

NAYARA VILELA AVELAR

**THERMAL DRYING OF BIOLOGICAL SLUDGE FROM PAPER MILL FOR
ENERGY PURPOSES**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Civil, para obtenção do título de *Doctor Scientiae*.

VIÇOSA
MINAS GERAIS – BRASIL
2017

**Ficha catalográfica preparada pela Biblioteca Central da Universidade
Federal de Viçosa - Câmpus Viçosa**

T

A948t
2017 Avelar, Nayara Vilela, 1986-
Thermal drying of biological sludge from paper mill for
energy purposes / Nayara Vilela Avelar. – Viçosa, MG, 2017.
xiii, 87f. : il. (algumas color.) ; 29 cm.

Orientador: Ana Augusta Passos Rezende.
Tese (doutorado) - Universidade Federal de Viçosa.
Inclui bibliografia.

1. Biomassa. 2. Biocombustíveis. 3. Lodo. 4. Fornalhas.
5. Meios de transferência de calor. I. Universidade Federal de
Viçosa. Departamento de Engenharia Civil. Programa de
Pós-graduação em Engenharia Civil. II. Título.

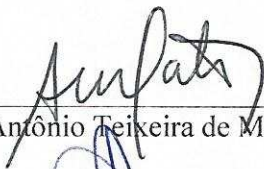
CDD 22 ed. 662.88

NAYARA VILELA AVELAR

**THERMAL DRYING OF BIOLOGICAL SLUDGE FROM PAPER MILL FOR
ENERGY PURPOSES**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Civil, para obtenção do título de *Doctor Scientiae*.

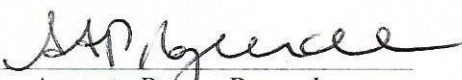
APROVADA: 10 de março de 2017.


António Teixeira de Matos


António Marcos de Oliveira Siqueira


Angélica de Cássia Oliveira Carneiro
(Coorientadora)


Cláudio Mudadu Silva
(Coorientador)


Ana Augusta Passos Rezende
(Orientadora)

Aos meus avós, Itevaldo, Gil e Sara

(in memoriam).

À minha vó, Selma.

AGRADECIMENTOS

À Deus, pelo dom da vida e da sabedoria.

À Universidade Federal de Viçosa e ao Programa de Pós-Graduação em Engenharia Civil, pela oportunidade de realizar este curso.

À professora Ana Augusta, pela amizade e orientação.

Aos professores Cassinha Carneiro, Cláudio Mudadu, Márcio Arêdes e Antônio Marcos Siqueira, pela ajuda e pelos aconselhamentos durante a realização deste trabalho.

Aos estagiários, pela ajuda na realização dos experimentos e da modelagem matemática, especialmente ao Benício Ribeiro, pela competência, dedicação, apoio nas decisões e amizade.

Às equipes dos laboratórios de Energia da Madeira, de Meio Ambiente, e de Resíduos da Indústria Florestal, que disponibilizaram parte do seu tempo e sua experiência na área.

Aos amigos e colegas do Programa de Pós-Graduação em Engenharia Civil e do Laboratório de Resíduos da Indústria Florestal, pela aprendizagem e crescimento compartilhados.

À CAPES, pela concessão de bolsa de estudos.

À Indústria Ponte Nova Papéis e ao Engenheiro Ambiental Marco Antônio Almeida, por ter disponibilizado o material utilizado nesta pesquisa.

Aos meus amigos que, em momentos distintos, estiveram presentes, me dando forças para percorrer este caminho.

Aos meus pais, Liliane e Tadeu, irmãos, Danilo e Henrique, tios e primos, pelo amor incondicional e pelo grande e contínuo apoio no meu dia a dia e no conquistar de novos horizontes.

Ao Thiago Luange pelo amor, paciência, compreensão e apoio nos momentos difíceis.

TABLE OF CONTENTS

LIST OF FIGURES	vi
LIST OF TABLES	viii
NOMENCLATURE	ix
ABSTRACT	xii
RESUMO	xiii
GENERAL INTRODUCTION	1
REFERENCES	3
CHAPTER I	4
THERMAL DRYING OF SLUDGE FOR ENERGY PURPOSES: A REVIEW	4
Abstract	4
1. Introduction	5
2. Biomass as energy resource	6
2.1. Fuel properties of biomass	7
2.2. Industrial sludge	9
3. Thermal drying of biosludge	10
3.1. Heat and mass transfer	18
3.2. Behavior of sludge during drying	20
4. Combustion processes	23
4.1. Combustion of sludge	24
5. Conclusions	25
References	25
CHAPTER II	34
EVALUATION OF PHYSICAL AND THERMOCHEMICAL CHARACTERISTICS OF BIOSLUDGE AS A POTENTIAL ENERGY SOURCE	34
Abstract	34
1. Introduction	35
2. Materials and methods	36
2.1. Materials and characterization	36
2.2. Thermal analysis	36
3. Results and discussion	37
3.1. Thermal characterization	37
3.2. Thermal analysis	38
4. Conclusions	41
References	41
CHAPTER III	46
THERMAL DRYING OF INDUSTRIAL SLUDGE USING FORCED AERATION	46
Abstract	46
1. Introduction	47
2. Material and methods	48
2.1. Biosludge, eucalyptus chips and bark	49

2.2. Drying apparatus and process operation.....	51
2.3. Sampling and analysis	53
2.4. Statistical analysis	54
3. Results and discussion	54
3.1. Biosludge, eucalyptus chips and bark	54
3.2. Temperature distribution	57
3.3. Biosludge mixture drying.....	58
4. Conclusions.....	61
References	62
CHAPTER IV	69
COMPUTATIONAL MODELING OF BIOSLUDGE DRYING	69
Abstract	69
1. Introduction.....	70
2. Material and methods.....	71
2.1. Biosludge drying	71
2.2. Model description.....	72
2.2.1. Governing equations	75
2.3. Model validation	77
3. Results and discussion	77
3.1. Computer simulation	77
3.2. Comparison of temperature and moisture content profiles of experiment and simulation	80
3.3. Parametric analysis.....	81
4. Conclusions.....	82
References	83
GENERAL CONCLUSIONS	86

LIST OF FIGURES

CHAPTER I

Figure 1 – Rotary sludge dryer (Metcalf & Eddy, 2004).....	11
Figure 2 – Flash dryer (Chen <i>et al.</i> , 2002).....	11
Figure 3 – Fluidized-bed dryer (Chen <i>et al.</i> , 2002).....	12
Figure 4 – Belt dryer (Chen <i>et al.</i> , 2002).....	12
Figure 5 – Vertical multi-tray dryer (Metcalf & Eddy, 2004).....	13
Figure 6 – Schematic diagram of the fry-drying system for sludges (Ohm <i>et al.</i> , 2009).	14
Figure 7 – Schematic view of the covered solar drying plant (Salihoglu <i>et al.</i> , 2007)...	15
Figure 8 – Schematic diagram of S&HPSDS (Slim <i>et al.</i> , 2008).....	16
Figure 9 – Schematic view of different steps for sludge spray drying: (1) settler; (2) high velocity centrifugation; (3) sieve and additives, if any; (4) spray dryer; (5) cyclone; (6) gas cleaning (biofilter); (7) clear water; (8) condenser; (9) dried sludge; (10) tertiary treatment, if necessary (Cusidó and Cremades, 2012).....	16
Figure 10 – Schematic illustration of the pilot-scale high velocity cyclone (Mäkela <i>et al.</i> , 2014).....	17
Figure 11 – Simplified scheme of the Tornado process (Lahdeniemi <i>et al.</i> , 2013).....	18
Figure 12 – Water distribution in sludge (Chen <i>et al.</i> , 2002).....	20
Figure 13 – Typical sludge drying curves. (a) Drying curve: moisture content vs. time. (b) Krischer curve: drying rate vs. moisture content (Bennamoun, 2012; Kemp <i>et al.</i> , 2001; Foust <i>et al.</i> , 1982; Bagnoli <i>et al.</i> , 1963).....	21

CHAPTER II

Figure 1 – TG-DTG curves of biosludge (BS), eucalyptus chips (EC) and eucalyptus bark (EB).....	39
Figure 2 – TG-DTG curves of mixtures of biosludge with (a) eucalyptus chips and (b) eucalyptus bark.....	39

CHAPTER III

Figure 1 – Experimental setup.....	49
Figure 2 – Drying system. (a) Plant and (b) flowchart: (A) direct fired coal furnace; (B) cyclone; (C) fan; (D) electric engine; (E) terrace; (F) distribution duct; (G) aeration diffuser.....	51
Figure 3 – Transverse view of each pile: (a) Control treatment; (b) Treatment 1; (c) Treatment 2; (d) Treatment 3; (e) Treatment 4.....	52
Figure 4 – Photos of each pile: (a) Control treatment; (b) Treatment 1; (c) Treatment 2; (d) Treatment 3; (e) Treatment 4.....	53
Figure 5 – Temperature profiles of Control treatment, Treatment 1, Treatment 2, Treatment 3 and Treatment 4.....	58

CHAPTER IV

Figure 1 – Drying system. (a) Plant and (b) flowchart: (A) direct fired coal furnace; (B) cyclone; (C) fan; (D) electric engine; (E) terrace; (F) distribution duct; (G) aeration diffuser.	72
Figure 2 – Geometry used in the simulation of sludge drying process.....	73
Figure 3 – Mesh used in the simulation of sludge drying process.	73
Figure 4 – Temperature distribution in biosludge pile after 5 hours (18,000s) of drying.	78
Figure 5 – Moisture concentration distribution in biosludge pile after 5 hours (18,000s) of drying.....	78
Figure 6 – Temperature profile of biosludge pile.	79
Figure 7 – Moisture content profile of biosludge pile.....	79
Figure 8 – Temporal average (a) temperature and (b) moisture content profile obtained for experimental and simulation.	81

