer substitute. The use of compost in agriculture not only reduces the total amount of waste being dumped but also contributes to eliminate most of the pathogenic microorganisms and reduces odours to environment. Thus, the use of compost in agriculture represents a sustainable alternative for the treatment of bio-waste from the MSW. A critical issue in the composting is the management of the home composting process which can limited its use as organic fertilizer or in soil amendment. The gaseous emissions (CH_4, N_2O, NH_3 and VOC's) of the composting process play an important role in the environmental performance of the horticultural systems. In the current case study was demonstrated that the differences in the composting process for the two home composts with high and low gaseous emissions of the composting process considerably affected the environmental performance of a horticultural cauliflower crop. As shown in Table 7.1, differences in CH_4 and N_2O accounted a high impact of 241% for global warming potential category. Meanwhile, differences in NH_3 accounted high impacts of 210%, 25% and 33% for acidification potential, eutrophication potential and photochemical oxidation, respectively.

Table 7.1 Emissions and impacts per categories for the two home composts

			HC-HE[1]			HC-LE[2]			DIFERENCE		
Element	**Impact category affected**	**Equivalent Units**	**Emission kg/tonne of LRFV[2]**	**Impacts**		**Emission kg/ton of LRFV**	**Impacts**		**Emission kg/tonne of LRFV**	**Impacts**	
CH_4 N_2O**	GWP[4]	kg CO2 eq.	1.350 1.160	-0.020	-	0.295 0.200	-0.069	=	1.055 0.960	0.049	241%
	AP[5]	kg SO_2 eq.		4.830			1.560			3.270	210%
NH_3	EP[6]	kg PO_4 eq.	1.30	-2.860	-	0.025	-3.570	=	1.275	0.710	25%
	POP[7]	kg C_2H_4 eq.		-0.031			-0.041			0.010	33%

[1]HC-HE: Home compost high emission
[2]HC-LE: Home compost low emission
[3]LFRV: Left over of fruit and vegetables
[4]GWP: Global warming potential
[5]AP: Acidification potential
[6]EP: Eutrophication potential
[7]POP: Photochemical oxidation
**N_2O was the highest contributor for GWP (~90%).

Although, both composts (i.e. high and low gaseous emissions of the composting process) were produced under similar conditions for energy, water and materials consumption. However some differences in the compost production management were found, for example, in HC-LE the composting material was more frequently mixed than HC-HE; the humidity was rigorously monitored and adjusted for HC-LE. Others external factors affected the gaseous emissions such as temperature which was a little higher in HC-LE. Many factors influence the gaseous emissions of the composting process. Some of them are external variables such as: quality and composition of waste stream, weather conditions (ambient temperature and precipitation) which are clearly beyond the control of compost producers, although many other factors can be managed with proper planning. Some of these factors, for example, include type of equipment used for turning the compostable material, frequency of turning, quantities, and/or ratios of feedstocks, and composting methods. Compost mixing should be based on feedstock properties such as C:N ratios, moisture content, bulk density, and particle size. Another important issue to consider is the good aeration of the composting to offer the environmental conditions for the aerobic microbe activity. As microbial activity increases in the composter, the microbes will consume more oxygen. If the oxygen supply is not replenished, composting can shift to anaerobic decomposition, thus slowing the rate of the composting process and leading to foul odors, high emission of N_2O, among others. Therefore, understanding the interactions and trade-offs associated with such factors will help compost managers to adjust the quality and consistency of their compost.

7.1.4 Environmental assessment of fertilizers in a crop sequence

The final part of this dissertation presented in chapter 6 considered the study of a crop sequence of cauliflower and tomato for one-year horticultural cycle. Agronomical and environmental issues related to each crop and for the entire crop sequence were considered in the research. Mineral fertilizer treatment had better yields than the crop fertilized with organic fertilizers (industrial and home compost). The better yields for mineral fertilizers are explained in part due to organic fertilizer is a slow nutrient release, in contrast, with mineral fertilizer which the nutrient (N) content in the KNO_3 is already mineralized and almost immediately available to be used by the crops. In general, the fruit yields were affected for both crops due to the atypical whether conditions observed at the beginning of the cauliflower crop. High rainfall and temperatures were registered regarding other years. The high rainfall maybe caused the loss of nutrients content in organic fertilizer and delay mineral fertilizers application. Although, statistically (95% confidence) the differences were not significant between cauliflowers fertilized with mineral fertilizer versus organic fertilizer, those yield differences obtained in cauliflower were considerably higher than tomato crop fertilized for both fertilizers (i.e. organic versus mineral fertilizers).

Regardless the allocation procedure used for the allocation of compost to crops, it was observed that the total nutrients (N) provided to tomato was 1.85 times higher than cauliflower. The irrigation water was the main contributor of N to crops. The irrigation water provided to tomato (~ 300 $L \cdot m^{-2}$) was 3 times higher than cauliflower (~100 L · m-2). Tomato was grown in summer season which is characterized by low rainfall in the Mediterranean countries. Furthermore, as explained before, the high rainfall at the beginning of the cauliflower crop reduced greatly the quantity of groundwater applied.

The ground water where the crops were grown (Santa Susana, NE Catalonia) had 1.86 meq. (N = 26.1 $gN \cdot m^{-3}$). This concentration of N in groundwater is out of the limit sets by the EU Directive 91/676 (European Economic Community, 1991). Therefore, in a context of sustainable agriculture, the irrigation of crops with groundwater favored the crops in the experiment. This issue must be carefully monitored by authorities. Otherwise, this groundwater represents a potential pollution risk for the environment (e.g. eutrophication) as well as for the health of nearby people to crop zone.

The N balance (N uptake – N supplied) carried to the crop sequence showed that N uptake by crops was higher than the N applied. As shown in results, the N uptake for cauliflower and tomato was in average of 27 $gN \cdot m^{-2}$ and 19 $gN \cdot m^{-2}$ for the three fertilization treatments (industrial compost, home compost and mineral fertilizer). In the case of cauliflower, the N supplied to crop was in average of 5.4 $gN \cdot m^{-2}$ for organic fertilizers and 3.8 $gN \cdot m^{-2}$ for mineral fertilizer. While, the N supplied to tomato crop was in average of 11 $gN \cdot m^{-2}$ for organic fertilizers and 17.9 $gN \cdot m^{-2}$ for mineral fertilizer. Therefore, according to N balance a great shortage was observed specially in cauliflower. This N shortage had to be supplied by soil which acts as N reservoir. The risk of nutrient depletion is latent, as in this case, when the amount of nutrient added to crop is less than the amount of nutrients removed from the soil in form of crop yields and residues. Other potential consequences of nutrient depletion are that soil fertility declines, crop growth and inputs of carbon to the soil declines, and for instance, the soil is left open to the negative effects of erosion.

Regarding the environmental assessment, in general tomato crop showed highest impacts than cauliflower in all categories considered. Electricity consumption in tomato crop was the element that most affected its environmental performance. The fact that tomato was grown in summer season implied higher amount of water to irrigate the crops. Electricity was consumed to pump water from well and to irrigate the crops. Then, the home compost treatment had the best environmental performance in all impact categories for the two crops except in terrestrial acidification where the best result was for mineral fertilizers. Emissions of NH_3 presented during the home composting process as well emissions post cultivation was one of the main impact contributor for terrestrial acidification for home composting treatment.

Now, with regards to the procedures to allocate the compost to crops, the home composting allocation procedure based on the allocation time had a better environmental performance than the mineralization N degree in soil for both crops. Meanwhile, in the case of industrial compost, the allocation procedure based on time allocation showed the best environmental performance in most of the categories considered expect in climate change and marine eutrophication were the best result was for the allocation procedure based on the degree N mineralization in soil.

Finally, the study showed that the crop sequence had the lowest impacts in all categories studied. This finding was made by calculating the impacts for the crop sequence per day which were compared with the single impacts per day for each crop.

7.1.5 Comparative summary for waste treatment alternatives for the global warming indicator

Figure 7.1 shows the results for the global warming indicator for the production of 1 tonne of compost (i.e. kg of CO2 eq. · tonne of compost^{-1}) for the three alternatives studied in this dissertation (i.e. compost from autoclaved organic fiber (OF), industrial compost and home compost). These alternatives were compared with others alternatives for waste treatment (i.e. incineration and landfill) and mineral fertilizer production. This last option was considered due to the three compost had the quality properties (i.e. physico-chemical characteristics) to be used as substitute for mineral fertilizers. As shown in Figure 7.1, waste composting represented the best alternative for municipal solid waste treatment. The compost produced from the OF resulting from autoclaving had the best environmental performance regarding to industrial compost and home compost. The material recovery (i.e. avoid virgin material production) from recyclable fractions (PET and metals) and the energy recovery from the incineration of the mixed plastic fraction were credited to the systems (autoclaving + sorting + biological treatments). Despite of landfill was credited with the energy recovery (i.e. electricity production) from the collected biogas. This alternative was the worst option regarding all alternatives considered. The mineral fertilizer production also showed the highest global warming potential against the composts. Therefore, considering the quality of the composts studied, these products represented a suitable alternative to be used as mineral fertilizer substitute or as soil amendments.

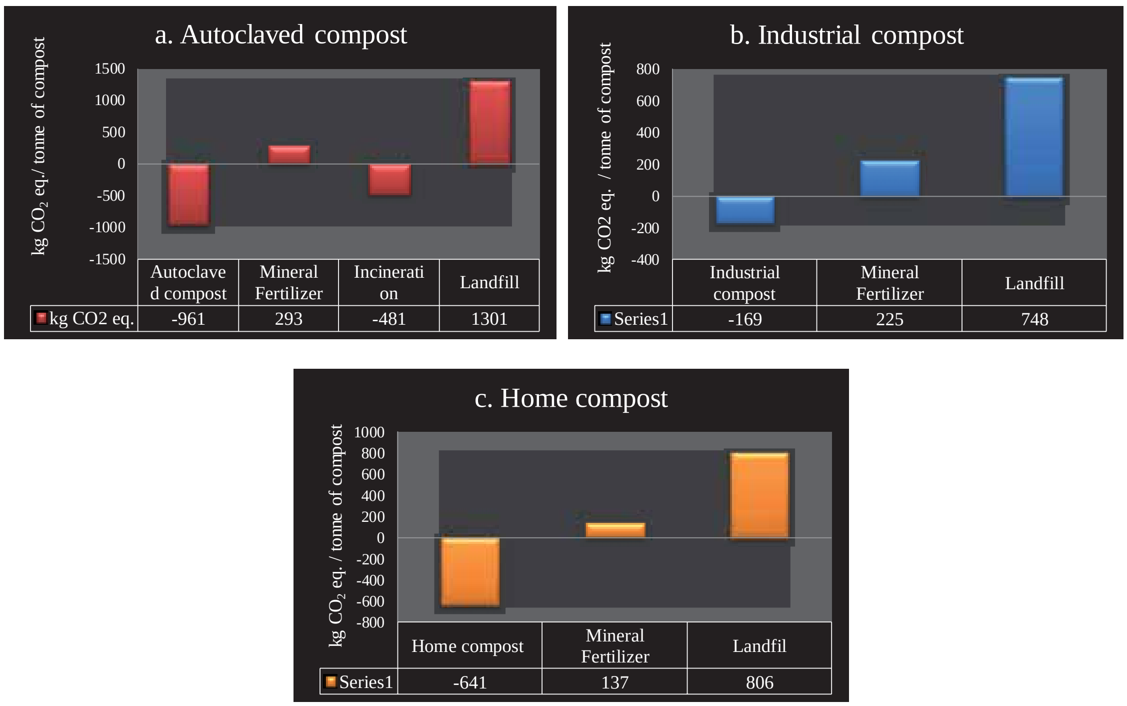


Figure 7.1 Global warming indicator for different waste treatments

7.1.6 Summary of impacts by crops per each fertilization treatment

Table 7.2 shows a summary of impacts (kg CO_2 eq. · $tonne^{-1}$ of fruit) for cauliflower and tomato per each fertilization treatment. The values shown in Table 7.2 are based on the time allocation procedure for the compost applied to crops. The differences in values were due to tomato crop was three times more irrigated than cauliflower, so high electricity consumption was registered for pumping water from well and to irrigated the crop. Likewise, a lower quantity of mineral fertilizer was applied to cauliflower. The high rainfall delayed mineral fertilizer application to cauliflower, so the final quantity of mineral fertilizer was considerably lower (i.e. almost ten times lower) than the quantity applied to tomato.

The home compost treatment showed the best environmental performance than industrial compost and mineral fertilizer. In the case of industrial compost, the transportation of compost from production facility to crops site was one of the main contributor. While for mineral fertilizer, the energy consumption thru the all life cycle was the main contributor to global warming potential.

Table 7.2 Global warming indicator by fruit and fertilization treatment*

Fruit	Units	IC	HC	MF
Cauliflower	Kg CO_2 eq. · tonne of fruit^{-1}	-268	-405	290
Tomate	Kg CO_2 eq. · tonne of fruit^{-1}	91	6	338

IC: Industrial compost; HC: Home compost; MF: Mineral fertilizer

*Values were calculated for the allocation time procedure

7.2 Conclusion

This dissertation presents technologies to treat municipal solid waste and strategies for the treatment of the organic matter from municipal solid waste in a sustainable way. This section summarizes in brief the main research findings of the dissertation, based on the objectives established for each case study. All chapters from 2, 3, 4 and 6 present their own research results, specific discussion and conclusions with recommendation where appropriate. Furthermore, most of the conclusions of the dissertation were broadly detailed in the final discussion section.

7.2.1 Technologies to treat municipal solid waste

Autoclaving is a novel technology to treat unsorted municipal solid waste. The OF resulting from autoclaving was processed thru biological technologies (aerobic and anaerobic digestion). The results were compared with two well-known technologies (i.e. incineration and landfill) to treat municipal solid waste. In order to consider autoclaving as strategy for unsorted municipal solid waste, the autoclaved sub-products from is process (i.e. mixing plastic and recyclable fraction) should process for energy recovery. Therefore, the autoclaving technology integrated with the biological treatments for processing the OF resulting from autoclaving represents a solution to treat unsorted municipal solid waste, for those countries which has not yet implemented the selective collection of waste. The autoclaving also can be used to treat the residual waste from the mechanical biological treatments which common in those countries who already had implemented selective collection of municipal solid waste.