LIST OF TABLES

CHAPTER I

Table 1 – Composition of different biomass (dry basis).....	8
Table 2 – Composition of different industrial biosludge (dry basis).	9

CHAPTER II

Table 1 – Immediate analysis, elementary composition and heating value of the materials and mixtures.	37
Table 2 – Mass loss (%) of the materials as a function of temperature.	40

CHAPTER III

Table 1 – Treatments performed for biosludge drying.	50
Table 2 – Initial mass and piles dimension for biosludge drying.	52
Table 3 – Characteristics of materials and mixtures.	55
Table 4 – Average values of the moisture reduction (%) of biosludge as a function of the bulking agent and proportion of bulking agent.	59
Table 5 – Average values of the final total solids content (FTS), specific energy consumption (SEC) and drying efficiency (DE) of biosludge mixtures, as a function of the bulking agent and proportion of bulking agent.	60

CHAPTER IV

Table 1 – Input parameters of the biosludge pile.....	74
Table 2 – Input variables of the biosludge pile.	75
Table 3 – Effect of initial moisture on final temperature and moisture reduction.	82

NOMENCLATURE

A	area
AC	ash content
BS	biosludge
C	pile moisture concentration
C_0	initial pile moisture concentration
C_{air}	air moisture concentration
CC	charcoal consumption
c_p	specific heat
D	diffusivity
d.b.	dry basis
DE	drying efficiency
dT/dx	temperature gradient
DTG	derivative thermogravimetric
EB	eucalyptus bark
EC	eucalyptus chips
EE	electricity consumption
FBC	fluidized bed combustion
FC	fixed carbon
FTS	final total solids content
h	convection transfer coefficient
h_{ev}	vaporization latent heat of water
h_{mass}	mass transfer coefficient

h_{rad}	radiation transfer coefficient
HHV	higher heating value
k	thermal conductivity
LHV	lower heating value
MAE	mean absolute error
M_{evap}	mass of water evaporated
NHV	net heating value
q_{cond}	conductive heat transfer rate
q_{conv}	convective heat transfer rate
q_{rad}	radiation heat transfer rate
R^2	coefficient of determination
REA	reaction engineering approach
RMSE	root mean square error
SEC	specific energy consumption
S&HPSDS	solar and heat pump sludge drying system
T	pile temperature
t	time
T_0	initial pile temperature
T_g	gas source temperature
TG	thermogravimetric
TGA	thermogravimetric analysis
T_{gas}	gas temperature
T_r	radiant source temperature

T_s	sludge source temperature
T_∞	air temperature
VM	volatile matter
W	moisture content
w.b.	wet basis
W_E	equilibrium moisture content
WTP	wastewater treatment plants
ε	emissivity of the drying surface
λ	molar latent heat of vaporization
ρ	density
σ	Stefan-Boltzmann constant

ABSTRACT

AVELAR, Nayara Vilela, D.Sc., Universidade Federal de Viçosa, March, 2017. **Thermal drying of biological sludge from paper mill for energy purposes.** Adviser: Ana Augusta Passos Rezende. Co-advisers: Cláudio Mudadu Silva, Angélica de Cássia Oliveira Carneiro and Márcio Arêdes Martins.

This research proposes and investigates a drying system using hot gases from a direct coal-furnace as the energy source for biosludge drying, in order to transform it into a fuel for biomass boilers. The materials used were biosludge from a paper mill, and eucalyptus chips and bark as bulking agents. Two different proportions (15% and 25%) were applied. The thesis was divided into four chapters: Chapter I is a paper review that investigated the use of thermal sludge drying technologies for energy purposes. In Chapter II, the characteristics and thermal behavior of the materials and their mixtures were determined. In Chapter III, the drying system was evaluated according to its moisture reduction capacity, final total solids content, drying process efficiency and specific energy consumption. In Chapter IV, a simulation model for the biosludge drying process was implemented to predict the temperature and moisture distribution inside the biosludge, using the COMSOL Multiphysics® simulation program v5.2. The results showed that the addition of either eucalyptus chips or bark improved the biosludge physical and thermochemical characteristics. The proposed drying system was a promising technique when a bulking agent was added to the biosludge. The mixture of biosludge with 25% eucalyptus bark achieved the best drying results, increasing the total solids content from 31 to 72%, over a 5 hour drying interval. The simulation model was found to be an important tool to optimize the drying process and develop better strategies for the control of the system. It can be concluded that the results obtained are a significant step in the development of drying methods capable of using secondary energy (gases released from boilers), potentially available in industrial environments. The combustion of biosludge mixtures may provide an attractive option for the disposal and utilization of a renewable waste source such as industrial sludge.

RESUMO

AVELAR, Nayara Vilela, D.Sc., Universidade Federal de Viçosa, março de 2017. **Secagem térmica de lodo biológico da indústria de papel para fins energéticos.** Orientadora: Ana Augusta Passos Rezende. Coorientadores: Cláudio Mudadu Silva, Angélica de Cássia Oliveira Carneiro e Márcio Arêdes Martins.

Esta pesquisa teve como objetivo propor e investigar um sistema de secagem utilizando gases quentes de uma fornalha de fogo direto como fonte de energia para secar o lodo biológico para transformá-lo em combustível para caldeiras de biomassa. Os materiais utilizados foram o lodo biológico de uma indústria de papel, cavaco de madeira e casca de eucalipto, que foram utilizados como materiais estruturantes em duas diferentes proporções (15% e 25%). A presente tese foi dividida em quatro capítulos: o Capítulo I trata-se de uma revisão bibliográfica que investigou as tecnologias de secagem térmica de lodo para fins energéticos. No Capítulo II, foram determinadas as características e o comportamento térmico dos materiais, bem como de suas misturas. No Capítulo III, o sistema de secagem foi avaliado através da redução da umidade, do teor final de sólidos totais, da eficiência do processo de secagem e do consumo específico de energia. No Capítulo IV, foi implementado um modelo de simulação para o processo de secagem do lodo biológico como o objetivo de prever a temperatura e a distribuição de umidade dentro do lodo, utilizando o programa de simulação COMSOL Multiphysics® v5.2. Os resultados mostraram que a adição de cavaco de madeira e casca de eucalipto melhorou as características físicas e termoquímicas do lodo. O sistema de secagem mostrou-se bastante promissor quando material estruturante foi adicionado ao lodo. A mistura de lodo com 25% de casca de eucalipto apresentou os melhores resultados de taxa de secagem, aumentando o teor de sólidos totais de 31 para 72%, em um intervalo de secagem de 5 horas. O modelo de simulação pode ser considerado uma ferramenta importante para otimizar o processo de secagem e desenvolver melhores estratégias para o controle do sistema. Pode-se concluir que os resultados obtidos representam uma importante etapa no desenvolvimento de métodos de secagem capazes de utilizar energias secundárias (gases liberados pelas caldeiras), potencialmente disponíveis em ambientes industriais. Pode-se também concluir que a combustão de misturas de lodo biológico proporciona uma ótima opção para a eliminação e utilização de uma fonte de resíduos renováveis, tais como o lodo industrial.

GENERAL INTRODUCTION

Paper mills generate a considerable amount of sludge as a result of the biological wastewater treatment (WTP) process, which constitutes 50% of the paper production process (Sutcu and Akkurt, 2009). The composition of this residue depends on the raw materials used and the manufacturing and WTP processes applied in the industry (Boni *et al.*, 2004).

Disposal of paper sludge, usually into landfills, is an environmental and economical quandary for the industry. For this reason, paper mills are increasingly considering alternative waste management solutions. Amongst these solutions, energy recovery through thermochemical processes, such as combustion, appears to be the most promising alternative, since both reduces and stabilizes the sludge and is a harmless treatment (Fytili and Zabaniotou, 2008).

However, the high water content of sludge may constitute a barrier to its beneficial use. In fact, dewatered sludge from WWT plants still has a moisture content that may range from 70 to 90% of its weight, which usually prevents its energy from being directly recovered (Bianchini *et al.*, 2015). Therefore, a thermal drying process is an essential step prior to the use of paper sludge as a fuel in biomass boilers.

Thermal drying has often been considered an attractive process to facilitate sludge management. It reduces the water content of the sludge leading to mass and volume reductions, consequently reducing storage, handling and transportation costs. Drying can also disinfect the sludge for safe disposal and increases its heating value, transforming the product into an acceptable fuel.

Sludge drying before combustion can increase heat efficiency, reduce the need for auxiliary fuel, provide safe operation and reduce gaseous emissions during the process (Chai, 2007; Li *et al.*, 2014).

Nevertheless, in most cases, thermal drying is neither cost-effective or an environmentally friendly process due to the use of nonrenewable energy sources. Additionally, initial outlays and operational costs are relatively high due to the complex apparatuses. The industry has been searching for drying technologies with higher

thermal efficiency, lower emissions, less operator involvement, cheaper capital outlays and a better final product.

The general objective of this research was to propose and investigate a drying system using hot gases from a direct coal-furnace as the energy source for drying biosludge of a paper mill, to allow its use as a fuel in biomass boilers.