7.2.2 Processing the organic matter from municipal solid waste

Compost well-done represents a suitable alternative for the treatment of the organic matter from municipal solid waste. Due to its physico-chemical and biological characteristics the compost from high-scale facilities (i.e. industrial compost) and from homes can be used in soil amendment as soil restoration or as mineral fertilizer substitute, among others. Compost also avoids the dumping of organic to landfill which is according landfill Directive 1999/31/EC. Mineral fertilizers have the characteristic of great energy consumption due to its production process with the consequences of pollution to environment. Although, higher yields where obtained for the crops (i.e. cauliflower and tomato) fertilized with mineral fertilizers, the homes compost showed the best environmental performance in the most environmental impact categories assessed. Likewise, comparing home compost with industrial compost, the former has the benefit that can be produced nearby the application sites, so avoiding the transportation and the emissions that it implies. The compost production implies emissions of several gaseous pollutants to environment such as nitrous oxides, ammonia, methane and volatic organic compounds. These emissions depend on external and internal variables. Some internal variables are type of material to be composted, frequency mixing of the composted material, humidity, bulking agent, among others. These gaseous emissions can be mitigated or reduce with an efficient management of the composting process. Weather conditions (i.e. temperature and rainfall) are identified as the main external variable which mostly is out of the compost practitioners control.

7.3 Future research

This section remarks future lines of research that may be followed from this research thesis. The section was structured in three main points: future research for autoclaving and the OF resulting from its process; the production on compost in different stages and the application of fertilizers to crops.

This thesis is part of a serial of research studies for technologies for the treatment of municipal solid waste and for the processing the organic matter from municipal solid waste to produce compost in full-scale facilities and home composting. Compost production researches have been driven by the Group d'Investigació en Compostatge (GICOM) at the Universidad Autónoma de Barcelona. Likewise, researches of compost applications in crops had been carried out thru the Institut de Reserca i Tecnología Agroalimentaries (IRTA).

Although some outstanding results have been achieved so far with the researches conducted, it is clearly seen the need to expand researches on the topics considered in this dissertation and others discussed below.

7.3.1 Autoclaving and organic fiber

Autoclaving is novel technology which is still under investigation. There is a lack of research of autoclaving process at laboratory scale and for full-scale facilities. In the dissertation an average composition of waste stream found in Europe was autoclaved in a full-scale facility to study the sub-products from its process. However, it is recommended future trials for different unsorted waste stream compositions. The OF resulting from autoclaving process depends on the quality and quantity of the biodegrable (i.e. organic material and paper & cardboard) content in the input waste. The studies at scale laboratory showed that due to its physico-chemical characteristics, this fiber was assimilable to the organic fraction of municipal solid waste. Therefore, the OF is a material suitable to be processed thru biological treatments (i.e. aerobic and anaerobic digestion). Although, in this dissertation, the results of processing the OF thru biological treatments showed quite good results, more research is requested at laboratory and full-scale facilities. These trials will permit to observe the real effects of different compositions of waste stream on final products as well as to see the effects of different concentrations of humidity and organic matter, among others.

One of the main assumptions of this research was that the "compost" produced from the autoclaved OF can be used as mineral fertilizer substitute. This assumption was based on its quality parameters that were according to Spanish Royal Decree 506/2013. This decree sets the parameters that should compost comply to be used as substitutes of mineral fertilizers. However, due to this material was not really applied to crop, it is important a future development research to use this material in crops. A real comparision between "compost" from autoclaved OF and compost from municipal solid waste (i.e. industrial compost and home compost) should be made. Furthermore, a comparision (i.e. agronomical and environmental) of application of compost from autoclaved OF versus mineral fertilizer is also recommended in future.

7.3.2 Production of compost

The quality of compost is an essential issue to consider the compost as a suitable product to be used in soil amendments such as soil restoration or as a substitute of mineral fertilizers. Several factors determine the quality of final product from the degradation of the organic matter (i.e. compost). This quality is also intrinsically related to emissions from the composting process. Some of the most critical variables related to compost production are: type and quality of material (i.e. organic waste stream) to be composted, which are related to organic matter content and content of nutrients (N, P and K); some physical-chemical characteristics that should be monitored such as: organic matter content, humidity, pH, temperature, porosity, among others. Others related to the mixing frequency of the composted material and the close monitoring of mentioned physico-chemical parameters. Many of mentioned characteristics depend on great part of the compost production management. Therefore, it is important to follow with the same research trend to observe the quality and emissions of compost during the composting process under different stages. A combination of variables, e.g. frequency of mixing for different water concentration in the composting material will permit to study the evolution of the main gaseous emissions presented in the composting process such as methane, nitrous oxide and ammonia. Then, a life cycle assessment for different stages from these results can show the level of environmental impact for the different qualities of compost.

Weather condition is another important variable that determines the airborne emissions from the composting process. Home composting which generally is produced in open building is greatly affected by the weather conditions. This is another key point to be researched in future studies. Emission to air and water can be reduced by determining the optimal conditions for home compost production under different seasons and weather conditions.

7.3.3 Application of fertilizers to crops and related cultivation stages

The compost is a slow nutrient release in soil. The mineralization of nutrients (N) present in the compost applied is a complex process that depends on several variables: type of soil, quality of compost applied (i.e. grade of stabilization), crops type, weather condition, cultivation management, among others. Although, it is very difficult to accurately determine the degree of N mineralization, researches should be continued in the same plots were the thesis experiments were carried out. A database should be developed to follow future sequence of nutrient behavior in crop sequences. Furthermore, studies of carbon sequestration, leachates and emission to air and water should be closely monitored and values registered in the experimental plots.

For an integrated crop management, along with the elements above mentioned, the different stages of the cultivation phase (fertirrigation, irrigation, machinery and tools, nursery and phytosanitary substances) also should be monitored and registered for different crop sequences. The implementation of this practice will permit to compare the entire cycle of a crop sequence to study the environmental performance of horticultural systems which serves a basis for scientific community and different stakeholders (farmers, communities, authorities, so forth).

References

Adani, F., Genevini, P., Gasperi, F., Zorzi, G., 1997. Organic matter evolution index (OMEI) as a measure of composting efficiency. Compost Science & Utilization, 5, 5-62.

AEA, 2001.WasteManagementOptions and ClimateChange. Final report to the European Commission, DG Environment. http://europa.eu.int

Agencia de Residuos de Catalunya (ARC), 2001. Informe sobre el canvi climàtic a Catalunya.

Agència de Residus de Catalunya, 2012. Informe Annual (Annual Report). Departament de Medi Ambient i Habitatge. Generalitat de Catalunya, Barcelona, Spain (in Catalan).

Ahring, B.K., 2003. Biomethanation. Eds. T. Scheper and B.K. Ahring. Springer-Verlag: Berlin, Heidelberg, I & II.

Amlinger, F., Peyr, S., Cuhls, C., 2008. Green house gas emissions from composting and mechanical biological treatment. Waste Manag. Res. 26, 47–60.

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162.

Andersen, J.K., Boldrin, a, Christensen, T.H., Scheutz, C., 2010. Greenhouse gas emissions from home composting of organic household waste. Waste Manag. 30, 2475–2482.

Andersen, J.K., Boldrin, a, Christensen, T.H., Scheutz, C., 2012. Home composting as an alternative treatment option for organic household waste in Denmark: An environmental assessment using life cycle assessment-modelling. Waste Manag. 32, 31–40.

Annabi, M., Le Bissonnais, Y., Le Villio-Poitrenaud, M., Houot, S., 2011. Improvement of soil aggregate stability by repeated applications of organic amendments to a cultivated silty loam soil. Agric. Ecosyst. Environ. 144, 382–389.

Antón, A., 2004. Utilización del análisis del ciclo de vida en la evaluación del impacto ambiental del cultivo bajo invernadero mediterráneo. Universidad Politécnica de Catalunya (UPC), Barcelona, Spain (in Spanish).

Arena, U., Mastellone, M.., Perugini, F., 2003. The environmental performance of alternative solid waste management options: a life cycle assessment study. Chem. Eng. J. 96, 207–222.

Assamoi, B., Lawryshyn, Y., 2012. The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste Manag. 32, 1019–1030.

Astrup, T., Møller, J., Fruergaard, T., 2009. Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 789–799.

Audsley, E., 1997. Harmonisation of Environmental Life Cycle Assessment for Agriculture. Final Report Concerted Action AIR 3-CT94-2028. European Commission DG VI Agriculture, Silsoe, UK.

Baky, A., Eriksson, O., 2003. Systems Analysis of Organic Waste Management in Denmark. Danish Environmental Protection Agency, Copenhagen, Denmark. Available from: www.mst.dk/ udgiv/publications/2003/87-7972-740-9/pdf/87-7972-741-7.pdf (web side consulted on 15th July 2013).

Banar, M., Cokaygil, Z., Ozkan, A., 2009. Life cycle assessment of solid waste management options for Eskisehir , Turkey. Waste Manag. 29, 54–62.

Banks, C., 2008. The effect of autoclaving on the anaerobic digestion of mixed MSW. Report to Defra. University of Southampton, UK Waste Implementation Programme.

Beck-Friis, B., Smårs, S., Jönsson, H., Kirchmann, H., 2001. SE—Structures and Environment. J. Agric. Eng. Res. 78, 423–430.

Beigl, P., Lebersorger, S., Salhofer, S., 2008. Modelling municipal solid waste generation: A review. Waste Manag. 28, 200–214.

Benitez C, Tejada M, Gonzalez JL. Kinetics of the mineralization of nitorgen in a pig slurry compost applied to soils. Compost Sci Util. 2003;11:72–80.

Bentrup, F., Küesters, J., 2000. Methods to estimate the potential N emissions related to crop production. In: Weydema, B., Meeusen, M. (Eds.), Agricultural Data for Life Cycle Assessments, vol. 1. Agricultural Economics Research Institute, The Haugue, The Netherlands, pp. 133-151

Bernat C, Casado D, Ferrando C, Paulet S, Pujol M, Soliva M . Compost, manure and sewage sludge applied to a crop rotation. In: Sangiorgi, F. (Ed.), Ramiran 2000, Proceedings of the 9th International Workshop of the Network General Theme

Technology Transfer. Institute of Agricultural Engineering, University of Milan, pp. 231-36.

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.

Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. Waste Manag. 27, 1021–1031.

Binner, E., 2003. MBT with view to landfilling stabilised biowaste. In: H. Langenkamp (Soil and Waste Unit, Institute for Environment and Sustainability, Joint Research Centre), Luca Marmo (Sustainable Resources Unit, Directorate-General Environment, European Com- mission): Workshop Biological Treatment of Biogradable Waste – Technical Aspects, 8–10 April, 2002, Brussels: 2003, EUR 20517 EN, p. 355 f.

Björklund, A., Finnveden G., 2005. Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies. Resour Conservat Recycl 44, 309–317

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. Con-serv. Recycling 52 (12), 1373-1381

Blonk, H., Kool, A., Luske, B., Ponsioen, T., 2010. Methodology for assessing carbon footprints of horticultural products horticultural products. www.blonkmilieuadvies.nl. (web side consulted on 12th November 12, 2013).

Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 800–812.

Boldrin, A., Neidel, T.L., Damgaard, A., Bhander, G.S., Møller, J., Christensen, T.H., 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste Manag. 31, 619–630.

Bonmatí, A., 2001. Thermal energy uses for the improvement of pig slurry anaerobic digestion and the recovery of useful products. Phd Thesis. Departament de Medi Ambient i Ciències del Sòl. Universitat de Lleida. Catalunya, Spain.

Bovea, M.D., Gallardo, A., 2010. Environmental assessment of alternative municipal solid waste management strategies . A Spanish case study. Waste Manag. 30, 2383–2395.

Bovea, M.D., Powell, J.C., 2006. Alternative scenarios to meet the demands of sustainable waste management. J. Environ. Manage. 79, 115–132.

Bradley, D., Christodoulou, M., Caspari, C., Di Luca, P., 2002. Integrated crop management systems in the EU. European Commission DG Environment

Burke, A., 2001. Dairy waste anaerobic digestion handbook. United States, Environmental Energy Company, Olympia, WA.

Buttol, P., Masoni, P., Bonoli, a, Goldoni, S., Belladonna, V., Cavazzuti, C., 2007. LCA of integrated MSW management systems: case study of the Bologna District. Waste Manag. 27, 1059–1070.

Cadena, E., 2009. Analysis at full-scale OFMSW biological treatment plants. Focus on gaseous emission. Phd Thesis. Departament d'Enginyeria Química. Universidad Autónoma de Barcelona. Barcelona, Spain.

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.

Cadena, E., Colón, J., Sánchez, A., Font, X., Artola, A., 2009. A methodology to determine gaseous emissions in a composting plant. Waste Manag. 29, 2799–2807.

Chan, Y.C., Sinha, R.K., Weijin Wang, 2011. Emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia). Waste Manag. Res. 29, 540–8.

Chan, K., Dorahy, C., Tyler, S., 2007. Determining the agronomic value of composts produced from garden organics from metropolitan areas of New South Wales, Australia. Aust J Exp. Agric. 47, 1377

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy 34, 2116–2123.

Christensen, T.H., Simion, F., Tonini, D., Møller, J., 2009. Global warming factors modelled for 40 generic municipal waste management scenarios. Waste Manag. Res. 27, 871–884.

Chung, Y.C., 2007. Evaluation of gas removal and bacterial community diversity in a biofilter developed to treat composting exhaust gases. J. Hazard. Mater. 144, 377–385.

Chynoweth, D. P., Owens, J. M., & Legrand, R., 2001. Renewable methane from anaerobic digestion of biomass. Renewable Energy, 22, 1-8

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: a comparative analysis of selected peer-reviewed literature. Environ. Int. 35, 1256–1266.

Clemens, J., Cuhls, C., 2003. Greenhouse gas emissions from mechanical and biological waste treatment of municipal waste. Environ. Technol. 24, 745–754.

Colón, J., 2012. Determinació i tractament de les emissions gasoses procedents del tractament biológic de la FORM. Impacte ambiental de les diferents tipologies d´instal·lacions. Phd Thesis. Departament d'Enginyeria Química. Universidad Autónoma de Barcelona. Barcelona, Spain.

Colón, J., Cadena, E., Pognani, M., Barrena, R., Sánchez, A., Font, X., Artola, A., 2012. Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. Energy Environ. Sci. 5, 5731-5741

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.

Compostadores SL. Home page: http://www.compostadores.com; 2008 (web side consulted on 04th October, 2013)

Consonni S., Giugliano M., Grosso M., 2005. Alternative strategies for energy recovery from municipal solid waste. Part A: mass and energy balances. Waste Management 25. 123–135

Council of the European Union. Directive 1999/31/EC, of 26 April 1999 on the landfill of waste. Official Journal L 182, 1e19.

CREA, Centro Regional de Estudios del Agua, Universidad de Castilla de la Mancha. Hoja Informativa No 11. 2005.

Cronje A, Barker A, Guy S, Turner C, Williams A. Ammonia emissions and pathogen inactivation during composting. In: Proceedings of the 2002 International Scientific Symposium on Composting and Compost Utilization, 6–8 May, Columbus, USA (Published on CD-ROM); 2002.