This thesis is divided into four chapters:

- Chapter I: “Thermal drying of sludge for energy purposes: a review”. This Chapter reviews the use of biomass and sludge as an energy source, the modern sludge thermal drying technologies for energy purposes, and the behavior of sludge drying and combustion.
- Chapter II: “Evaluation of physical and thermochemical characteristics of biosludge as a potential energy source”. This Chapter presents the physical-chemical characteristics of biosludge for energy purposes, and the study of the biosludge thermal conversion process using thermogravimetric analysis.
- Chapter III: “Thermal drying of industrial sludge using forced aeration”. In this Chapter an efficient and low cost biosludge drying system was proposed and investigated.
- Chapter IV: “Computational modeling of biosludge drying”. In this Chapter a simulation model for the biosludge drying system was implemented, using the COMSOL Multiphysics® simulation program.

REFERENCES

Chai, L. H. Statistical dynamic features of sludge drying systems. **International Journal of Thermal Sciences**, v.46, p.802-811, 2007.

Bianchini, A.; Bonfiglioli, L.; Pellegrini, M.; Saccani, C. Sewage sludge drying process integration with a waste-to-energy power plant. **Waste Management**, v.42, p.159-165, 2015.

Boni, M. R.; D'Aprile, L.; De Casa, G. Environmental quality of primary paper sludge. **Journal of Hazardous Materials**, v.108, n.1-2, p.125-128, 2004.

Fytily, D.; Zabaniotou, A. Æ. Utilization of sewage sludge in EU application of old and new methods – A review. **Renewable and Sustainable Energy Reviews**, v.12, p.116-140, 2008.

Li, S.; Li, Y.; Lu, Q.; Zhu, J.; Yao, Y.; Bao, S. Integrated drying and incineration of wet sewage sludge in combined bubbling and circulating fluidized bed units. **Waste Management**, v. 34, p. 2561-2566, 2014.

Sutcu, M.; Akkurt, S. The use of recycled paper processing residues in making porous brick with reduced thermal conductivity. **Ceramics International**, v.35, n.7, p.2625-2631, 2009.

CHAPTER I

THERMAL DRYING OF SLUDGE FOR ENERGY PURPOSES: A REVIEW

Abstract

Considerable increases in industrial and urban wastewater sludge generation in recent years require proper treatment and disposal. Thermal drying has become an important procedure for sludge treatment. The advantages of this technology include reduced transportation costs, disinfection, lower storage requirements, and marketability. Furthermore, thermally dried wastewater sludge has interesting properties that allow its use as an alternative fuel. This paper reviews modern sludge thermal drying technologies for purposes of subsequent energy generation. The use of biomass and sludge as a source of energy applying different sludge thermal drying technologies are discussed. The behavior of sludge drying and combustion is presented.

Keywords: biomass combustion, sludge drying, heat and mass transfer.

1. Introduction

Biomass is the general term for all organic material that stems from plants, trees, crops and algae (Dermibas, 2005). Energy produced from biomass or from its conversion byproducts represents an important share of current energy sources, since as it is renewable, abundant and has domestic usage, these biomass sources help the world reduce its dependence on petroleum products and natural gas (Haykiri-Açma, 2003).

Industrial sludge is a byproduct from biological wastewater treatment plants. The management of sludge is one of the most difficult problems to be tackled and solved in both industrialized and developing countries. Although this byproduct represents only a small percentage, in volume, of treated wastewater, its handling accounts for up to 50% of total operating costs of a treatment plant (Spinosa *et al.*, 2011).

Sludge management includes operations such thickening, dewatering, stabilization, sanitation and drying. Sludge treatment and disposal should be managed to minimize environmental problems such as odor and release of chemical and biological contaminants into the environment.

Among the various sludge management options, energy recovery through thermochemical valorization processes seems one of the key alternatives, especially through the valorization of sludge energy content and minimization of the environmental impacts in order to meet increasingly stringent standards (Manara and Zabaniotou, 2012).

The most common thermochemical processes for sludge treatment are pyrolysis, gasification, wet oxidation and combustion (Fytili and Zabaniotou, 2008).

Combustion is the most widely used and well established process; however, it is necessary for the sludge to present total solids content above 50% (Kraft and Orender, 1993; Werther and Ogada, 1999; Kudra *et al.*, 2002; Frei *et al.*, 2004). Thus, as the sludge presents high moisture content even after its conventional dewatering in presses and centrifuges, its additional thermal drying becomes a fundamental step, allowing an increase of sludge low calorific value, transforming the product into an acceptable combustible (Bennamoun, 2012).

Thermal drying involves the application of heat to evaporate water and to reduce moisture content of sludges (Metcalf & Eddy, 2004), quickly obtaining a product with high solid content (Zhao *et al.*, 2010). This process effectively reduces sludge volume, improving storage, handling and transportation. Furthermore, dried sludge is a pathogen-free, stabilized material due to high-temperature treatment (Léonard *et al.*, 2008).

2. Biomass as energy resource

In energy terms, biomass is all organic matter, of animal or plant origin, which can be used to obtain energy. Biomass resources include wood and wood residues, agricultural residues (straw, vegetable/fruit peels and crop wastes), food crops (sugarcane, corn or maize, soybean, wheat, sugar beet and vegetable oils such as rapeseed, palm, and sunflower oils), aquatic plants and algae, hydrocarbon-rich plants and herbaceous crops developed specifically for energy production (Hohenstein and Wright, 1994; Demirbas *et al.*, 2009; Abbasi and Abbasi, 2010). Other resources, although they may include industrial wastes, residues from the production of paper, food wastes, sewage and industrial sludge and municipal solid wastes, which are not strictly natural components are also termed biomass (Pronobis, 2006).

Biomass is an effective renewable energy source that can help to reduce greenhouse gas emissions, which may impact climate change, provide environmental sustainability, improve health and increase agricultural productivity (Herbert and Krishnan, 2016).

Biomass may be used to meet a wide variety of energy needs, including generating electricity, providing process heat for industrial facilities, heating homes and fuelling vehicles (Caputo *et al.*, 2005). The conversion of biomass into useful forms of energy, also called bio-energy, can be achieved using thermochemical or biochemical/biological processes (Caputo *et al.*, 2005). The thermochemical processes have the advantage of converting nearly all the organic components of biomass, whereas biochemical processes only use the polysaccharide content of biomass (Abbasi and Abbasi, 2010).

The main thermochemical processes used in biomass conversion are the following: (i) combustion, used to convert biomass energy into heat, mechanical power or electricity (Caputo *et al.*, 2005); (ii) gasification, conversion of biomass into gaseous fuels by means of partial oxidation of the biomass at high temperatures (Saidur *et al.*, 2011); (iii)

pyrolysis, thermal destruction of organic materials in the absence of oxygen (Fytli and Zabaniotou, 2008; Saidur *et al.*, 2011; Demirbas, 2004).

As far as biochemical processes are concerned, the main conversion options are the following: (i) anaerobic digestion, conversion of biomass into biogas; and (ii) fermentation, used to produce ethanol.

The choice of the appropriate conversion process is influenced by many key factors, such as type and quantity of biomass resource, energy carriers and the end-use applications, environmental standards and economic conditions (Caputo *et al.*, 2005).

2.1. Fuel properties of biomass

The most important properties of biomass for energy conversion processes are moisture content, density, immediate chemical analysis (volatile matter, fixed carbon and ash content), elementary chemical composition (carbon, hydrogen, nitrogen, sulfur and oxygen) and heating value (Saidur *et al.*, 2011; Demirbas, 2004; Nakomcic-Smaragdakis, 2016; Khan *et al.*, 2009; Werther *et al.*, 2000).

Moisture content ($\text{kg water} \cdot \text{kg}^{-1}$ dry or wet material) is an important fuel characteristic (Dai *et al.*, 2012). The moisture content influences the combustion and volume of flue gas produced per energy unit (Khan *et al.*, 2009). High moisture content in biomass fuels can cause ignition and combustion problems (Demirbas, 2004). Furthermore, high moisture content decreases the heating value of the fuel, and leads to high fuel usage generating large flue gas amounts and therefore requires large equipment dimensions (Khan *et al.*, 2009). The maximum moisture content of raw materials for thermochemical processes can be up to 65% (Dai *et al.*, 2012).

Immediate chemical analysis is a very important feature of the combustion phenomenon of biomass (Saidur *et al.*, 2011). Biomass generally has a very high volatile content (Khan *et al.*, 2009), indicating that it is easier to ignite and burn, although the combustion is expected to be rapid and difficult to control (Werther *et al.*, 2000). The fixed carbon is the fraction of the material that burns in solid state. High levels of volatile matter and fixed carbon increase the heating value of any biomass fuels (Saidur *et al.*, 2011).

Ash content is the percentage of inert material that does not produce heat, i.e., reduces the fuel heating value. The chemical composition of ash is an important parameter to be considered during the thermochemical conversion which can lead to significant operational issues such as formation of slag at higher temperatures, thus reducing the process efficiency and increasing the process costs (Nanda *et al.*, 2013).

The heating value is defined as the energy released per unit mass or per unit volume of fuel when it is completely burned (Ghugare *et al.*, 2014). The heating value can be defined by the higher heating value (HHV), which is basically the energy content on a dry basis; and the lower heating value (LHV) is calculated by subtracting the energy needed to evaporate the moisture content of the fuel (Khan *et al.*, 2009). The heating value is of great importance, especially in the use of waste as an energy source to replace petroleum fuels and energy recovery (Werther *et al.*, 2000; Williams *et al.*, 2001; Erol *et al.*, 2010). In Table 1 the heating value and immediate chemical composition of different biomass are presented.