Damgaard, A., Manfredi, S., Merrild, H., Stensøe, S., Christensen, T.H., 2011. LCA and economic evaluation of landfill leachate and gas technologies. Waste Manag. 31, 1532–1541.

De Guardia, A, Mallard, P., Teglia, C., Marin, A, Le Pape, C., Launay, M., Benoist, J.C., Petiot, C., 2010. Comparison of five organic wastes regarding their behaviour during composting: part 1, biodegradability, stabilization kinetics and temperature rise. Waste Manag. 30, 402–14.

Del Amor, F.M., 2007. Yield and fruit quality response of sweet pepper to organic and mineral fertilization. Renew. Agric. Food Syst. 22, 223-238.

Diaz, L.F., Savage, G.M., Eggerth, L.L., 2005. Alternatives for the treatment and disposal of healthcare wastes in developing countries. Waste Manag. 25, 626–637.

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.

Doka G. Life cycle inventories of waste treatment services. Ecoinvent report No. 13. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland. 2007

Doltra, J., and Muñoz, P., 2010. Simulation of nitrogen leaching from a fertigated crop rotation in a Mediterranean climate using the EU- Rotate_N and Hydrus-2D models. Agric Water Manage. 97, 277–285

EC, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. European Commission, Brussel

EEA (2012) European Environment Agency: Agriculture. In:
http://www.eea.europa.eu/themes/agriculture/about-agriculture (web side consulted on 12th March 2014).

EEA, 2013. European Environmental Agency. Managing municipal solid waste: a review of achievements in 32 European conuntries. EEA Report No 2/2013

Eklind, Y., Kirchmann, H., 2000. Composting and storage of organic household waste with different litter amendments. II: Nitrogen turnover and losses. ioresour. Technol. 74, 125–133.

Ekvall, T., Planning, T.E., 1997. Open-Loop Recycling: Criteria for Allocation Procedures 2, 155–162.

Ekvall, T., Weidema, B., 2004. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 9, 161–171.

Eley, M.H., Guinn, G.R. & Bagghi J., 1995. Cellulosic materials recovered from steam classified municipal solid wastes as feedstocks for conversion to fuels and chemicals. Applied Biochemistry and Biotechnology. 51/52, 387–397.

Eriksson O.,Carlsson Reich M., Frostell B., Björklund A., Assefa G., Sundqvist J-O., Granath J., Baky A., Thyselius L., 2005. Municipal solid waste management from a system perspective. J Cleaner Prod 13, 241–252

Ermolaev, E., Sundberg, C., Pell, M., Jönsson, H., 2013. Greenhouse gas emissions from home composting in practice. Bioresour. Technol. 151C, 174–182.

EU (European Union), 1999 EC Directive 1999/31/CE on the Landfill of Waste. europa.eu.int/eur-lex/pri/fr/oj/dat/1999/l_182/l_18219990716fr00010019.pdf (07/01/05).

EU (European Union), 2006. Waste Management options and climate change. (http://europa.eu.int). (web side consulted on 02 May, 2013).

European Commission, 1999. EU Directive 1999/31/EC, 1999. Official Journal of the European Communities, L 182, 16/07/1999.

European Commission, 2001. Working document. Biological treatment of biowaste. 2nd draft. URL: http://www.compost.it/www/pubblicazioni_on_line/biod.pdf (web side consulted on 20th May, 2013).

European Commission (2006a) Thematic Strategy for Soil Protection. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Brussels.

European Commission (2006b) Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. COM(2006) 232, Brussels.

European Commission (2006c) Impact Assessment of the Thematic Strategy on Soil. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Brussels.

European Commission, 2008. Green paper on the management of biowaste in the European Union. Committee on the Environment, Public Health and Food Safety.

European Commission, 2009. Green Paper on the Management of Bio-waste in the European Union 2008. Off. J. Eur. Communities (web side consulted on 05th August, 2012).

European Commission. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. Official Journal of the European Communities 1994;L 365:266–87.

European Commission. Working document. Biological treatment of biowaste. 2nd draft. URL: http://www.compost.it/www/pubblicazioni_on_line/biod.pdf; 2001. (web side consulted on 20th October, 2013).

European Economic Community. Directive 91/676/ECC, of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Off J Eur Commun. 1991.

European Soil Bureau Network (2012) Soil Atlas of Europe. European Comission. In: eusoils.jrc.ec.europa.eu/projects/soil_atlas/index.html (web site consulted on 12th April, 2014).

Eurostat. Fertilizers consumed in EU-27 for 2010; 2012. Statistics, European Commission. http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home (web side consulted on 15th October 2012).

Eurostat. Municipal waste generated/landfilled/incinerated; 2010. Statistics, European Commission. (web side consulted on 15th August, 2013).

Eurostat: statistical office of the European communities, 2010. Online database, http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/data- base; 2010 (web side consulted on 14th February, 2014)

Eurostat: statistical office of the European communities, 2012. Online database, http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/data- base; 2012 (web side consulted on 10th March, 2014)

Eurostat: statistical office of the European communities, 2014. Online database, http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/data- base; 2012 (web side consulted on 18th February, 2014)

FCM., (2004). Solid waste as a resource, review of waste technologies, 111. Federation of Canadian Municipalities. Available on: http://www.sustainablecommunities.ca/files/ Capacity_Building__Waste/SW_Guide_Technology.pdf

Ferrer, I., Ponsá, S., Vázquez, F., & Font, X, .2008. Increasing biogas production by thermal (70ºC) sludge pre-treatment prior to thermophilic anaerobic digestion. Biochemical Engineering Journal, 42, 186-192

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21.

Finnveden, G., Johansson, J., Lind, P., Moberg, Å., 2005. Life cycle assessment of energy from solid waste – part 1: general methodology and results. Journal of Cleaner Production 13, 213–229

Fisher, K., 2006. Impact of Energy from Waste and Recycling Policy on UK Greenhouse Gas Emissions – Final Report. Prepared by Environ- ment Resource Management (ERM) for Department for Environ- ment, Food and Rural Affairs (Defra), Oxford, UK. http://randd.

defra.gov.uk/Document.aspx?Document=WR0609_5737_FRP.pdf (web side consulted on 15th March, 2014).

Flotats, X., Bonmatí, A., Fernández, B., Magrí, A., 2009. Manure treatment technologies: on-farm versus centralized strategies. NE Spain as case study. Bioresour. Technol. 100, 5519–26.

Fragkou, M.C., Vicent, T., Gabarrell, X., 2010. A general methodology for calculating the MSW management self-sufficiency indicator: Application to the wider Barcelona area. Resour. Conserv. Recycl. 54, 390–399.

Fricke, K., Santen, H., Wallmann, R., 2005. Comparison of selected aerobic and anaerobic procedures for MSW treatment. Waste Manag. 25, 799–810.

Frischknecht, R., Jungbluth, N., 2003. Implementation of Life Cycle Impact Assessment Methods. Ecoinvent Report N3, v2.0. Swiss Centre for Life Cycle Inventory, Dübendorf, Switzerland.

Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA perspective. Waste Manag. 31, 572–582

Fruergaard, T., Christensen, T.H., Astrup, T., 2010. Energy recovery from waste incineration: assessing the importance of district heating networks. Waste Manag. 30, 1264–1272.

Gaillard G, Hausheer J. Ökobilanz des Weizenanbaus. Agrarforschung Band. 1999; 6 (1): 37-40.

Galante, G., Aiello, G., Enea, M., Panascia, E., 2010. A multi-objective approach to solid waste management. Waste Manag. 30, 1720–1728.

García, A., Maulini, C., Torrente, J.M., Sánchez, A., Barrena, R., Font, X., 2012. Biological treatment of the organic fibre from the autoclaving of municipal solid wastes; preliminary results. Biosyst. Eng. 112, 335–343.

Gea, T., Barrena, R., Artola, A., Sánchez, A., 2004. Monitoring the biological activity of the composting process: Oxygen uptake rate (OUR), respirometric index (RI), and respiratory quotient (RQ). Biotechnol. Bioeng. 88, 520–7.

Gentil, E.C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S., Kaplan, P.O., Barlaz, M., Muller, O., Matsui, Y., Ii, R., Christensen, T.H., 2010. Models for waste life cycle assessment: review of technical assumptions. Waste Manag. 30, 2636–2648.

Giró, F., 1994. Regulation Proposal for the Compost of MunicipalWaste on Catalonia. Junta de Residus de Catalunya, Barcelona, Spain (in Catalan).

Giró, F., 2001. Chapter 7. Operación de una planta para producción de compost, tratamiento de la FORM procedente de la recogida selectiva en origen (in Spanish). In: Feijoo, G. and Sineiro., J., (Eds.), Residuos: Gestión, minimización y tratamiento. Santiago de Compostela, Spain.

Giugliano, M., Cernuschi, S., Grosso, M., Rigamonti, L., 2011. Material and energy recovery in integrated waste management systems . An evaluation based on life cycle assessment. Waste Manag. 31, 2092–2101.

Gómez Palacio, J.M., Ruiz de Apodac, A., Rebollo, C., Azcárate, J., 2002. European policy on biodegradable waste: a management perspective. Water Sci. Technol. 46, 311–318.

Goodland, R., Bank, W., 2002. Sustainability : Human , Social , Economic and Environmental. Soc. Sci. 6, 220–225.

Gratacós-Cubarsí, M., Ribas-Agustí, A., García-Regueiro, JA., Castellari M., 2010. Simultaneous evaluation of intact glucosinolates and phenolic compounds by UPLC-DAD-MS/MS in Brassica oleracea L. var. botrytis. Food Chem 121, 257–263.

Gronauer, A., Claassen, N., Ebertseder, T., Fischer, P., Gutser, R., Helm, M., Popp, L. & Schön H., 1997. Bioabfallkompostierung: Verfahren und Verwertung. Schriftenreihe Heft 139. Bayerisches Landesamt für Umweltschutz, München, Germany.

Gronauer, A., Claassen, N., Ebertseder, T., Fischer, P., Gutser, R. & Helm, M., 1997. Biowaste composting: Techniques and recycling. BayerischesLandesamt Für Umweltschutz; Schrift-Enreihe Heft, München, Germany, 139.

Grunditz, C., Dalhammar, G., 2001. Development of nitrification inhibition assays using pure cultures of Nitrosomonas and Nitrobacter. Water Res. 35, 433–440.

Guinee JB et al., 2001. Life Cycle Assessment An operational guide to the ISO standards, Volume 1, 2 and 3. Centre of Environmental Science Leiden University, Leiden, The Netherlands

Guinée, J., 2001. Life Cycle Assessment: An Operational Guide to the ISO Standards. Part 1 and 2. Ministry of Housing. Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), The Netherlands.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste. FAO Report, Rome38–39.

Hanandeh, A. El, El-Zein, A., 2010. Life-cycle assessment of municipal solid waste management alternatives with consideration of uncertainty: SIWMS development and application. Waste Manag. 30, 902–911.

Hansen, T.L., 2006. Environmental modelling of use of treated organic waste on agricultural land: a comparison of existing models for life cycle assessment of waste systems. Waste Manag. Res. 24, 141–152.

Hargreaves, J.C., Adl, M.S., Warman, P.R., 2008. A review of the use of composted municipal solid waste in agriculture. Agric. Ecosyst. Environ. 123 (1-3), 1-14.

Haug, R., 1993. The Practical Handbook of Composting Engineering. Lewis Publishers, Boca Raton, Florida, USA.

Hayer, F., Bonnin, E., Carrouée, B., Gaillard, G., Nemecek, T., 2010. Designing sustainable crop rotations using Life Cycle Assessment of crop combinations 903–911.

He, Y., Inamori, Y., Mizuochi, M., Kong, H., Iwami, N., Sun, T., 2000. Measurements of N2O and CH4 from the aerated composting of food waste. Sci. Total Environ. 254, 65–74.

Hobson, A.M., Frederickson, J., Dise, N.B., 2005. CH4 and N2O from mechanically turned windrow and vermicomposting systems following in-vessel pre-treatment, in: Waste Management. pp. 345–352.

Huerta-Pujol, O., López-Martínez, M., & Soliva, M., 2011.Composting process: Samples characterization (in Catalan). Diputació de Barcelona.

Humer, M., Lechner, P., 1999. Methane oxidation in compost cover layers on landfills. Proceedings of the Seventh International Waste Management and Landfill Symposium 3, 403–410.

IDESCAT, 2007. Anuari d'estadísitca de Catalunya 2006. Barcelona.: Institut d'Estadística de Catalunya.

IDESCAT, 2014. Residuos Municipales por tipos de tratamiento. http://www.idescat.cat/economia/inec?tc=3&id=8613&lang=es (web side consulted on 15th May, 2014)

International Organisation for Standardisation, 2006. ISO 14040–14044. Environmental Management, Life Cycle Assessment. International Standard, Geneva, Switzerland.

IPCC (Intergovernmental Panel on Climate Change). IPCC Guidelines for National Greenhouse Gas Inventories. 2006. <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm> (web side consulted on 15th October, 2013).

IPCC, 2006. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Biological Treatment of Solid Waste. Guidelines for National Greenhouse Gas Inventory.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)] . International Panel on Climate Change, Geneva.

Iriarte, A., Gabarrell, X., Rieradevall, J., 2009. LCA of selective waste collection systems in dense urban areas. Waste Manag. 29, 903–914.

ISO 14040. Environmental Management e Life Cycle Assessment e Requirements and Guidelines (Geneva, Switzerland). 2006.

ISO 14044: Environmental Management e Life Cycle Assessment e Requirements and Guidelines (Geneva, Switzerland); 2006.

ISO, 2006a. ISO 14040 environmental management e life cycle assessment e principles and framework.

ISO, 2006b. ISO 14044 environmental management e life cycle assessment requirements and guidelines.

Jakobsen, ST., 1995. Aerobic decomposition of organic wastes II: value of compost as a fertilizer. Resour Conserv Recycl. 13, 57–71.

Jungbluth N., Frischknecht R., 2004. Implementation of Life Cycle Impact Assessment Methods. ecoinvent Report No. 3; <www.ecoinvent.ch>.

Juniper Consultancy Service LTD, 2005. Mechanical-biological-treatment: A guide for decision makers-process, policies and markets. (www.juniper.co.uk)

Keeney, D.R., Nelson, D.W., 1982. Nitrogen inorganic form. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis Part II. ASA, Madison,WI, pp. 643–698.

Kirkeby, J.T., Birgisdottir, H., Bhander, G.S., Hauschild, M., Christensen, T.H., 2007. Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program EASEWASTE. Waste Manag. 27, 961–970.

Laegreid, M., Bockman, O., Kaarstad, O., 1999. Agriculture, Fertilizers and the Environment. CABI Publishing, Wallingford.

Liamsanguan, C., Gheewala, S.H., 2008. LCA: a decision support tool for environmental assessment of MSW management systems. J. Environ. Manage. 87, 132–138.