Table 1 – Composition of different biomass (dry basis).

Parameter	Coal ^{a,b,c}	Sawdust ^a	Straw ^b	Pine cone ^d	Soybean ^d
High heating value (MJ.kg ⁻¹)	22-27	18.9	15.4	18.5	18.3
Volatile matters (%)	13-32	82.5	72.0	78.0	76.9
Ash content (%)	9-26	1.38	14.2	6.89	7.14
Fixed carbon (%)	60-69	16.1	38.5	15.2	16.0

^aJiang *et al.* (2010)

^bSaidur *et al.* (2011)

^cMagdziarz and Werle (2014)

^dErol *et al.* (2010)

Elementary chemical composition gives the elemental percentages of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S). C, H and S are elements that contribute positively to energy release during the combustion process, while oxygen contributes negatively as a fuel component. However, the presence of oxygen contributes to oxidation reactions, acting as a combusting (Obernberger *et al.*, 2006). In addition, the quantification of nitrogen and sulfur contents can be used to estimate the amount of nitrogen oxides (NO_x) and sulfur oxides (SO_x), gases that might be generated in the combustion process.

The density expresses the amount of material per volume unit; therefore, the higher the density, the more concentrated the energy. However, low densities complicate processing, transportation, storage and firing of the fuels (Werther *et al.*, 2000).

2.2. Industrial sludge

During industrial wastewater treatment approximately 40% of the biologically removed organic carbon is converted to biomass (biosludge) (Winkler *et al.*, 2013), which contains organic and mineral components (Neyens and Baeyens, 2003).

Properties of biosludge depend on the industrial typology and production process, and the type of wastewater treatment technology. Obviously, in order to treat and dispose of the biosludge effectively, it is crucial to know the characteristics of the sludge that will be processed (Fytili and Zabaniotou, 2008). However, significant differences in the origin of biosludges cause them to differ considerably in water content, solid structure, chemical composition, ability to concentrate, drying characteristics, type of fermentation, etc (Adamiec, 2002). In Table 2 the composition of different industrial biosludges are presented.

Table 2 – Composition of different industrial biosludge (dry basis).

Parameter	Pulp and paper sludge ^a	Petrochemical sludge ^b	Textile sludge ^c	Recycled paper sludge ^d
High heating value (MJ.kg ⁻¹)	11-20	-	21.82	12-14
Low heating value (MJ.kg ⁻¹)	-	21.19	20.35	11-12
Volatile matters (%)	61-64	87.92	81.0	47-64
Ash content (%)	15-28	0.85	11.8	32-51
Fixed carbon (%)	7.9	10.15	7.21	1.3-8.6
Carbon (%)	32-48	50.31	46.7	23-33
Hydrogen (%)	5.5	6.35	6.54	2.8-5.2
Nitrogen (%)	3.9-6.6	11.61	6.19	0.2-2.9
Sulfur (%)	1.5	8.41	1.32	0.1-1.4
Oxygen (%)	25	23.32	27.5	18-27

^aHippinen and Ahtila (2013); Rodrigues *et al.* (2010); Chang *et al.* (2013).

^bChen *et al.* (2015)

^cAvelar *et al.* (2016)

^dMäkela *et al.* (2014); Strezov and Evans (2009); Vamvuka *et al.* (2009); Xie and Ma (2013); Yanfen and Xiaoqian (2010); Areeprasert *et al.* (2015).

Biosludge can be disposed of in landfills or composted to be used in agriculture. Another potential use for this material is combustion as biofuel, but its high moisture content makes direct combustion difficult (Huilinir and Villegas, 2014). Therefore,

drying is a necessary step during the process of sludge treatment, because it reduces water content and, consequently, mass and volume, which leads to a cost reduction in transportation, handling and storage, and increases the heating value of the sludge, which can be used as an acceptable source of combustibles (Chai, 2007; Deng *et al.*, 2015).

3. Thermal drying of biosludge

Thermal drying is one of the most efficient and flexible ways to reduce the moisture of dewatered sludges. In thermal drying, heat is applied to remove the water from the sludge. The high temperature treatment reduces the sludge moisture to much lower values than those achieved by the mechanical dewatering, reaching values below 5% dry solids (Bennamoun, 2012; Chen *et al.*, 2002). Thermal drying can also be classified as a stabilization process due to thermal elimination of pathogens and to the reduction of odors originating from biosludge.

The major benefits of thermal sludge drying are the decrease of waste mass and volume and in consequence the reduction of the cost for storage, handling and transportation; the increase of low heating value, transforming the product into an acceptable combustible; and the final product is pathogen free stabilized material (Bennamoun, 2012).

There are various types of thermal dryers that can be used for sludge drying, such as rotary dryer, flash dryer, fluidized-bed dryer, belt dryer and vertical multi-tray dryer.

Rotary dryers (Figure 1), one of the most widely used biosludge drying methods, consists of a cylindrical steel shell that is rotated on bearings (Metcalf & Eddy, 2004). In these dryers, the drying inlet temperature is up to 1000°C with a water evaporation rate ranging from at least 800 kg.h⁻¹ to as much as 50000 kg.h⁻¹ (Chen *et al.*, 2002), reaching a dry solids content of 90 to 95% (Metcalf & Eddy, 2004).

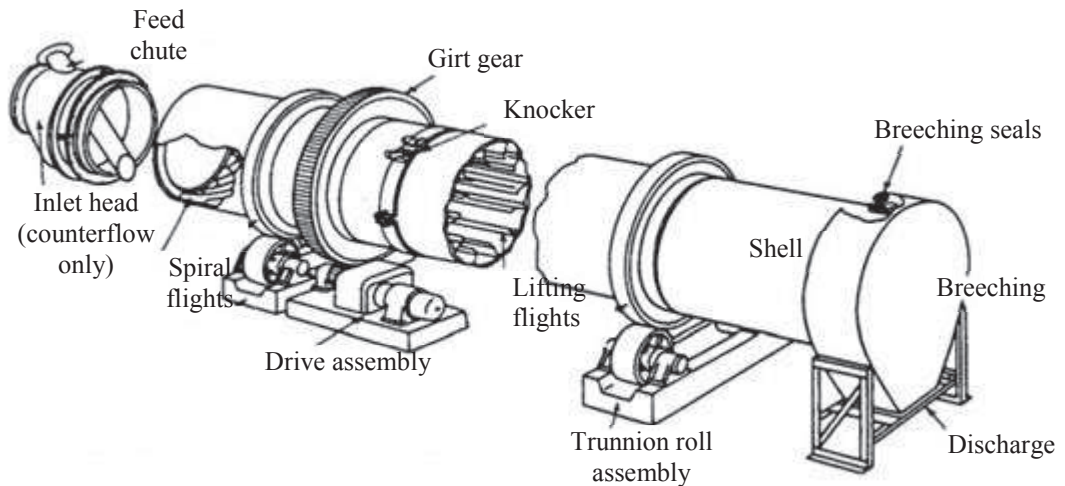


Figure 1 – Rotary sludge dryer (Metcalf & Eddy, 2004).

Flash dryers (Figure 2) consist of a long vertical tube (cage mill) where the sludge is pulverized in the presence of hot gases. In this system, the cage mill receives a mixture of wet sludge and recycled dried sludge with approximately 40 to 50% moisture, where hot gases (500-700°C) pulverized the sludge and rapidly evaporate the water in the sludge, obtaining a final product with 8 to 10% moisture (Metcalf & Eddy, 2004).

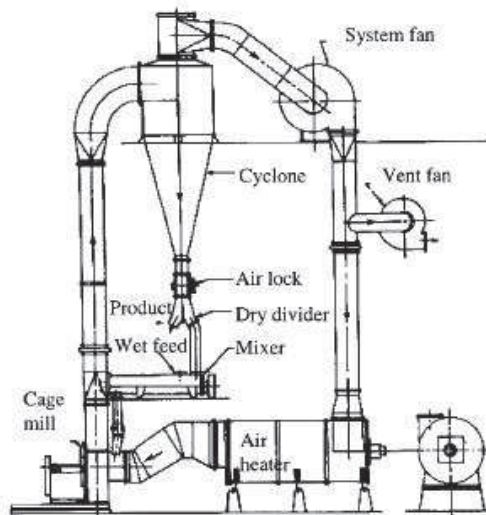


Figure 2 – Flash dryer (Chen *et al.*, 2002).

Fluidized-bed dryers consist of a sand fluidized-bed with perforated bottom, through which a stream of heated air is introduced. The air heated to about 85°C provides some heat and mainly ensures that the sludge granules stay in a fluidized state to enhance the heat transfer between the sludge and the hot tube surface, thus allowing the sludge drying to 5% moisture (Fouhy and Moore, 1994).

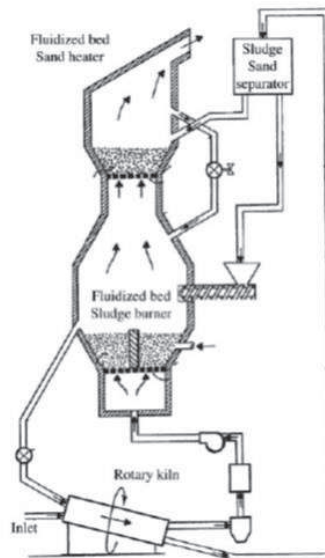


Figure 3 – Fluidized-bed dryer (Chen *et al.*, 2002).