Lleó, T., Albacete, E., Barrena, R., Font, X., Artola, A., Sánchez, A., 2013. Home and vermicomposting as sustainable options for biowaste management. J. Clean. Prod. 47, 70–76.

Longden, D., Brammer, J., Bastin, L., Cooper, N., 2007. Distributed or centralised energy-from-waste policy? Implications of technology and scale at municipal level. Energy Policy. 35, 2622–2634.

Lou, X.F., Nair, J., 2009. The impact of landfilling and composting on greenhouse gas emissions a review. Bioresour. Technol. 100, 3792–3798.

Lundie, S., 2005. Life cycle assessment of food waste management options. J. Clean. Prod. 13, 275–286.

MAGRAMA (Ministerio de Agricultura, Alimentación y Medio Ambiente de España) Anuario de Estadística 2010.

Majumdar, D., Patel, J., Bhatt, N., Desai, P., 2006. Emission of methane and carbon dioxide and earthworm survival during composting of pharmaceutical sludge and spent mycelia. Bioresour. Technol. 97, 648–658.

Manfredi, S., Christensen, T.H., 2009. Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. Waste Manag. 29, 32–43.

Manfredi, S., Tonini, D., Christensen, T.H., 2011. Environmental assessment of different management options for individual waste fractions by means of life-cycle assessment modelling. Resour. Conserv. Recycl. 55, 995–1004.

MAPA. Real Decreto 1201/2002, de 20 de noviembre, por el que se regula la producción integrada de productos agrícolas. Boletín Oficial del Estado (in Spanish); 2002

Marchettini, N., Ridolfi, R., Rustici, M., 2007. An environmental analysis for comparing waste management options and strategies. Waste Manag. 27, 562–571.

Martínez-Blanco, J., Antón, A., Rieradevall, J., Castellari, M., Muñoz, P., 2010. Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization. Int. J. Life Cycle Assess. 16, 12–26.

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., Muñoz, P., Antón, A., Rieradevall, J., 2009. Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops. Resour. Conserv. Recycl. 53, 340–351.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod. 19, 985–997.

Martínez-Blanco, J., 2012. Sustainability assessment of municipal compost use in horticulture using a life cycle approach. Phd Thesis. Sostenipra Research Group. Instittu de Ciència i Tecnología Ambientals (ICTA). Universitat Autònoma de Barcelona.

Martínez-Blanco, J., Rieradevall, J., Antón, A., Muñoz, P., 2014. Multifunctionality-solving approaches of compost application in crop rotations. J. Clean. Prod. 64, 384–395.

Martín-González, L., Castro, R., Pereira, M.A., Alves, M.M., Font, X., Vicent, T., 2011. Thermophilic co-digestion of organic fraction of municipal solid wastes with FOG wastes from a sewage treatment plant: reactor performance and microbial community monitoring. Bioresour. Technol. 102, 4734–41.

McConnell, DB., Shiralipour, A., Smith WH., 1993. Agricultural impact—compost application improves soil properties. Biocycle. 34, 61–3.

Ministerio de la Presidencia, 2005. Royal Decree 824/2005, on fertilizing products (in Spanish).

Ministerio de la Presidencia, 2013. Royal Decree 506/2013, on fertilizing products (in Spanish).

MMAMRM Registro de Productos Fitosanitarios (in Spanish). Sección de Agricultura del Ministerio de Medio Ambiente y Medio Rural y Marino; 2008. Home page: www.mma.es/portal/secciones.

Moberg A., Finnveden G., Johansson J., Lind P., 2005. Life cycle assessment of energy from solid waste—part 2: landfilling compared to other treatment methods. J Cleaner Prod. 13, 231–240

Monni, S., 2012. From landfilling to waste incineration: Implications on GHG emissions of different actors. Int. J. Greenh. Gas Control 8, 82–89.

Montgomery, D.C and Runger, G.C., 2007. Applied Statistic and Probability for Engineers, 2a ed., John Wiley & Sons, Nueva York.

Morselli, L., Bartoli, M., Bertacchini, M., Brighetti, a, Luzi, J., Passarini, F., Masoni, P., 2005. Tools for evaluation of impact associated with MSW incineration: LCA and integrated environmental monitoring system. Waste Manag. 25, 191–196.

Mueller, D., Hamilton, P., Helsel, D., Hitt, J., Ruddy, B., 1995. Nutrients in ground water and surface water of the United States – An analysis of data through 1992, U.S. Geological Survey Water-Resources Investigation Report; 95-4031.

Muñoz, I., Rieradevall, J., 2002. Análisis del ciclo de vida aplicado a diferentes alternativas de gestión de residuos urbanos y lodos de depuradora según el Plan Integral de Gestión de Residuos Urbanos de Gipuzkoa en 2016. Institute of Environmental Science and Technology-Universidad Autónoma de Barcelona, Cerdanyola del Vallès, Spain (in Spanish).

Muñoz, P., Antón, A., Paranjpe, A., Ariño, J., Montero, J., 2008. High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield. Agron. Sustain. 28, 489.

Nilsson, J., Olsson, K., Engqvist, G., Ekvall, J., Olsson, M., Nyman, M., Akesson, B., 2006. Variation in the content of glucosinolates, hydroxycinnamic acids, carotenoids, total antioxidant capacity and low-molecular-weight carbohydrates in Brassica vegetables. J. Sci. Food Agric. 86, 528–538.

Obersteiner, G., Binner, E., Mostbauer, P., Salhofer, S., 2007. Landfill modelling in LCA - a contribution based on empirical data. Waste Manag. 27, S58–74.

Ongley, E., 1996. Control of Water Pollution from Agriculture. FAO Irrigation and Drainage Paper No.55. FAO, Rome.

Oonk, J., Boom, A., 1995. Landfill gas formation, recovery and emissions, TNO-rapport 95-203, TNO, Apeldorn, the Netherlands.

Pagans, E., Font, X., Sánchez, A., 2006. Emission of volatile organic compounds from composting of different solid wastes: abatement by biofiltration. J. Hazard. Mater. 131, 179–86.

Papadimitriou, E. K., 2007. Evaluating the effect of autoclaving on the rate of bioprocessing of waste-characteristics of autoclaving condensate and autoclaved biodegradables from non-segregated MSW. Report to Defra. University of Leeds, UK Waste Implementation Programme. Available at http://archive.defra.gov.uk (web side consulted on 10th January, 2012).

Papadimitriou, E.K., 2010. Hydrolysis of organic matter during autoclaving of commingled household waste. Waste Manag. 30, 572–582.

Papadimitriou, E.K., Barton, J.R., 2009. Report: Factors affecting the content of potentially toxic elements in the biodegradable fraction of autoclaved household waste. Waste Manag. Res. 27, 685–692.

Papadimitriou, E.K., Barton, J.R., Stentiford, E.I., 2008. Sources and levels of potentially toxic elements in the biodegradable fraction of autoclaved non-segregated household waste and its compost/digestate. Waste Manag. Res. 26, 419–430.

Pipatti, R., Wihersaari, M., 1998. Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. Mitigation and Adaptation Strategies for Global Change 2, 337–358.

Pires, A., Chang, N.-B., Martinho, G., 2011b. Reliability-based life cycle assessment for future solid waste management alternatives in Portugal. Int. J. Life Cycle Assess. 16, 316–337.

Pires, A., Martinho, G., Chang, N., 2011a. Solid waste management in European countries: A review of systems analysis techniques. J. Environ. Manage. 92, 1033–1050.

Podsędek, A., 2007. Natural antioxidants and antioxidant capacity of Brassica vegetables: A review. LWT - Food Sci. Technol. 40, 1–11.

Pognani, M., Barrena, R., Font, X., Sánchez, A., 2012. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. Waste Manag. 32, 799–805.

PRé Consultants, 2011. SimaPro Software Versión 7.3.2. PRé Consultants, The Netherlands.

PRé Consultants, 2012. SimaPro Software Versión 7.3.2. PRé Consultants, The Netherlands.

PRé Consultants, 2013. SimaPro Software Versión 7.3.3. PRé Consultants, The Netherlands.

Profu, 2004. Evaluating waste incineration as treatment and energy recovery method from an environmental point of view. Final version 2004-05-13. www.profu.se

Quirós, R., Gabarrell, X., Villalba, G., Barrena, R., García, A., Torrente, J., Font, X., 2014a. The application of LCA to alternative methods for treating the organic fiber produced from autoclaving unsorted municipal solid waste: case study of Catalonia. J. Clean. Prod. 1–13.

Quirós, R., Villalba, G., Muñoz, P., Font, X., Gabarrell, X., 2014b. Environmental and agronomical assessment of three fertilization treatments applied in horticultural open field crops. J. Clean. Prod. 67, 147–158.

Riber, C., Petersen, C., Christensen, T.H., 2009. Chemical composition of material fractions in Danish household waste. Waste Management 29, 1251–1257.

Richard, T., 1992. Municipal solid waste composting. Physical and biological processing. Biomass & Bioenergy 3:163–180

Rigamonti, L., Grosso, M., Giugliano, M., 2010. Life cycle assessment of sub-units composing a MSW management system. J. Clean. Prod. 18, 1652–1662.

Rigamonti, L., Grosso, M., Sunseri, M.C., 2009. Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. Int. J. Life Cycle Assess. 14, 411–419.

Rives, J., Rieradevall, J., Gabarrell, X., 2010. LCA comparison of container systems in municipal solid waste management. Waste Manag. 30, 949–957.

Ruggieri, L., Cadena, E., Martínez-Blanco, J., Gasol, C.M., Rieradevall, J., Gabarrell, X., Gea, T., Sort, X., Sánchez, A., 2009. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the com- posting process. J. Cleaner Prod. 17, 830-838.

RuralCat . Xarxa Agrometeorològica de Catalunya. (Catalan Agricultural Mete- orology Net). http://www.ruralcat.net/web/guest/agrometeo.estacions? (web side consulted on 15th December, 2013).

Russo, G., De Lucia, B., Vecchietti, L., Rea, E., Leone, A., 2011. Environmental and agronomical analysis of different compost-based peat-free substrates in potted rosemary. ACTA HORTICULTURAE. p. 265-272.

Sabbas, T., Polettini, a, Pomi, R., Astrup, T., Hjelmar, O., Mostbauer, P., Cappai, G., Magel, G., Salhofer, S., Speiser, C., Heuss-Assbichler, S., Klein, R., Lechner, P., 2003. Management of municipal solid waste incineration residues. Waste Manag. 23, 61–88.

SCLCI, Swiss Centre for Life Cycle Inventories. Ecoinvent Data v2.0. Duebendorf, Switzerland; 2013.

Sendra, C., 2008. Análisi dels fluxos de materials de sistemes. Phd Thesis. Departament d’Enginyeria Química. Universidad Autónoma de Barcelona. Barcelona, Spain.

SETAC, 1993. Society of Environmental Toxicology and Chemistry (SETAC): Guidelines for Life-Cycle Assessment: A 'Code of Prac- tice'. From the SETAC Workshop held at Sesimbra, Portugal, March 31 - April 3, 1993. Edition 1, August 1993.

Smet, E., Van Langenhove, H., De Bo, I., 1999. The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste. Atmospheric Environment 33, 1295–1303

Smith A, Brown K, Ogilvie S, Rushton K & Bates J. Waste Management Options and Climate Change. Final report to the European Commission, DG Environment, Office for Official Publications of the European Communities, Luxembourg; 2001.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O′Mara, F., Rice, C., Scholes, B. and Sirotenko, O. (2007) Agriculture. In: Metz,B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds.). Climate Change 2007: Mitigation.Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Solomon S, et al. Climate Change 2007. The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 19–91. Cambridge University Press, Cambridge. UK; 2007.

Sonesson, U., Bjo, A., 2000. Environmental and economic analysis of management systems for biodegradable waste. Conserv. Recycl. 28, 29–53.

Stentiford, E. I., Hobbis, P. G., Barton, J. R., Wang, Z., & Banks, C. J., 2010. Evaluating the effect of autoclaving on the rate of bioprocessing of waste. Report to Defra. University of Leeds, UK Waste Implementation Programme.

Swiss Centre for Life Cycle Inventories., 2010. Ecoinvent Data v2.2 Dübendorf, Switzerland.

Swiss Centre for Life Cycle Inventories., 2012. Ecoinvent Data v2.2 Dübendorf, Switzerland.

Thangarajan, R., Bolan, N.S., Tian, G., Naidu, R., Kunhikrishnan, A., 2013. Role of organic amendment application on greenhouse gas emission from soil. Sci. Total Environ. 465, 72–96.

Thorneloe SA.,Weitz KA., Jambeck J., 2005. Moving from solid waste disposal to materials management in the United States. Proceed- ings Sardinia 2005, Tenth International Waste Management and Landfill Symposium; S. Margherita di Pula, Caglia

Tonini, D., Astrup, T., 2012. Life-cycle assessment of a waste refinery process for enzymatic treatment of municipal solid waste. Waste Manag. 32, 165–176.

Trémier, A., 2006. Evaluating the effect of autoclaving on the rate of bioprocessing of waste e Experimental trials with MSW autoclaved at 20 ^{0}C. Cemagref Report PUB00019753. http://en.scientificcommons.org/43841929. (web side consulted on 12th July, 2013).

Van-Camp, L., Ujarrabal, B., Gentile, A., Jones, R.J.A., Montanarella, L., Olazabal, C. and Selvaradjou, S-., 2004. Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. EUR 21319 EN/3, Luxembourg.

Van Zeijts, H., Leneman, H., Wegener Sleeswijk, a, 1999. Fitting fertilisation in LCA: allocation to crops in a cropping plan. J. Clean. Prod. 7, 69–74.

WCED, 1987. Our Common Future. Oxford University Press, Oxford.

Wihersaari, M., 2005. Evaluation of greenhouse gas emission risks from storage of wood residue. Biomass and Bioenergy 28, 444–453.

WSOFM (Washington State Office of Financial Management). Schedule A—capital asset commodity class code list and useful life schedule. (www.ofm.wa.gov/default.asp) (web side consulted on 13th november, 2013).

WSOFM (Washington State Office of Financial Management). Schedule A—capital asset commodity class code list and useful life schedule. State Administrative & Accounting Manual, section 30.50.10; 2008 (www.ofm.wa.gov/default.asp) (web side consulted on 12th January, 2014).

Zaman, A.U., 2010. Comparative study of municipal solid waste treatment technologies using life cycle assessment method. Environ. Eng. 7, 225–234.

Zhao, W., Voet, E. Van Der, Zhang, Y., Huppes, G., 2008. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions : Case study of. Sci. Total Environ. 407, 1517–1526.

ANNEXES

This section contains all the annexes mentioned in the dissertation document. Annexes are in a separate word file along with the current dissertation document.

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Chapter	Annexes	Description
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ANNEXES

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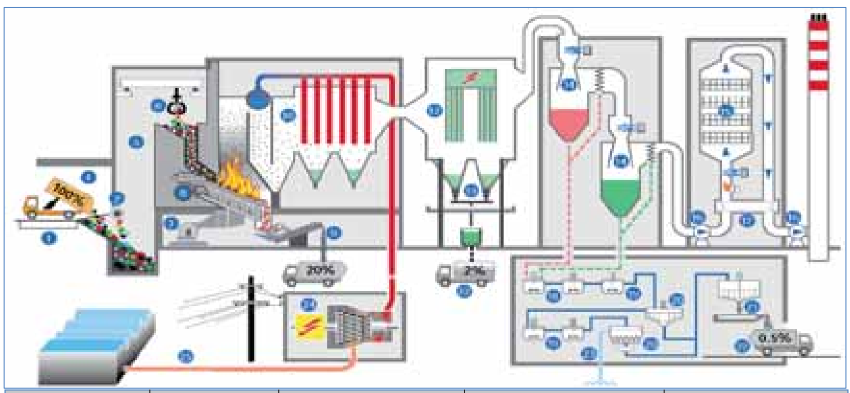
Chapter 1

Introduction, methodology and objectives

1. Chapter 1

Annex 1.1 Description of the incineration process

Figure 1.1 shows the elements involved in the incineration process which are considered in the ecoinvent database. The inventories are based on the technology encountered in Switzerland, but can be used as a good proxy for modern waste incineration in Europe **(Swiss Centre for Life Cycle Inventory, 2010).** A full description of the incineration process can be found in the ecoivent database reports.



Waste delivery	Incinerator	Flues gas purification	Waste water treatment	Energy conversion
1 Scale	7 Combustion air vent	11,12 Electrostatic precipitador	18 Neutrilisation	24 Steam turbine / generator
2 Coarse refuse shredder	8 Incinerator grate	13 Electrostatic precipitator ash	19 Precipitation	25 Heat to district heating system
3,4 Unloading bay	9 Slag (bottom ash)	14 Flue gas scrubber	20 Sedimentation	
5 Waste bunker	10 Steam boiler	15 DeNOx stage	21 Sludge dewatering	
6 Waste crane		16 Flue gas blower	22 Residual waste to landfill	
		17 Heat recuperator	23 Purified waste discharged to river	

Figure 1.1 Diagram process for a municipal solid waste incinerator
Source: Adapted from the ecoinvent database v.2.2

The typical design for a municipal solid waste incinerator plant **(MSWI)** consists of two or three incineration lines in parallel. Each incineration line is equipped with a grate-type furnace (8). At the end of the grate the unburnable remains are collected as slag (bottom ash) and quenched in water (9). The raw gas is led to an integrated steam boiler (10). The recovered heat is passed to a steam turbine (24) to generate electricity. The expanded steam is sometimes directed to a district heating network (25) or use as process steam for neighbouring industries. After being cooled down in the steam boiler, the flue gas of the MSWI is then passed into an electrostatic precipitator for fly separation (12). Electrostatic precipitators (**ESP**) use the principle of electrostatic attraction to remove particles from the raw gas. They consist of rows of discharge electrodes (wires or thin metal rods), though which a high voltage is applied, and which run between an array of parallel rows metal plates which collect the charged particles.

After the ESP, a multistage wet scrubber (14) is used to eliminate harmful components of the flue gas like $SO_{x,}$ HCL by washing the raw gas in a reactive tower. Designed to provide a high gas-liquid contact, the gases are cooled by water in the first stage, removing HCL, HF, some particulates and some heavy metals. In the second stage hydroxide or another suitable alkali is used to remove SO_x and any remaining HCl. The scrubbing liquid is neutralised (18), heavy metals are precipitated (19) and separated as a sludge (20) in a wastewater treatment facility. The treated water is usually discharged to a river. After the wet scrubber is purified flue gas enters a DeNOx installation (15). The purified flue gas is led into a stack. Approximately 75% of the original waste mass is transferred to gaseous compounds like carbon dioxide CO_2, elemental Nitrogen N_2 and waste H_2O and minor trace gases. Usually a SCR or SNCR-DeNOx technology is employed. Placement of the DeNOx facility depends on the technology employed: SNCR DeNOx takes place directly in the incineration chamber, SCR-high dust before the wet scrubber (i.e. in high-dust environment), SCR-low dust after the wet scrubber (i.e. in a low-dust environment).

Annex 1.2 Analytical methods for gaseous emissions measurement at home composting

Gaseous emissions of the composting process for full-scale composting facilities and for home composting was measured in situ following the methodology described by Colón et al., 2012 and Cadena, 2009. Following a brief description of the methodology presented in Colón et al., 2012. Air flow velocity and ammonia, nitrous oxide, methane and VOC's concentration on the surface of the composting pile, composting bin or the biofilter were simultaneously measured on the material surface of the composter in order to calculate the gas outlet emission rate (mg s^{-1}). Air velocity was determined using a thermo-anemometer and Venture tube. The product of each pollutant concentration (mg m^{-3}) and air velocity (m s^{-1}) result in the mass flow of a given compound released per surface are unit studied (mg s^{-1} m^{-2}) was multiplied by the entire emitting surface area resulting in the outlet mass flow emission (mg s^{-1}) at the moment for each component (Colón et al., 2012).

Ammonia concentration in gaseous emissions was determined in situ using an ammonia sensor ITX T82 with a measurement range of 0 to 200 ppmv. Gaseous samples were also collected in Teldar bags for the laboratory determination of VOC, methane and nitrous oxide. The total *VOC* content from gaseous samples was determined as the total carbon content using a gas chromatograph equipped with a flame ionization detector (FID) and a dimethylpolysiloxane 2 m x 0.53 mm x 3.0 mm column (Tracsil TRB-1, Teknokroma, Barcelona, Spain). This column permits the determination of total VOC as a unique peak.

Methane was also analyzed by gas chromatography using a Flame Ionization Detector (FID) and a HP-Plot Q column (30 m x 0.53mm? 40 mm) with a detection limit of 1 ppmv. Nitrous oxide was analyzed by gas chromatography using an Electron Capture Detector (ECD) and a HP-Plot Q column (30 m x 0.53 mm x 40 mm) with a detection limit of 50 ppbv. The gas chromatography operation conditions for each pollutant element can be seen broadly in Colón et al., 2012. Figure 1.2 shows some elements used for compost emissions masurements.

a. Chromatographer

b. Tedlar bags

Figure 1.2 Equipment used for compost emissions measurements

Annexes

Chapter 2

Technologies to treat municipal solid waste

2. **Chapter 2**

Annex 2.1 Process flow diagram for composting in tunnels (CT)

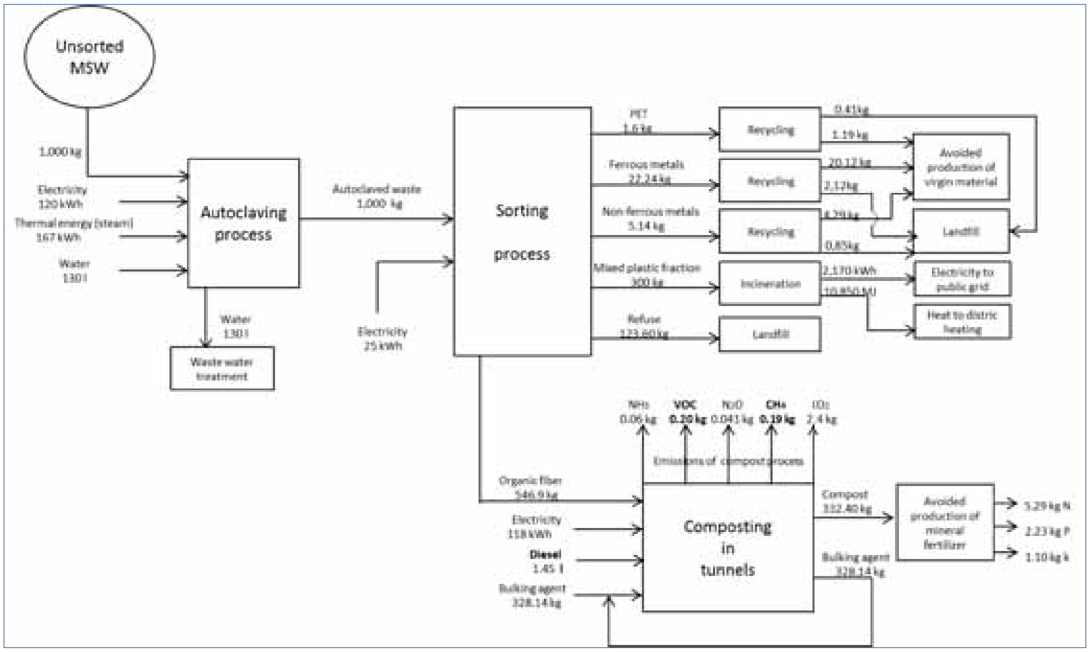


Figure 2.1Process flow diagram for composting in tunnels (CT)

Annex 2.2 Process flow diagram for composting in confined windrows (CCW)

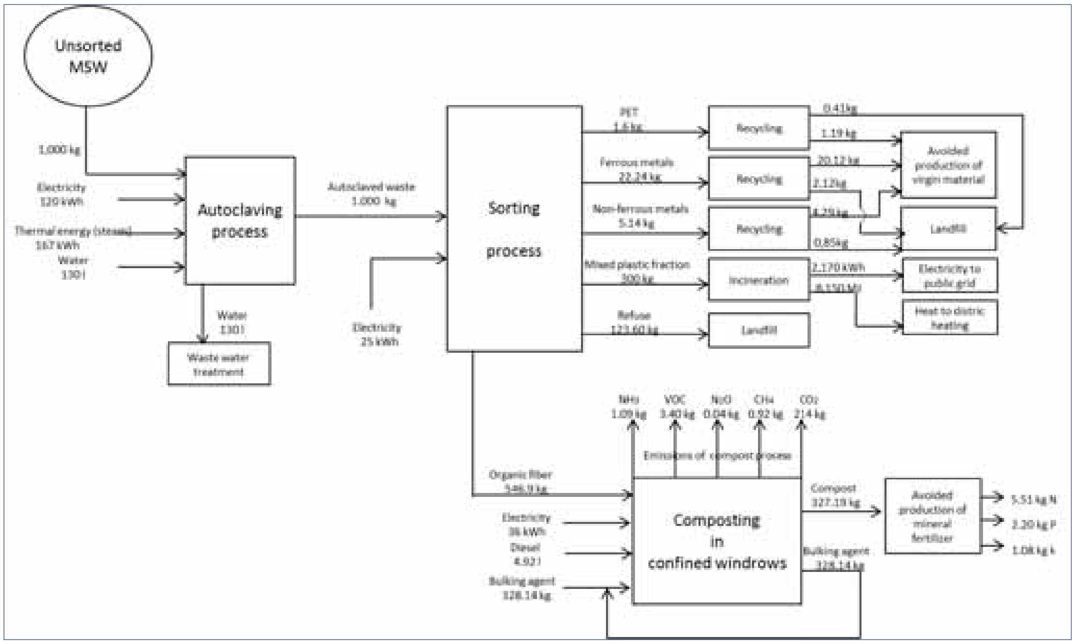


Figure 2.2 Process flow diagram for composting in confined windrows (CCW)

Annex 2.3 Process flow diagram for turning windrow composting (TW)

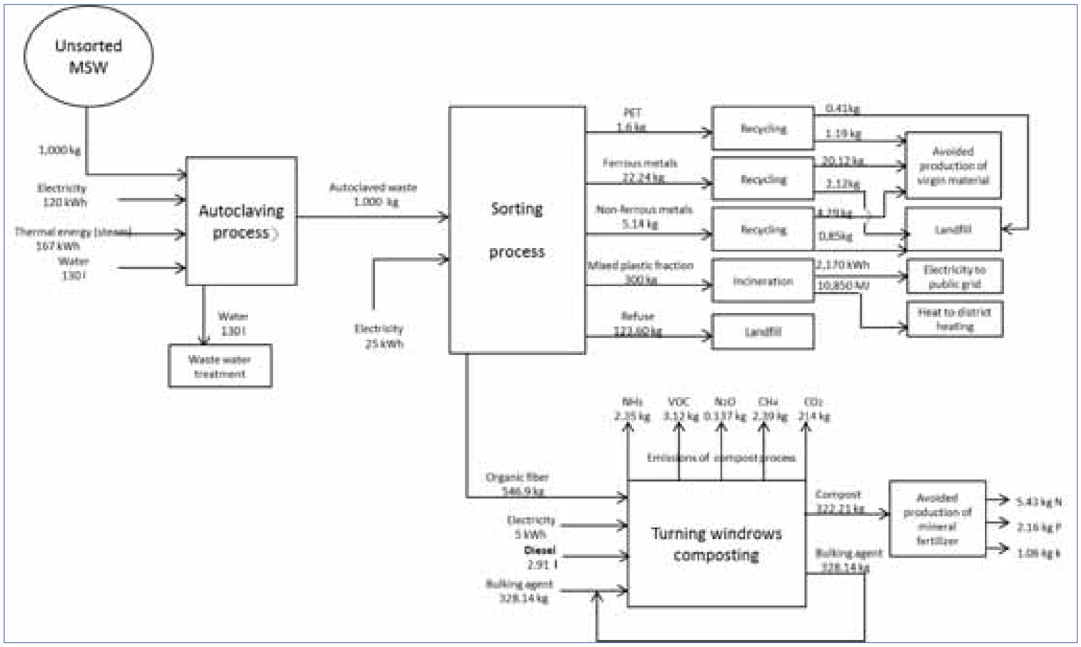


Figure 2.3 Process flow diagram for turning windrows composting (TW)