A belt dryer is a continuously operating machine using hot air circulation (150°C) (Fouhy and Moore, 1994) with a conveyor belt on which the wet sludge is fed and conducted through a heating tunnel (Figure 4).

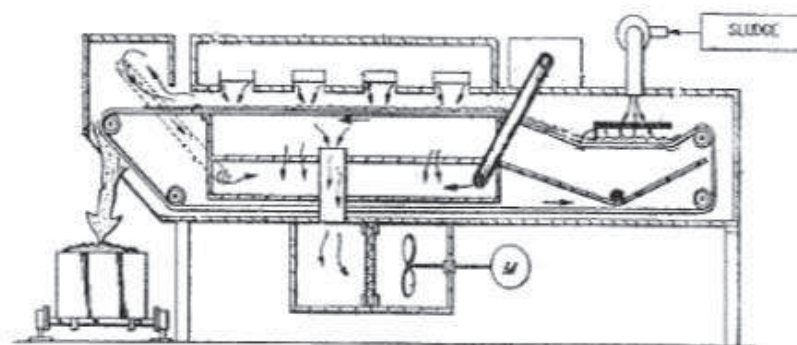


Figure 4 – Belt dryer (Chen *et al.*, 2002).

A vertical multi-tray dryer (Figure 5) consists of a cylindrical chamber containing in its interior a series of stationary trays internally heated by steam or hot oil (250°C) (Fouhy and Moore, 1994), responsible for the indirect heat transfer to the sludge. In these dryers, the sludge is fed via the top inlet and moved by the rotating arms from one heated tray to another in a zig-zag path until it exits the bottom as a dried and pelletized product with up to 95% total solid content (Chen *et al.*, 2002).

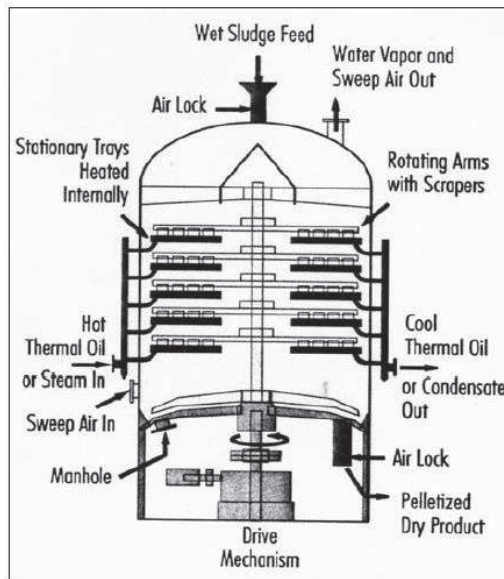


Figure 5 – Vertical multi-tray dryer (Metcalf & Eddy, 2004).

Technological progress, in the drying field, has allowed the development of several more efficient, sustainable and often low cost techniques for sludge drying.

In recent years, some researchers have applied the fry-drying technology using hot oil to dry sludge (Wu *et al.*, 2012; Peregrina *et al.*, 2008; Ohm *et al.*, 2009; Ohm *et al.*, 2010; Chang *et al.*, 2013). Similarly to the fry cooking technique commonly used in the food industries, fry-drying technology involves immersion of the wet sewage sludge in an oil bath at a temperature higher than the boiling point of water (Wu *et al.*, 2012), usually between 140-160°C (Peregrina *et al.*, 2008). In this process, the oil rapidly evaporates the water contained in the sludge, and the heating value of the dried sludge increases dramatically as the oil replaces the water in the sludge (Ohm *et al.*, 2009).

Figure 6 shows the fry-drying system for wastewater sludge used in the research performed by Ohm *et al.*, 2009. This system is divided into three parts: the first part consists of sludge feeding equipment, which feeds the sludge into the evaporative drying tank. The second part is the sludge fry-drying tank where the sludge is dried. The third part is the condenser, where steam, oil, and volatile organic compounds (VOCs) generated from the drying equipment are separated into condensed liquids and VOCs. And the condensed liquids are separated into water and oil at the oil-water separator. The separated oil is then transferred to the waste oil tank, and the condensed water is stored in the wastewater tank. The entire process, from the input of the sludge to the

output of the finished product, takes about 10min, and the equipment can treat 50-100kg of sludge in 1h (Ohm *et al.*, 2009).

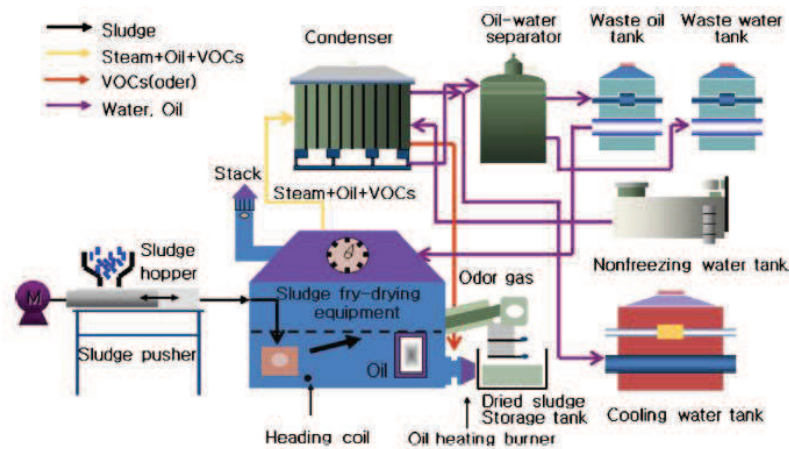


Figure 6 – Schematic diagram of the fry-drying system for sludges (Ohm *et al.*, 2009).

Biological drying or simply “bio-drying”, an alternative method of composting to treat sludge to reduce its moisture content, has been developed in recent years (Zhao *et al.*, 2010; Huilindir and Villegas, 2014). The main mechanism of bio-drying is convective evaporation, which utilizes heat produced from the aerobic degradation of organic matter and is facilitated by mechanically controlled aeration (Frei *et al.*, 2004; Zhao *et al.*, 2010; Cai *et al.*, 2012; Navaee-Ardeh *et al.*, 2010; Li *et al.*, 2015).

Studies performed by Zhao *et al.* (2010) showed that sludge bio-drying is an effective volume and weight reduction process. Moreover, it can be used as a pretreatment for sludge and renders the output more suitable for post-treatment through partial biostabilization, reducing its moisture content to below 48%.

Applying free solar energy is another alternative solution for sludge drying, however the application of this source of energy to dry sludge is still subject to intensive studies (Bennamoun *et al.*, 2013), such as recent research published by Bennamoun (2012), Salihoglu *et al.* (2007), Mathioudakis *et al.* (2009) and Slim *et al.* (2008).

Salihoglu *et al.* (2007) conducted their drying experiments using a covered and an open sludge drying plant. For both plants, the sludge was spread out on the floor in 25 cm-layers. The covered plant (Figure 7) was constructed as a tunnel type greenhouse, where the indoor air accumulated in the plant during the day is directed to the rock bed for energy conservation. Aeration was provided by an indoor ventilator installed in the roof, wherein the saturated air accumulated was discharged by two air fans mounted above

the doors of the plant, and air renewal was provided. The plant floor was heated with hot water pipes connected to two flat plate solar collectors. In the open plant, surface aeration was supplied through wind action, and the sludge was heated by direct exposure to the solar radiation. The results showed that the covered plant was more effective than the open plant. After 55 days, the sludge moisture reduced from 80 to 20% in covered plant, and from 80 to 60% in open plant.

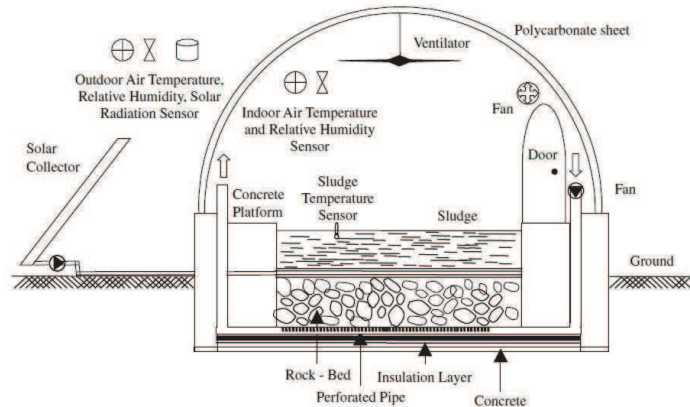


Figure 7 – Schematic view of the covered solar drying plant (Salihoglu *et al.*, 2007).

Mathioudakis *et al.* (2009) used two pilot-scale solar drying plants to dry dewatered sludge. The first plant was equipped with a gravel floor, where hot water, generated by a commercial solar water heater, was circulated. A commercial fan was installed inside both plants in order to provide a turbulent air stream able to remove the moisture from the surface layer of the sludge. The results show that the moisture content of sludge has decreased from 85 to 6% within 7-12 days in summer and to 10% within 9-33 days in autumn.

Slim *et al.* (2008) proposed a new drying process called Solar and Heat Pump Sludge Drying System (S&HPSDS) that combines two energy sources, solar energy and the energy supplied by a heat pump (Fig. 8). In this hybrid system, wet sludge was uniformly spread over a concrete floor under a transparent greenhouse cover, being intermittently mixed. The purpose of adding a heat pump was to boost the sludge drying especially during periods of non-favorable climactic conditions. This can be achieved by heating the surrounding ambient air and the floor, thus improving evaporation conditions and enhancing the diffusive moisture transportation from inside the sludge to its surface.