Annex 2.4 Process diagram for anaerobic digestion mesophilic plus composting

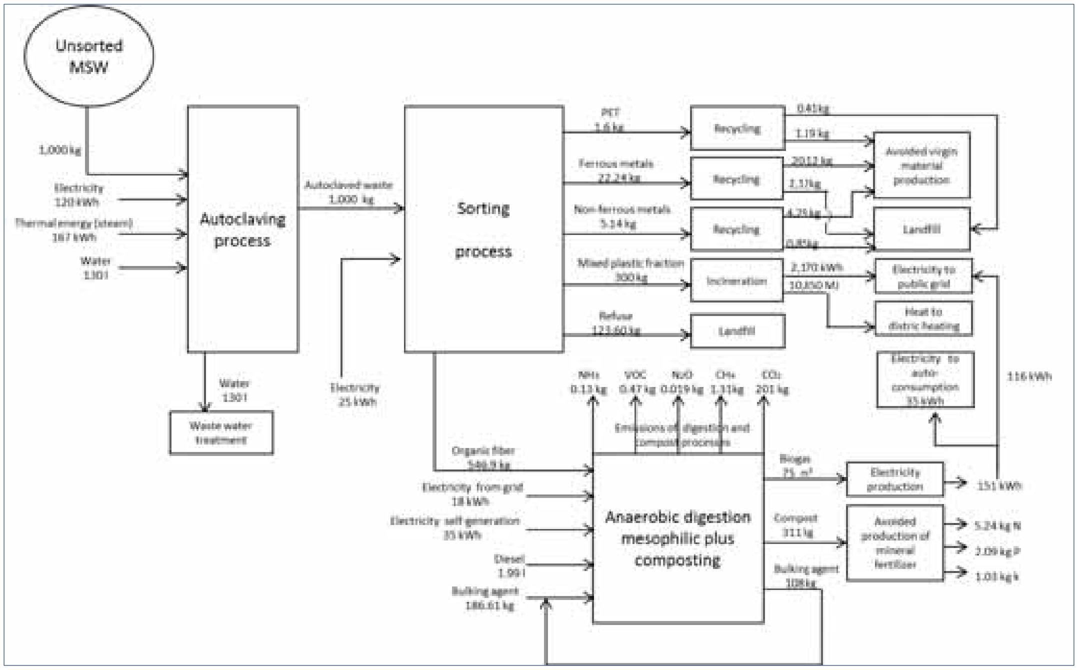


Figure 2.4 Process flow diagram for anaerobic digestion mesophilic plus composting (ADC-M)

Annex 2.5 Properties for the final compost obtained from autoclaved organic fiber

Table 2.1Properties of final compost obtained from autoclaved organic fiber and legislation

Parameter	Units	Compost from organic fiber	Spanish legislation (Class A/B/C for heavy metals)
Dry matter content	%	63.1	60-70
Organic matter content	%, dry basis	77.6	>35
pH	1:5 w:v extract	8.06	No value
Elec. Conductivity	1:5 w:v extract, mS/cm	3.1	No value
Nitrogen (Kjeldahl)	%, dry basis	2.86	No value
C/N ratio		14	<20
Respiration index	mg O^2 kg^{-1} TS h^{-1}	504	No value
Bulk density	kg/L	0.35	No value
Air filled porosity	%	53.8	No value
E.coli	CFU/g	<20	<1000
Salmonella	presence/absence in 25g	absence	absence
Nickel	mg kg^{-1}, dry matter basis	22	25/90/100
Lead	mg kg^{-1}, dry matter basis	54	45/150/200
Copper	mg kg^{-1}, dry matter basis	148	70/300/400
Zinc	mg kg^{-1}, dry matter basis	387	200/500/1000
Mercury	mg kg^{-1}, dry matter basis	0.13	0.4/1.5/2.5
Cadmium	mg kg^{-1}, dry matter basis	0.5	0.7/2/3
Chromium	mg kg^{-1}, dry matter basis	43	70/250/300
Chromium VI	mg kg^{-1}, dry matter basis	Not detected	Not detected

*Spanish legislation, Real Decree 506/2012 (Ministerio del Presidencia, 2013)

Annex 2.6 Electricity balance for the anaerobic digestion

Table 2.2 Electricity balance for the anaerobic digestion processes

Item	ADC-T[a] kWh · MF$^{-1,c}$	ADC-M[b] kWh · MF^{-1}
Total self-generated electricity from biogas	227	151
Electricity consumption	78	53
From public grid	25	18
From Self-generated electricity from biogas	53	35
Self-generated electricity from biogas sold to an electricity distribution company	174	116
% of self-generated electricity used in internal processess	23%	23%
% of self-generated electricity sold to an electricity distribution company	77%	77%

[a]ADC-T: Anaerobic digestion thermophilic plus composting
[b]ADC-M: Anaerobic digestion mesophilic plus composting
[c]MF: Material flow (546 kg of organic fiber)

Annex 2.7 Sensitivity analysis

Table 2.3 Sensitivity analysis for energy recovery and LHV*

Incineration of one tonne MSW[1] with energy recovery

Options	Alternatives	Efficiencies for electricity conversion				Efficiencies for heat conversion				LHV[2] (MJ / tonne of MSW)			GWP[3]
		13%	20%	25%	30%	26%	30%	35%	40%	8,000	9,000	11,740	kg CO_2 eq
1	Inc[4] 1,1	X				X				X			209
	Inc 1,2		X				X			X			129
	Inc 1,3			X				X		X			55
	Inc 1,4				X				X	X			-19
2	Inc 2,1	X				X					X		144
	Inc 2,2		X				X				X		47
	Inc 2,3			X				X			X		-43
	Inc 2,4				X				X		X		-133
3	Inc 3,1	X				X						X	71
	Inc 3,2		X				X					X	-46
	Inc 3,3			X				X				X	-155
	Inc 3,4				X				X			X	-264

Biological treament technologies (one tonne of unsorted MSW)[5]

		Efficiencies for electricity conversion				Eficiencies for heat conversion				LHV (MJ / tonne of mixed plastic			GWP
		13%	20%	25%	30%	26%	30%	35%	40%	20,000	25,000	31,000	kg CO_2 eq.
4	ADC-T[6] 1,1	X				X				X			-99
	ADC-T 1,2		X				X			X			-159
	ADC-T 1,3			X				X		X			-214
	ADC-T 1,4				X				X	X			-250
5	ADC-T 2,1	X				X					X		-154
	ADC-T 2,2		X				X				X		-208
	ADC-T 2,3			X				X			X		-298
	ADC-T 2,4				X				X		X		-352
6	ADC-T 3,1	X				X						X	-221
	ADC-T 3,2		X				X					X	-296
	ADC-T 3,3			X				X				X	-400
	ADC-T 3,4				X				X			X	-486
7	CT[7] 1,1	X				X				X			23
	CT 1,2		X				X			X			-37
	CT 1,3			X				X		X			-92
	CT 1,4				X				X	X			-148
8	CT 2,1	X				X					X		-32
	CT 2,2		X				X				X		-107
	CT 2,3			X				X			X		-177
	CT 2,4				X				X		X		-246
9	CT 3,1	X				X						X	-99
	CT 3,2		X				X					X	-192
	CT 3,3			X				X				X	-278
	CT 3,4				X				X			X	-364
10	TW[8] 1,1	X				X				X			-51
	TW 1,2		X				X			X			-110
	TW 1,3			X				X		X			-166
	TW 1,4				X				X	X			-222
11	TW 2,1	X				X					X		-106
	TW 2,2		X				X				X		-181
	TW 2,3			X				X			X		-249
	TW 2,4				X				X		X		-320
12	TW 3,1	X				X						X	-173
	TW 3,2		X				X					X	-265
	TW 3,3			X				X				X	-351
	TW 3,4				X				X			X	-438

[1]MSW: Municipal Solid Waste; [2]LHV: Low Heating Value; [3]GWP: Global Warming Potential;[4] Inc: Incineration
[5]Biological treatments considers the incineration of the mixed plastic fraction;[6]ADC-T: Anaerobic Digestion Thermophilic plus Composting;[7]CT: Composting in Tunnels

*The sensitivity analysis lead per technology for GWP (Global Warming Potential) indicator. The analysis considers several ranges of LHV's for plastics and MWS and efficiencies for electricity and heat conversion for incineration of one tonne of unsorted municipal solid waste and for the incineration of the autoclaving mixed plastic fraction (300 kg).

Annexes

Chapter 3

Environmental assessment of three fertilizers

Chapter 3

Annex 3.1 Quality and origin of data

Table 3.1 Quality and origin of data used in the life cycle inventory

Phases	Stages	Sub-stages	Fertilizer treatments				Sources
			IC[1]	HC[2]	HC-LE[3]	MF[4]	
Compost production	Collection and transport	Distances and process	X				a
	Compost process	Energy, water, materials and materials waste management	X				c
				X			d
					X		e
	Gaseouss emissions	Ammonia, methane, nitrous oxides and volatile organic compounds	X				c
				X	X		b
Mineral fertilizer production	Raw material	Extraction				X	a
	Production	Process				X	a
	Gaseouss emissions	Subtances emissions				X	a
Transport	Transport	Distances and process	X				a
						X	a
Cultivation	Fertirrigation	Infraestructure and infraestructure waste management	X	X	X	X	b
	Management	Phitosanitary substances, machinery and tools, irrigation, post-application emissions and nursery	X	X	X	X	b

[a]Ecoinvent data base V2.2
[b]Experimental data
[c]Colón et al. (2012)
[d]Lleó et al., (2012)
[e]Colón et al., (2010)
[1]IC: Industrial compost
[2]HC: Home compost
[3]HC-LE: Home compost with low gaseous emissions of the production process
[4]MF: Mineral fertilizer

Annex 3.2 Inventories for home compost production

Table 3.2 Inventories for home compost production

Stages	Element	Flow		Units (ton^{-1}· LFRV[1])	Lifespam (yr)	Source
Fertilization treatment			**HC[2]**			
Inputs						
Collection of LRFV and PW	LRFV collection bin	PP	0.048	kg	7	SLCI (2013), WSOFM (2008)
Composter and tools	Composter	HDPE	3.122	kg	12	SLCI (2013), Compostadores SL (2008) and Colón et al. (2009), Iriarte et al. (2009) and Colón et al. (2010)
	Transport (composter)	Transport	1.561	tkm	-	Google maps and SLCI (2013)
	Plastic container collection	HDPE	0.004	kg		SLCI (2013)
	Plastic collection. Cleaning	HDPE	0.006	L	-	SLCI (2013)
	Garden clipper	Stell	0.174	kg	10	Compostadores SL (2008), SCLCI (2013), WSOFM (2008),
		HDPE	0.174	kg		Experimental measurements and SLCI (2013)
	Bag for PW collection	PP	0.047	kg	3	SLCI (2013)
	Shovel	Stell	0.017	kg	12	SLCI (2013)
		Wood	0.009	kg	12	SLCI (2013)
	Mixing tool	Iron	0.078	kg	6	SLCI (2013)
	Watering can	PP	0.002	kg	-	SLCI (2013)
	Gloves	Cotton	0.007	kg	-	SLCI (2013)
	Transport national	Transport	0.213	tkm	-	Google maps and SLCI (2013)
	Transport regional	Transport	0.008	tkm	-	Google maps and SLCI (2013)
Water consumption	Moistening water	Tap water	50.870	L	-	Experimental measurements
Energy consumption	Electricity consumption (clipper)	Electricity	5.991	kWh	-	Experimental measurements and Compostadores SL (2008)
Outputs						
Gasesous emissions**	Methane	CH_4	**1.350**	kg	-	Experimental measurements, Colón et al. (2010) and Lleó et al. (2013)
	Volatile organic compunds	VOC's	**-**	kg	-	Experimental measurements, Colón et al. (2010) and Lleó et al. (2013)
	Nitrous oxide	N_2O	**1.160**	kg	-	Experimental measurements, Colón et al. (2010) and Lleó et al. (2013)
	Ammonia	NH_3	**1.300**	kg	-	Experimental measurements, Colón et al. (2010) and Lleó et al. (2013)
Waste dumped	Waste management in landfill	Wood	0.009	kg	-	Compostadores SL (2008), SCLCI (2013), WSOFM (2008),
		Cotton	0.007	kg	-	and experimental measurements
		Plastic mix	4.380	kg	-	SCLI (2013)
	Transport to landfill	Transport	0.002	tkm	-	Google maps and SCLI (2013)

* [1]LFRV: Lefover of fruit and vegetables; [2]HC: Home compost; [3]HC-HE: Home compost high emissions
**Only HC was applied to crops

Annex 3.3 Inventories for cultivation phase

Table 3.3 Inventories for cultivation phase per fertilization treatment and stages

				Amounts per functional unit (FU)		
Stages and substages	Material	Lifespan	Units · FU^{-1}	IC[a]	HC[b]	MF[c]
1. Cutivation_fertirrigation stage						
1.1 Equipment and tools						
Water irrigation pump	Steel	20 years	kg	3.27E-03	1.13E-02	3.92E-02
Water extraction pump	Steel	20 years	kg	3.27E-03	1.13E-02	3.92E-02
Water storage tank	Steel	50 years	kg	1.65E-01	5.71E-01	1.98E+00
Water storage tank	Concrete	50 years	m^3	2.77E-03	9.57E-03	3.31E-02
Fertilizer storage tank	LDPE	10 years	kg	1.47E-02	5.09E-02	1.76E-01
Electrovalves	LDPE	10 years	kg	4.58E-04	1.59E-03	5.49E-03
Microsprinklers	PVC	1 years	kg	2.49E-03	8.63E-03	2.99E-02
Spaghetti pipes	LDPE	1 years	kg	8.00E-03	2.77E-02	9.58E-02
Primary pipes	LDPE	10 years	kg	6.61E-03	2.29E-02	7.92E-02
Secondary pipes	LDPE	1 years	kg	8.30E-02	2.87E-01	9.95E-01
Tank pipes	PVC	1 years	kg	3.10E-03	1.07E-02	3.71E-02
Supports rods	Steel	20 years	kg	7.48E-02	2.59E-01	8.96E-01
1.2Waste management			kg	2.89E-01	4.85E-01	7.33E-01
2.Cultivation_management stage						
2.1 Pesticides			kg	1.73E-01	1.15E-01	9.07E-02
2.2 Machinery and tools						
Tractor		7200 h	kg	5.74E-01	1.85E+01	2.68E-01
Diesel consumption			kg	3.10E+01	6.36E+03	1.50E+01
Plough		300 h	kg	2.83E-01	1.91E-01	1.34E-01
Tow		6000 h	kg	4.10E-02	3.29E+01	0.00E+00
Fertilizer spreader		800 h	kg	7.04E-03	5.66E+00	0.00E+00
Furrow opener		1190 h	kg	3.39E-01	2.25E-01	1.77E-01
Spray bag		1000h	kg	1.00E-01	6.64E-02	5.25E-02
Ancillary equipment			kg	3.96E+00	6.28E+00	9.31E+00
2.2 Irrigation						
Water			m^3	2.40E+02	1.60E+02	1.08E+02
Electricity used (water pump)			MJ	1.74E+02	1.15E+02	7.87E+01
Electricity used (well pump)			MJ	1.24E+02	8.13E+01	5.60E+01
2.3 Emissions (NH_3)						
From water			g	2.75E+02	1.81E+02	1.27E+02
From compost			g	4.59E+02	4.54E+02	0.00E+00
From mineral fertilizer			g	0.00E+00	0.00E+00	5.30E+05
2.4 Nursery plant				4.63E+03	3.06E+03	2.42E+03

[a]IC: Industrial compost, FU=4.5 tonnes of cauliflower · ha^{-1}; [c]HC: common home compost, FU=6.8 tonnes of cauliflower · ha^{-1}; [d]MF: mineral fertilizer, FU=8.6 tonnes of cauliflower · ha^{-1}

Annexes

Chapter 4

Environmental assessment of two home composts

Chapter 4

Annex 4.1 Quality and origin of data

Table 4.1Quality and origin of data used in the life cycle inventory

Phases	Stages	Sub-stages	Fertilizer treatments IC[1]	HC[2]	HC-LE[3]	MF[4]	Sources
Compost production	Collection and transp	Distances and process	X				a
	Compost process	Energy, water, materials and materials waste management	X				c
				X			d
					X		e
	Gaseouss emissions	Ammonia, methane, nitrous oxides and volatile organic compounds	X				c
				X	X		b
Mineral fertilizer production	Raw material	Extraction				X	a
	Production	Process				X	a
	Gaseouss emissions	Subtances emissions				X	a
Transport	Transport	Distances and process	X				a
						X	a
Cultivation	Fertirrigation	Infraestructure and infraestructure waste management	X	X	X	X	b
	Management	Phitosanitary substances, machinery and tools, irrigation, post-application emissions and nursery	X	X	X	X	b

[a]Ecoinvent data base V2.2
[b]Experimental data
[c]Colón et al., (2012)
[d]Lleó et al., (2012)
[e]Colón et al., (2010)
[1]IC: Industrial compost
[2]HC: Home compost
[3]HC-LE: Home compost with low gaseous emissions of the production process
[4]MF: Mineral fertilizer

Annex 4.2 Life cycle inventory for the cultivation phase

Table 4.2 Life cycle inventory for cultivation phase

Stages and substages	Material	Lifespan	Amount	FU^{-1}
1. Cutivation_fertirrigation stage				
1.1 Equipment and tools				
Water irrigation pump	Steel	20 years	1.13E-02	kg
Water extraction pump	Steel	20 years	1.13E-02	kg
Water storage tank	Steel	50 years	5.71E-01	kg
Water storage tank	Concrete	50 years	9.57E-03	m3
Fertilizer storage tank	LDPE	10 years	5.09E-02	kg
Electrovalves	LDPE	10 years	1.59E-03	kg
Microsprinklers	PVC	1 years	8.63E-03	kg
Spaghetti pipes	LDPE	1 years	2.77E-02	kg
Primary pipes	LDPE	10 years	2.29E-02	kg
Secondary pipes	LDPE	1 years	2.87E-01	kg
Tank pipes	PVC	1 years	1.07E-02	kg
Supports rods	Steel	20 years	2.59E-01	kg
1.2Waste management			4.85E-01	kg
2.Cultivation_management stage				
2.1 Pesticides			1.15E-01	kg
2.2 Machinery and tools				
Tractor		7200 h	1.85E+01	kg
Diesel consumption			6.36E+03	kg
Plough		300 h	1.91E-01	kg
Tow		6000 h	3.29E+01	kg
Fertilizer spreader		800 h	5.66E+00	kg
Furrow opener		1190 h	2.25E-01	kg
Spray bag		1000h	6.64E-02	kg
Ancillary equipment			6.28E+00	kg
2.2 Irrigation				
Water			1.60E+02	m3
Electricity used (water pump)			1.15E+02	MJ
Electricity used (well pump)			8.13E+01	MJ
2.3 Emissions				
From water			1.81E+02	g
From compost			4.54E+02	g
From mineral fertilizer			0.00E+00	g
2.4 Nursery plant			3.06E+03	

FU = 6.8 tonnes of cauliflower · ha^{-1}

Annex 4.3 Impact per stage, fertilization treatment and impact category

Table 4.3 Impacts per stage, fertilization treatment and impact category

		Compost production stages				Cultivation stages					
Fertilization treatment	Equivalent units	Cp_T[1]	Cp_E[2]	Cp_C[3]	Cp_E[4]	Cu_F[5]	Cu_P[6]	Cu_M[7]	Cu_I[8]	Cu_E[9]	Cu_N[10]
HC-LE[11]											
ADP	kg Sb eq.	2.55E-01	4.21E-02	3.32E-03	0.00E+00	5.77E-01	9.65E-03	8.03E-01	2.25E-01	0.00E+00	2.02E-01
AP	kg SO_2 eq.	7.60E-02	5.50E-02	8.58E-04	6.41E-02	1.81E-01	1.10E-02	7.09E-01	1.39E-01	8.64E-01	2.29E-01
EP	kg PO_4 eq.	2.30E-02	1.13E-02	2.72E-04	1.40E-02	1.12E-01	3.74E-03	1.74E-01	9.26E-02	1.89E-01	1.58E-01
GWP*	kg CO_2 eq.	1.99E+01	5.79E+00	2.52E-01	1.04E+02	4.65E+01	1.16E+00	1.01E+02	3.04E+01	0.00E+00	3.05E+01
OLDP	kg CFC-11	3.47E-06	3.13E-07	4.75E-08	0.00E+00	1.88E-06	3.49E-06	1.38E-05	1.29E-06	0.00E+00	1.35E-06
POP	kg C_2H_4 eq.	5.41E-03	2.04E-03	5.11E-05	1.32E-01	9.65E-03	6.74E-04	1.83E-02	5.57E-03	0.00E+00	1.23E-02
CED	CED	6.09E+02	1.17E+02	7.95E+00	0.00E+00	1.40E+03	2.33E+01	1.87E+03	6.68E+02	0.00E+00	5.13E+02
HC-HE[12]											
ADP	kg Sb eq.	2.55E-01	4.21E-02	3.32E-03	0.00E+00	5.77E-01	9.65E-03	8.03E-01	2.25E-01	0.00E+00	2.02E-01
AP	kg SO_2 eq.	7.60E-02	5.50E-02	8.58E-04	3.33E+00	1.81E-01	1.10E-02	7.09E-01	1.39E-01	8.64E-01	2.29E-01
EP	kg PO_4 eq.	2.30E-02	1.13E-02	2.72E-04	7.29E-01	1.12E-01	3.74E-03	1.74E-01	9.26E-02	1.89E-01	1.58E-01
GWP	kg CO_2 eq.	1.99E+01	5.79E+00	2.52E-01	5.93E+02	4.65E+01	1.16E+00	1.01E+02	3.04E+01	0.00E+00	3.05E+01
OLDP	kg CFC-11	3.47E-06	3.13E-07	4.75E-08	0.00E+00	1.88E-06	3.49E-06	1.38E-05	1.29E-06	0.00E+00	1.35E-06
POP	kg C_2H_4 eq.	5.41E-03	2.04E-03	5.11E-05	1.42E-01	9.65E-03	6.74E-04	1.83E-02	5.57E-03	0.00E+00	1.23E-02
CED	CED	6.09E+02	1.17E+02	7.95E+00	0.00E+00	1.40E+03	2.33E+01	1.87E+03	6.68E+02	0.00E+00	5.13E+02

Cp: Compost production stage; Cu: Cultivation stage
[1]Cp_T: Tools
[2]Cp_E: Energy
[3]Cp_C: Collection
[4]Cp_E_m: Emissions
[5]Cu_F: Fertirrigation
[6]Cu_P: Phitosanitary substances
[7]Cu_M: Machinery and Tools
[8]Cu_I: Irrigation
[9]Cu_E: Emissions
[10]Cu_N: Nursery
[11]HC-LE: Home compost low emissions
[12]HC-HE: Home compost high emissions

Annexes

Chapter 6

Life cycle assessment of fertilizers in a crop sequence

6. Chapter 6

Annex 6.1 Crop sequence fertilized with Industrial Compost (IC)

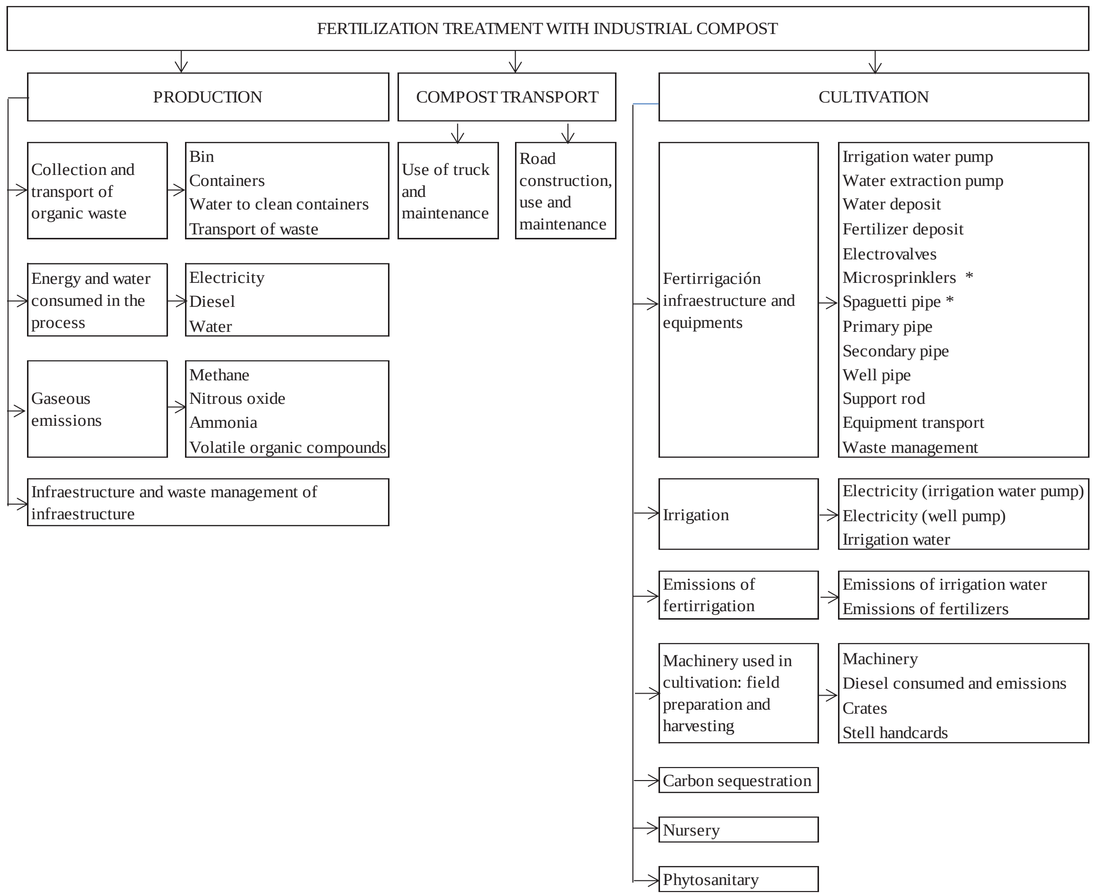


Figure 6.1 Stages and sub-stages for the crop sequence fertilized with Industrial Compost (IC)

*These elements were used only for the cauliflower crop that was a sprinkling irrigation system

Annex 6.2 Crop sequence fertilized with Home Compost (HC)

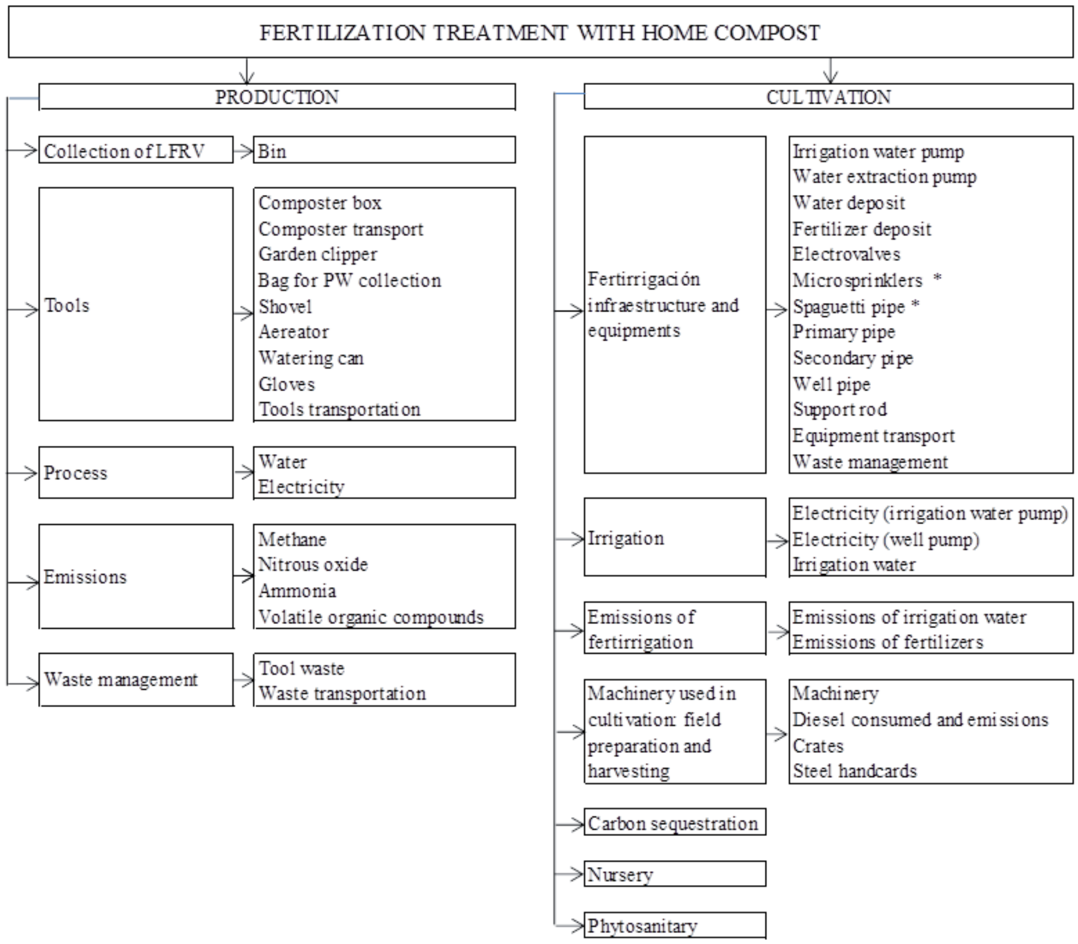


Figure 6.2 Stages and sub-stages for the crop sequence fertilized with home compost (HC)

*These elements were used only in the cauliflower crop that is a sprinkling irrigation system

Annexe 6.3 Crop sequence fertilizer with Mineral fertilizer (MF)