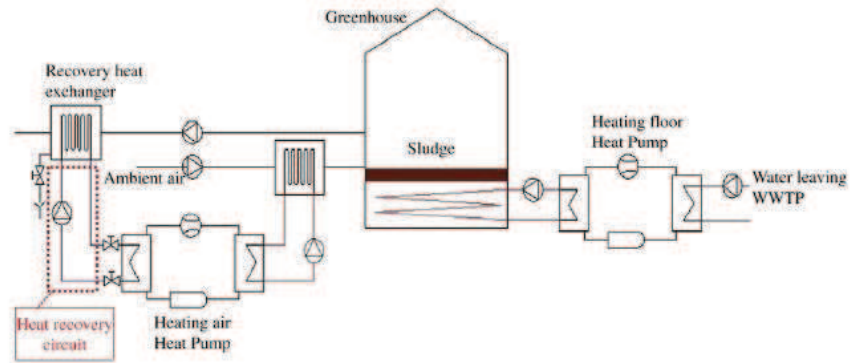


Figure 8 – Schematic diagram of S&HPSDS (Slim *et al.*, 2008).

Schneider (1996) patented an arrangement for reducing the moisture content of sludge. This system includes a spray dryer to which the sludge, a dispersion medium in the form of gas or vapor as well as hot gas can be supplied, converting the sludge into a solid product with high dry substance content.

Cusidó and Cremades (2012) studied primary sludge drying using spray-drying technology (Figure 9). This process involved the liquid phase removal of sludge in one continuous operation to get the solid phase as dry as possible. The spray dryer worked under the following conditions: hot air inlet temperature of 350°C, inlet flow of sludge of 68 m³.min⁻¹, inlet and outlet temperatures of sludge of 90°C and 120°C, respectively. The sludge moisture content reduced from 94 to 5%.

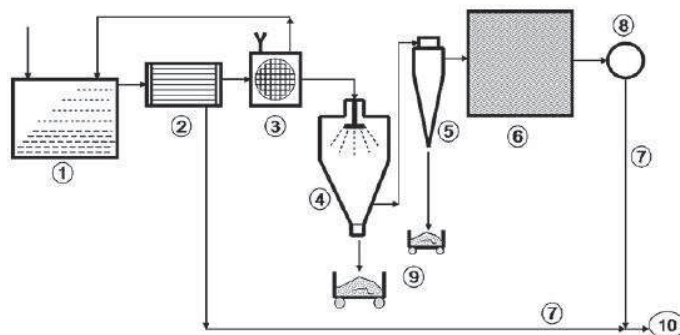


Figure 9 – Schematic view of different steps for sludge spray drying: (1) settler; (2) high velocity centrifugation; (3) sieve and additives, if any; (4) spray dryer; (5) cyclone; (6) gas cleaning (biofilter); (7) clear water; (8) condenser; (9) dried sludge; (10) tertiary treatment, if necessary (Cusidó and Cremades, 2012).

The use of high air velocities for drying sludge has also been studied by Mäkela *et al.* (2014), Lahdeniemi *et al.* (2013) and Lee and Cho (2010).

Mäkela *et al.* (2014) used a pilot-scale high velocity cyclone to dry recycled paper sludge. The dryer pilot is centered on a convective cyclone (Figure 10), where sludge

drying can be performed at low temperatures. The feed material with dry solids content of 46-51% is fed into the inlet air stream and the air-material suspension directed to the cyclone where changes in pressure and radial velocity induce water vaporization and possible particle grinding and separation phenomena. The inlet air stream can be heated to values above 90°C through the combustion of wood chips/pellets in a heating unit. The bulk of the dried material with dry solids content of 52-92% (accept fraction) is recovered from the bottom of the cyclone while the fine particles with dry solids content of 90-96% (rejection fraction) are captured from the humid exhaust air stream in a separate bag-house filter unit.

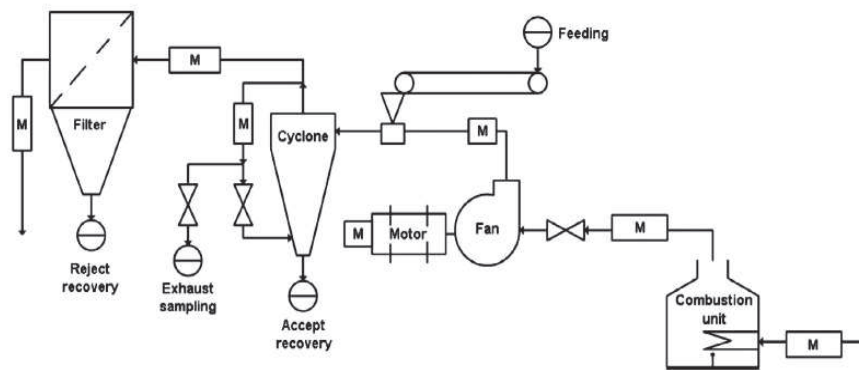


Figure 10 – Schematic illustration of the pilot-scale high velocity cyclone (Mäkela *et al.*, 2014).

Lahdeniemi *et al.* (2013) assessed the potential drying of deinking sludge with an air cyclone, the so-called Tornado cyclone (Figure 11). In this system, a powerful fan creates a high-velocity airstream, which is guided into an air channel to be mixed with the processed material. Materials with less than 50% solids content are sprayed into the air channel and then channeled into a cyclone-formed device in which the changes in radial velocity and pressure produce heavy vibrations in the sludge particles, causing them to disintegrate. Based on the results obtained, the described cyclone increased the total solids content of the samples from 67.9% to 96.3-98.9%, indicating very efficient moisture removal.

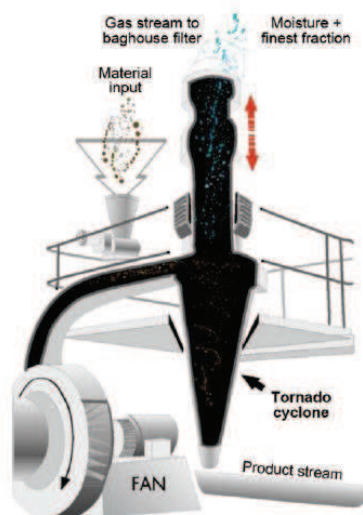


Figure 11 – Simplified scheme of the Tornado process (Lahdeniemi *et al.*, 2013).

Lee and Cho (2010) developed an air jet drying pilot scale equipment consisting of a turbo blower, air ejector, three stage cyclone and separator, converting the dewatered sludge with water content of 83.8% into an air dried powder with water content of 49.8% through only high speed air and circulation flow.

3.1. Heat and mass transfer

During a solid drying, two fundamental and simultaneous processes occur, heat and mass (moisture) transfer.

In the heat transfer process, the heat transferred to sludge increases the temperature and promotes evaporation of the water contained on the surface. During this process, a temperature gradient is formed from surface to solid interior, causing a moisture migration from interior to surface by mechanisms of capillary flow, diffusion and internal pressure differences caused by shrinkage of material.

The heat transfer to the sludge is affected by external conditions such as temperature, moisture, velocity and direction of the drying gas, exposure surface area, sludge physical form, agitation and detention time (WEF and ASCE/EWRI, 2010). Understanding these external conditions and their effects are important for the investigation of sludge drying characteristics, for the choice of appropriate dryer and to determine the best operating conditions.

According to Metcalf & Eddy (2004) there are three forms of heat transfer: (i) conduction (indirect drying), when a solid retaining wall separates the wet sludge from

the heat-transfer medium, usually steam or another hot fluid; (ii) convection (direct drying), when the wet sludge directly contacts the heat-transfer mechanism, usually hot gases; and (iii) radiation, when infrared lamps, electric resistance elements, or gas-fired incandescent refractories supply radiant energy that transfers to the wet sludge and evaporates moisture. The heat transfer by convection, conduction and radiation can be expressed, respectively, as follow:

$$q_{cond} = -kA \frac{dT}{dx} \quad (1)$$

$$q_{conv} = hA(T_g - T_s) \quad (2)$$

$$q_{rad} = \varepsilon\sigma A(T_r^4 - T_s^4) \quad (3)$$

Where:

q_{cond} = conductive heat transfer rate (W);

q_{conv} = convective heat transfer rate (W);

q_{rad} = radiation heat transfer rate (W);

k = thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$);

h = convective heat transfer coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$);

ε = emissivity of the drying surface (dimensionless);

σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$);

A = area of the surface exposed to drying medium (m^2);

dT/dx = temperature gradient ($\text{K}\cdot\text{m}^{-1}$)

T_g = gas source temperature (K);

T_s = sludge source temperature (K);

T_r = radiant source temperature (K).

In the mass transfer process, the mass is transferred from the interior to the material surface and is subsequently evaporated. The internal moisture movement in the solid material results from the concentration gradient, which depends on the solid characteristics.

The most important mechanisms of mass transfer are: (i) diffusion, which occurs due to the existence of a concentration gradient (Datta, 2002); and (ii) mass convection, which is the mass transfer mechanism between sludge surface and a moving fluid that involves

both mass diffusion and bulk fluid motion (Çengel, 2006). The diffusion and mass convection transfer can be expressed, respectively, as follow:

$$m_{diff} = -D_{AB}A \frac{dC_A}{dx} \quad (4)$$

$$m_{conv} = h_m A (C_s - C_\infty) \quad (5)$$

Where:

m_{diff} = diffusive mass flow rate (kg.s^{-1});

m_{conv} = convective mass flow rate (kg.s^{-1});

D_{AB} = diffusion coefficient ($\text{m}^2.\text{s}^{-1}$);

h_m = mass transfer coefficient (m.s^{-1});

A = area of the surface exposed to drying medium (m^2);

dC_A/dx = concentration gradient ($\text{kg.m}^{-3}.\text{m}^{-1}$)

$C_s - C_\infty$ = concentration difference between surface and fluid (kg.m^{-3}).