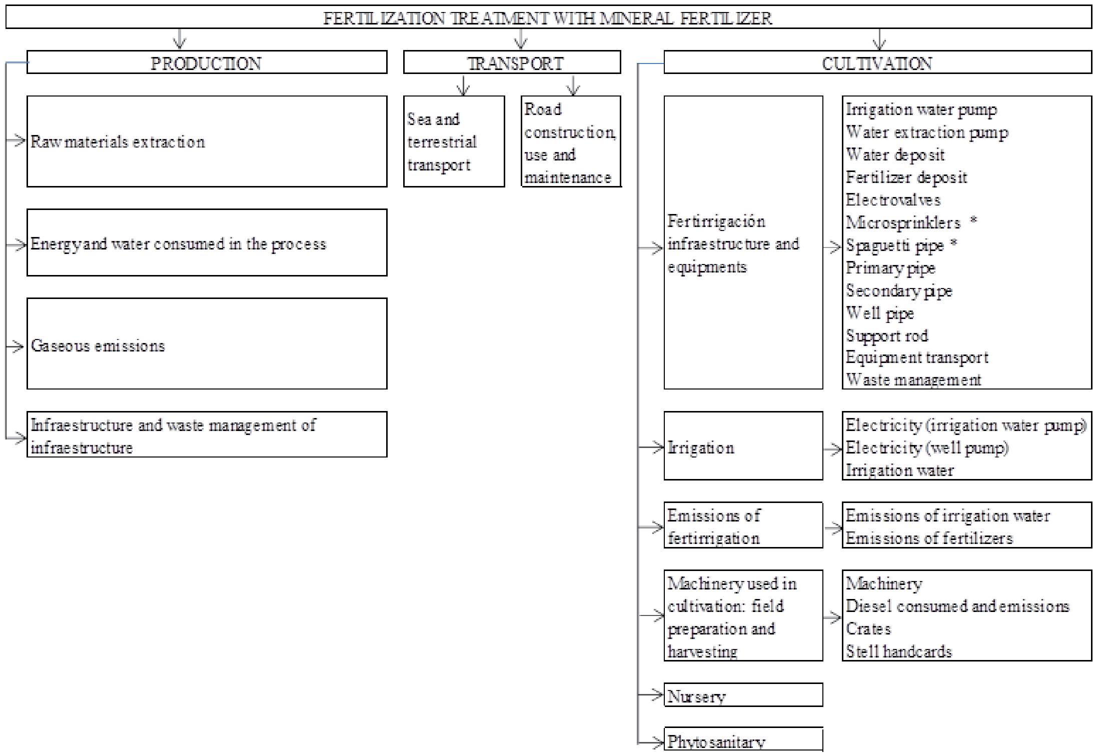


Figure 6.6.3 Stages and sub-stages for the crop sequence fertilized with mineral fertilizer (MF)

Annex 6.4 Quality and origin of data for life cycle inventory

Table 6.1 Quality and origin used for the life cycle inventories*

Stage	Substages	Substages-processes	Origin	References	Coments
Mineral fertilizers production		Production of KNO_3	DB	Ecoinvent database v.2.0	This process includes production infraestructure, transport of raw materials, synthesis of the chemical compost required and tha deposition and treatmente of waste generated
		Doses	EXR	Experimental results	
Industrial compost production		Collection and transport of municipal organic waste	DB-LR	Ecoinvent database v2.0 and Iriarte et al. 2008	
		Compost process	EXR	Experimental results and Colón et al. 2012	This process includes consumption of electricity, water, diesel, building and management of solid waste fraction to landfill
		Gaseous emissions of production process	EXD	Experimental results and Colón et al. 2012	This process includes emissions of NH_3, CH_4, N_2O and COV's
		Transport and waste management of solid waste in landfill	DB-LR	Ecoinvent database v.2.0; Barrena et al. 2012 and Ponsa et al. 2008	
		Building infraestructure and machinery	DB-LR	Ecoinvent database v.2.0; Althaus et al. 2004; IteC 2008; SCLCI 2005 and WSOFM 2008	
		Production of electricity, diesel and diesel emissions	DB	Ecoinvent database v.2.0	
Home compost production		Collection of organic waste	DB	Ecoinvent database v2.0	Collection bin for LRFV (left over of fruit and vegetables)
		Composter (production) and transport	DB	Ecoinvent database v2.0	Transport (Madrid to Barcelona, 600 km)
		Tools needed for the composting process	DB	Ecoinvent database v2.0	This process includes production of garden chipper, bag for PW (prunning waste) collection, shovel, mixing tool, watering can and gloves
		Process of transport of tools and distances	DB	Ecoinvent database v2.0	Transport from the store to the plots (50 km)
		Water consuption	EXR	Experimental results	
		Electricity consumption	EXR-DB	Experimental results and Ecoinvent database v2.0	Electricity consumed by the garden chipper
		Gaseous emissions of the production process	EXR	Experimental results	This process includes emissions of NH_3, CH_4, N_2O and COV's
Mineral fertilizers transport		Transport of mineral fertilizers from the plant to the crops and distances	DB	Ecoinvent database v.2.0	Maritime portion (transport from Israel to Barcelona 2975 km) and terrestrial portion (Barcelona port to Santa Susana, 50 km)
Industrial compost transport		Transpor of compost from the plant to the crops and distances	DB	Ecoinvent database v.2.0	
Cutivation	Fertirrigation	System design	EXR	Experimental results and MAPA 2002	
		Components production and transport	DB	Ecoinvent database v.2.0	Components include: tanks, plumps, electrovalves, pipes, rods and micro-splinklers
		Transport and management of waste	DB	Ecoinvent database v.2.0	
	Phystosanitary	Types	EXR	Experimental results and MAPA 2002	
		Doses	EXR	Experimental results and MMARMRM 2012	
		Production	DB	Ecoinvent database v.2.0	
	Machinery and tools	Machinery and tools needed	EXR	Experimental results	This process includes: machinery type, hours of operations, characteristics and fuel consumption
		Machinery and tools production and maintenance	DB	Ecoinvent database v.2.0	
		Diesel production and emissions	DB-LR	Ecoinvent database v.2.0 and Gasola et al. 2007	
	Irrigation	Water consumption	EXR	Experimental results	
		Electricity consumption of pumps	EXR	Experimental results	
		Rainfall	LR	Ruralcat 2008	
	Fertirrigation emissions	Emissions of NH_3, N2O, NOx and N_2 to air	LR	Audsley 1997; Bentrup and Küesters 2000	Emissions produced by organic fertilizers or nitrogenous mineral
		Emissions of NO_3 to water	LR	Bentrup and Küesters 2000	
	Nursery	Greenhouse, irrigation, fertilization, heating and transport	LR	Antón 2005; Matallana and Montero 2001	

*Three sources of data were used: experimental results (EXR), database (DB) and literature references (LR)

Annex 6.5 Inventories for the cultivation phase per stage and sub-stages

Table 6.2 Inventories for the cultivation phase per fertilization treatment and crops*

				COLIFLOR			TOMATE		
Stage	**Sub-stage**	**Flows**	**Units· m^{-2}**	IC[a]	HC[b]	MF[c]	IC	HC	MF
Fertirrigation	Water distribution pump	Stell	kg	9.44E-04	9.44E-04	9.44E-04	9.44E-04	9.44E-04	9.44E-04
	Water extraction pump	Stell	kg	9.44E-04	9.44E-04	9.44E-04	9.44E-04	9.44E-04	9.44E-04
	Water tank	Concrete	m^3	7.99E-04	7.99E-04	7.99E-04	7.99E-04	7.99E-04	7.99E-04
		Stell	kg	4.76E-02	4.76E-02	4.76E-02	4.76E-02	4.76E-02	4.76E-02
	Fertilizer tank	Polyethylene	kg	4.25E-03	4.25E-03	4.25E-03	4.25E-03	4.25E-03	4.25E-03
	Electrovalves	Polyvinylidenchloride	kg	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04
	Microaspersores	Polypropylene	kg	7.20E-04	7.20E-04	7.20E-04	-	-	-
	Spaguetti	Polyethylene	kg	2.31E-03	2.31E-03	2.31E-03	-	-	-
	Transport (ferrigation equipment)	Transport	tkm	4.60E-02	4.60E-02	4.60E-02	3.26E-02	3.26E-02	3.26E-02
	Primary distribution pipes	Polyethylene	kg	1.91E-03	1.91E-03	1.91E-03	1.91E-03	1.91E-03	1.91E-03
	Secondary distribution pipes	Polyethylene	kg	5.92E-02	5.92E-02	5.92E-02	2.39E-02	2.39E-02	2.39E-02
	Well pipes	Polyvinylidenchloride	kg	8.95E-04	8.95E-04	8.95E-04	8.95E-04	8.95E-04	8.95E-04
	Support rod	Stell	kg	2.16E-02	2.16E-02	2.16E-02	-	-	-
Phytosanitary	Phytosanitary		kg	7.80E-05	7.80E-05	7.80E-05	1.95E-03	1.95E-03	1.95E-03
	Transport	Transport	tkm	1.09E-05	1.09E-05	1.09E-05	1.37E-01	1.37E-01	1.37E-01
Emissions to air and water	Water		g	1.24E-01	1.24E-01	1.09E-01	3.47E-01	1.36E-01	1.23E+02
	Compost		g	2.07E-01	3.09E-01	-	6.97E-02	4.53E-01	-
	Mineral fertilizer		g	-	-	4.56E-03	-	-	1.67E+02
Irrigation	Water		m^3	1.09E-01	1.09E-01	9.40E-02	3.04E-01	2.96E-01	2.87E-01
	Water distribution pump	Electricity	MJ	7.85E-02	7.78E-02	6.77E-02	2.19E-01	2.13E-01	2.07E-01
	Water extraction pump	Electricity	MJ	5.58E-02	5.53E-02	4.81E-02	4.87E-01	4.75E-01	4.60E-01
Machinery and tools	Plough	Diesel and emission	kg	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03
		Ploughshare	kg	5.78E-05	5.78E-05	5.78E-05	5.78E-05	5.78E-05	5.78E-05
		Tractor	kg	4.07E-05	4.07E-05	4.07E-05	4.07E-05	4.07E-05	4.07E-05
	Loading and transpor of compost	Diesel and emissions	kg	1.11E-03	1.11E-03	-	1.11E-03	1.11E-03	-
		Tow	kg	8.95E-05	8.95E-05	-	8.95E-05	8.95E-05	-
		Tractor	kg	4.07E-05	4.07E-05	-	4.07E-05	4.07E-05	-
	Fertilizer spreader	Diesel and emissions	kg	4.03E-04	4.03E-04	-	4.03E-04	4.03E-04	-
		Spreader	kg	1.54E-05	1.54E-05	-	1.54E-05	1.54E-05	-
		Tractor	kg	8.71E-06	8.71E-06	-	8.71E-06	8.71E-06	-
	Mixing compost in soil	Diesel and emissions	kg	4.61E-03	4.61E-03	-	4.61E-03	4.61E-03	-
		Plousghshare	kg	5.78E-05	5.78E-05	-	5.78E-05	5.78E-05	-
		Tractor	kg	8.71E-05	8.71E-05	-	8.71E-05	8.71E-05	-
	Plough	Diesel and emissions	kg	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03
		Ploughshare	kg	5.78E-05	5.78E-05	5.78E-05	5.78E-05	5.78E-05	5.78E-05
		Tractor	kg	8.71E-05	8.71E-05	8.71E-05	8.71E-05	8.71E-05	8.71E-05
	Furrow opening	Diesel and emissions	kg	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03	4.61E-03
		Furrow opener	kg	1.53E-04	1.53E-04	1.53E-04	1.53E-04	1.53E-04	1.53E-04
		Tractor	kg	8.71E-05	8.71E-05	8.71E-05	8.71E-05	8.71E-05	8.71E-05
	Phytosanitary application	Diesel and emissions	kg	1.04E-03	1.04E-03	1.04E-03	1.04E-03	1.04E-03	1.04E-03
		Disk roller	kg	4.52E-05	4.52E-05	4.52E-05	4.52E-05	4.52E-05	4.52E-05
		Tractor	kg	1.53E-05	1.53E-05	1.53E-05	1.53E-05	1.53E-04	1.53E-05
	Crates for harvesting	Polyethylene	kg	3.24E-02	3.24E-02	3.24E-02	1.47E-02	1.47E-02	1.47E-02
	Handcarts for harvesting	Stell	kg	7.47E-03	7.47E-03	7.47E-03	7.47E-03	7.47E-03	7.47E-03
Nursery plant			plants	2.08E+00	2.08E+00	2.08E+00	5.00E-01	5.00E-01	5.00E-01
Fertirrigation waste	Transport of waste	Transport	tkm	3.64E-03	3.64E-03	3.64E-03	2.55E-03	2.55E-03	2.55E-03
	Waste management		kg	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Compost	Total compost applied to crops		kg	1.10E+00	1.60E+00	-	1.10E+00	1.60E+00	-
	Transport of compost	Transport	tkm	6.18E-02	-	-	6.18E-02	-	
Mineral fertilizer	Mineral fertilizer applied (KNO_3)		g	-	-	9.60E+01	-	-	7.43E+02
	Transport of mineral fertilizer	Transport	tkm	-	-	1.64E-03	-	-	1.43E-01

[a]IC: Industrial compost
[b]HC: Home compost
[c]MF: Mineral fertilizer
[d]Emissions to air of N_2O, N_2, NO_x and NH_3
[e]Emissions to water of NH_3
*Inventories are refered to functional unit (m^2)

Annex 6.6 Physico-chemical characterization for the composts applied

Table 6.3 Physico-chemical characterization for the composts applied

Properties	Units	IC[1]	HC[2]	References		
Moisture	%, wb	17	50	30-40[a]		
Organic matter	%, db	n.a[3]	75	≥ 35[a]		
pH (extract 1:5 w:v)	-	n.a	8,97	6.5-8[b]		
Electrical conductivity	mS · cm^{-1} (extract 1:5 w:v)	n.a	1,72	≤6[b]		
N-Kjeldhal	%, db	2,47	1,66	≥2[b]		
Dinamic respiration index	mg O_2 · g^{-1} OM h^{-1}	0,89	0,43	1.0[c]		
Salmonella	(presence / absence in 25 g)	n.a	Absence	Absence[a]		
Escherichia coli	(CUF / g)	n.a	<10	<10[a]		
Heavy metals content[a]				Spanish legislation		
Metals	Units	IC	HC	Class A	Class B	Class C
Zn	mg · kg^{-1}	186	194	200	500	1.000
Cu	mg · kg^{-1}	51	50	70	300	400
Ni	mg · kg^{-1}	19	9	25	90	100
Cr	mg · kg^{-1}	13	13	70	250	300
Pb	mg · kg^{-1}	35	26	45	150	200
Cd	mg · kg^{-1}	0,3	0,2	0,7	2	3

wb: web basis; db: dry basis; w: weight; v:volume; OM: organic matter
[1]IC: industrial compost; [2]HC: home compost; [3]n.a: not analyzed
[a]Spain legislation (Royal Decree 506/2013)
[b]Regulation proposal for municipal solid waste compost in Spain (Giró, 1994; Giró, 2001)
[c]European Commission for bio-waste management (2008)