3.2. Behavior of sludge during drying

In general, the behavior of a molecule of water during the drying process is largely dependent on its proximity to the solid (Vaxelaire and Cézac, 2004). Therefore, the water in sludge can be classified into four groups, as shown in Figure 12.

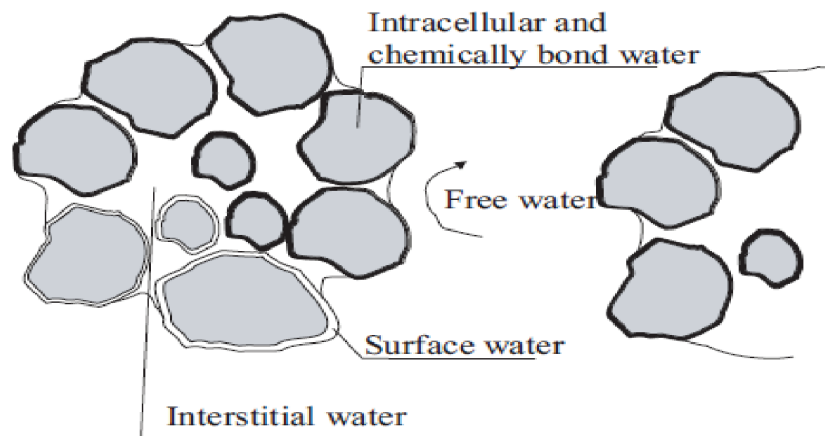


Figure 12 – Water distribution in sludge (Chen *et al.*, 2002).

The water distribution in sludge takes the following forms (Chen *et al.*, 2002; Vaxelaire and Cézac, 2004; Novak, 2006): (i) free water that is not attached by the solid particles, including void water not affected by capillary force, which can be removed by gravitational settling; (ii) interstitial water that is trapped between particles, within the

floc structure and within cells, which can be removed by strong mechanical forces; (iii) surface or vicinal water that is held on to the surface of solid particles by adsorption and adhesion and can be removed by drying; and (iv) intracellular and chemically bound water that is likely to be small and removed by high temperatures.

The amount of water that can be removed depends on the dewatering and drying processes and also the status of the water in the sludge (Chen *et al.*, 2002). The water that can be removed by mechanical dewatering is usually termed free water, and is not influenced by the solid particles, while the remainder is bound water, whose properties are modified due to the presence of the solid (Chen *et al.*, 2002; Vaxelaire and Cézac, 2004). Therefore, the free water includes the truly free, interstitial, and partial surface water, and the bound water includes the intracellular and chemically bound water and the partial surface water (Chen *et al.*, 2002).

One of the most important elements that gives information about product behavior during drying is the variation of product moisture over drying time, known as the drying curve (Bennamoun *et al.*, 2013). Figure 13 shows two typical drying curves.

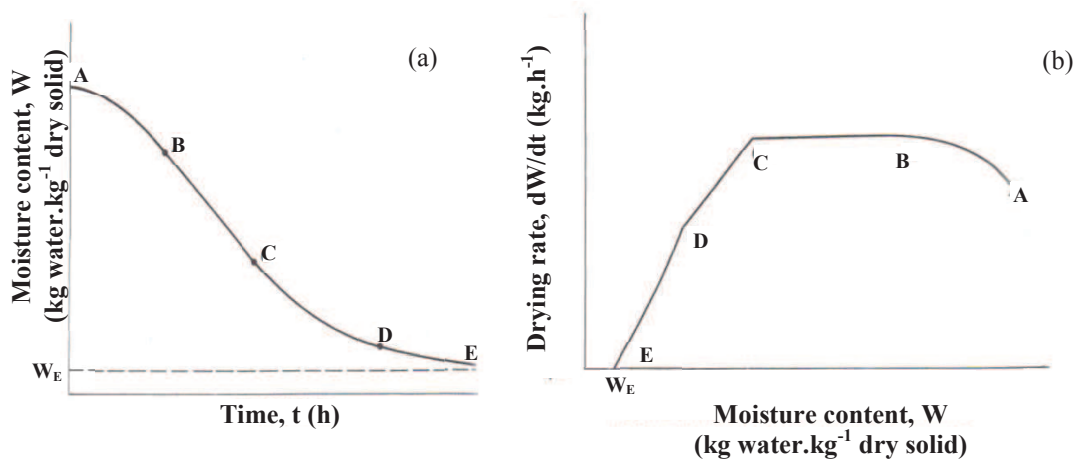


Figure 13 – Typical sludge drying curves. (a) Drying curve: moisture content vs. time. (b) Krischer curve: drying rate vs. moisture content (Bennamoun, 2012; Kemp *et al.*, 2001; Foust *et al.*, 1982; Bagnoli *et al.*, 1963).

In a general way, the drying kinetic starts by a short transient phase, also called an adaptation phase (line AB) (Bennamoun *et al.*, 2013). In this period, the drying velocity increases until it reaches a maximum value and the surface temperatures attain the wet-bulb temperature related to the air temperature and humidity (Bennamoun *et al.*, 2013; Foust *et al.*, 1982).

This phase is followed by a phase called a constant drying rate (line BC). The water removed during this part is considered free water (Bennamoun, 2012). In this period, the entire solid exposed surface is saturated with water, and drying occurs by liquid evaporation, without any direct influence on the solid drying rate (Foust *et al.*, 1982). During this phase, there is a balance between the rates of mass and heat transfer, and the temperature of the saturated surface remains constant (Bagnoli *et al.*, 1963).

The transition between the period of the constant rate and the falling rate period (line CD) is a typical point of the drying curve, called critical moisture (point C). This point represents the transition from a period where the process of drying is controlled by external conditions to a period where the transfer properties inside the product control the process (Vaxelaire and Cézac, 2004). This moisture content depends on the facility with which the moisture moves inside the solid, and therefore, the solid porous structure on drying speed (Foust *et al.*, 1982).

After the constant drying rate, there is a succession of two falling rates; the first is represented by the line CD and the second by the curve DE; the water removed in these phases is, respectively, interstitial and surface water (Bennamoun, 2012). During the curve CD, the surface becomes gradually lower in liquid, since the velocity of the liquid movement toward the surface is less than that of the mass transfer to the surface (Foust *et al.*, 1982). The point D represents the point at which the exposed surface becomes completely unsaturated and marks the beginning of the second falling rate, which is governed by the internal moisture rate to the material, with a decrease of the influence of external variables (Bagnoli *et al.*, 1963).

The last period of the curve is a short interval, where bound water is removed and moisture content equilibrium (W_F) is reached (Bennamoun, 2012). The moisture content equilibrium is reached when the vapor pressure of the liquid is equal to the partial vapor pressure in the gas drying (Foust *et al.*, 1982).

Studies have shown that these drying phases can change from one sludge to another and depend on the drying method used and the operating conditions.

Font *et al.* (2011), Deng *et al.* (2009) and Tao *et al.* (2005) observed in their experiments the inexistence of the constant drying rate during drying of sewage sludge

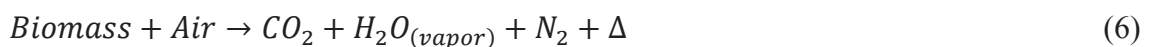
introduced into air injection, and concluded that the mechanical dewatering utilized before applying drying processes removed all the free water.

Reyes *et al.* (2004) and Léonard *et al.* (2005) have studied the effect of the influence of drying operation conditions, in particular the influence of air temperature and its superficial velocity during sewage sludge drying in the drying tunnel and micro dryer, respectively, and verified that drying is strongly affected by air temperature and to a lesser extent by its superficial velocity. Generally, increasing the temperature and superficial velocity leads to an increase in the drying rate (Bennamoun, 2012).

4. Combustion processes

Combustion is a complex phenomenon involving simultaneous coupled heat and mass transfer with chemical reaction and fluid flow (Jenkins *et al.*, 1998). The energy stored in the chemical bonds of the fuel is converted into heat energy and can be used in different places such as heavy industry and power plants to generate required steam for turbines that finally produce electricity and heat (Abuelnuor *et al.*, 2014). In the case of alternative fuels such as biomass, combustion means burning of organic materials (Abuelnuor *et al.*, 2014).

Biomass combustion is a sequence of chemical reactions in which carbon is oxidized into carbon dioxide, and hydrogen is oxidized into the water (Abuelnuor *et al.*, 2014). The reaction for the combustion of a biomass fuel is given as follow (Nunes *et al.*, 2014; Mendiara *et al.*, 2013):



When the combustion is incomplete there is a formation of many unwanted products, such as carbon oxide and methane, due to lack of oxygen. Thus, to ensure complete combustion it is necessary to provide an air volume higher than the stoichiometric amount and the locally available combustion air, called the excess air ratio. The excess air ratio is one of the main combustion parameters for high combustion efficiency (Abuelnuor *et al.*, 2014).

Biomass combustion occurs via a sequence of steps in parallel or sequentially, including heating and drying, devolatilisation, combustion of the volatiles and of the char and gas phase reactions (Khan *et al.*, 2009; Williams *et al.*, 2012).

Wet Biomass → heating/drying → *dry biomass* (7)

Biomass → *volatiles(tars and gases) + char* (8)

Volatiles + air → *CO + CO₂ + PAH + unburned hydrocarbons + soot + inorganic aerosols* (9)

Char + air → *CO + CO₂* (10)

Volatiles(N, S, K, etc) → *N, S, K based pollutants* (11)

Char(N, S, K, etc) → *N, S, K based pollutants* (12)

4.1. Combustion of sludge

Sludge combustion is an interesting option when considering the benefits of recycling these wastes, including odors minimization, volume reduction, thermal destruction of organic and toxic pollutants and energy recovery (Ye *et al.*, 2012; Kijo-Kleczkowska *et al.*, 2015). Consequently, it is reasonable to burn the waste to recover its energy content (Kijo-Kleczkowska *et al.*, 2015). However, large amount of pollutants can be generated during the process.

The classes of pollutant gases generated during combustion depend on the chemical composition of the sludge and on the process conditions (Virmond *et al.*, 2012). SO₂ and NO_x derive essentially from sulfur and nitrogen contained in the sludge. Acidic gases may also be emitted, such as HCl (hydrogen chloride) if chlorine compounds are present in the biofuel composition or others if lead or other heavy metals are present (Virmond *et al.*, 2011). CO, HCs and VOCs (volatile organic compounds) are products of incomplete combustion. Reactions between products of incomplete combustion with chloride compounds may lead to the formation of PCDD/PCDF (polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans) in the flue gases comprised in the VOC group (Batistella *et al.*, 2015). In addition, the exhaust gas may contain heavy metals in gaseous form, i.e., in active form (Piecuch, 2000).

The high moisture content of the sludge should be stressed, for its limiting autothermal combustion and necessitating the provision of additional fuel to maintain the combustion process or requires suitable pre-treatment, such as drying (Werther and Ogada, 1999; Kijo-Kleczkowska *et al.*, 2015; Batistella *et al.*, 2015).

Among the technologies for sludge combustion, fluidized bed combustion (FBC) is one of the most widely used due to its fuel flexibility and operating conditions (Werther and Ogada, 1999; Areeprasert *et al.*, 2015; Jang *et al.*, 2016). Furthermore, FBC is environmentally acceptable since it generates a relatively low amount of noxious gases due to its low and well-distributed temperature in the furnace.

The principle of FBC is based on a bed of sand or similar material, where the fuel is introduced and burned. Combustion air is blown at high speeds through open holes at the bottom of the furnace, maintaining the sand bed in a fluidized state (suspend). Depending on the combustion air speed, the sand bed can show different behaviors such as a fluid or porous bed. In this type of furnace it is possible to burn the sludge with solids content in the range of 41 to 65% (Fytli and Zabaniotou, 2008).

5. Conclusions

Industrial sludge can be used as a biomass resource for energy production; however the high water content makes the possible utilization of this material difficult, reducing its efficiency as an energy source. Drying is an essential step during wastewater management, as it increases sludge low calorific value, transforming it into an acceptable combustible. Several technologies currently exist for sludge drying and the selection of a particular dryer depends on initial and final moisture content, the sludge properties and the ability to operate and maintain the system. Despite there being many dryer systems available, technological progress has allowed the development of innovative drying technologies with higher thermal efficiency, lower emissions, less operator involvement, cheaper capital costs and a better final product.

References

Abbasi, T.; Abbasi, S. A. Biomass energy and the environmental impacts associated with its production and utilization. **Renewable and Sustainable Energy Reviews**, v.14, n.3, p.919-937, 2010.

Abuelnuor, A. A. A.; Wahid, M. A.; Hosseini, S. E.; Saat, A.; Saqr, K. M.; Sait, H. H.; Osman, M. Characteristics of biomass in flameless combustion: A review. **Renewable and Sustainable Energy Reviews**, v.33, p.363-370, 2014.

- Adamiec, J. Drying of waste sludges in a fluidized bed dryer with a mixer. **Drying Technology**, v.20, n.4-5, p.839-853, 2002.
- Areprasert, C.; Coppola, A.; Urciuolo, M.; Chirone, R.; Yoshikawa, K.; Scala, F. The effect of hydrothermal treatment on attrition during the fluidized bed combustion of paper sludge. **Fuel Processing Technology**, v.140, p.57-66, 2015.
- Avelar, N. V.; Rezende, A. A. P.; Carneiro, A. de C. O.; Silva, C. M. Evaluation of briquettes made from textile industry solid waste. **Renewable Energy**, v.91, p.417-424, 2016.
- Bagnoli, E.; Fuller, F. H.; Norris, R. W. Section 15 – Humidification and drying. In: Perry, J. H.; Perry, R. H.; Chilton, C. H.; Kirkpatrick, S. D. **Chemical Engineers' Handbook**. 4 ed. McGraw Hill, Inc., 1963. p. 15.32-15.45.
- Batistella, L.; Silva, V.; Suzin, R. C.; Virmond, E.; Althoff, C. A.; Moreira, R. F. P. M.; José, H. J. Gaseous emissions from sewage sludge combustion in a moving bed combustor. **Waste Management**, v.46, p.430-439, 2015.
- Bennamoun, L. Solar drying of wastewater sludge: A review. **Renewable and Sustainable Energy Reviews**, v.16, p.1061-1073, 2012.
- Bennamoun, L.; Arlabosse, P.; Léonard, A. Review on fundamental aspect of application of drying process to wastewater sludge. **Renewable and Sustainable Energy Reviews**, v.28, p.29-43, 2013.
- Cai, L.; Gao, D.; Che, T.; Liu, H.; Zheng, G.; Yang, Q. Moisture variation associated with water input and evaporation during sewage sludge bio-drying. **Bioresource Technology**, v.117, p.13-19, 2012.
- Caputo, A. C.; Palumbo, M.; Pelagagge, P. M.; Scacchia, F. Economics of biomass energy utilization in combustion and gasification plants: Effects of logistic variables. **Biomass and Bioenergy**, v.28, n.1, p.35-51, 2005.
- Çengel, Y. A. **Heat and mass transfer: a practical approach**. McGraw-Hill, New York, 900p., 2006.
- Chai, L. H. Statistical dynamic features of sludge drying systems. **International Journal of Thermal Sciences**, v.46, p.802-811, 2007.

- Chang, F. C.; Ko, C. H.; Wu, J. Y.; Wang, H. P.; Chen, W. S. Resource recovery of organic sludge as refuse derived fuel by fry-drying process. **Bioresource Technology**, v.141, p.240-244, 2013.
- Chen, G.; Yue, P. L.; Mujumdar, A. S. Sludge dewatering and drying. **Drying Technology**, v.20, n.4-5, p.883-916, 2002.
- Chen, J.; Mu, L.; Cai, J.; Yao, P.; Song, X.; Yin, H.; Li, A. Pyrolysis and oxy-fuel combustion characteristics and kinetics of petrochemical wastewater sludge using thermogravimetric analysis. **Bioresource Technology**, v.198, p.115-123, 2015.
- Cusidó, J. A.; Cremades, L. V. Atomized sludges via spray-drying at low temperatures: An alternative to conventional wastewater treatment plants. **Journal of Environmental Management**, v.105, p.61-65, 2012.
- Dai, J.; Cui, H.; Grace, J. R. Biomass feeding for thermochemical reactors. **Progress in Energy and Combustion Science**, v.38, n.5, p.716-736, 2012.
- Datta, A. K. **Biological and bioenvironmental heat and mass transfer**. Marcel Dekker, C., New York, 383p., 2002.
- Demirbas, A. Combustion characteristics of different biomass fuels. **Progress in Energy and Combustion Science**, v.30, n.2, p.219-230, 2004.
- Demirbas, A. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. **Progress in Energy and Combustion Science**, v.31, n.2, p.171-192, 2005.
- Demirbas, M. F.; Balat, M.; Balat, H. Potential contribution of biomass to the sustainable energy development. **Energy Conversion and Management**, v.50, n.7, p.1746-1760, 2009.
- Deng, S.; Wang, X.; Tan, H.; Mikulčić, H.; Li, Z.; Cao, R.; Wang, Z. Vujanović, M. Experimental and modeling study of the long cylindrical oily sludge drying process. **Applied Thermal Engineering**, v.91, p.354-362, 2015.
- Deng, W. Y.; Yan, J. H.; Li, X. D.; Wang, F.; Lu, S. Y.; Chi, Y.; Cen, K. F. Measurement and simulation of the contact drying of sewage sludge in a Nara-type paddle dryer. **Chemical Engineering Science**, v.64, n.24, p.5117-5124, 2009.

- Erol, M.; Haykiri-Açma, H.; Küçükbayrak, S. Calorific value estimation of biomass from their proximate analyses data. **Renewable Energy**, v.35, n.1, p.170-173, 2010.
- Frei, K. M.; Cameron, D.; Stuart, P. R. Novel drying process using forced aeration through a porous biomass matrix. **Drying Technology**, v.22, n.5, p.1191-1215, 2004.
- Font, R.; Gomez-Rico, M. F.; Fullana, A. Skin effect in the heat and mass transfer model for sewage sludge drying. **Separation and Purification Technology**, v.77, p.146-161, 2011.
- Foust, A. S.; Wenzel, L. A.; Clump, C. W.; Maus, L.; Andersen, L. B. **Principles of units operations**. 2 ed. John Wiley & Sons, Inc., 1982. 670p.
- Fytili, D.; Zabaniotou, A. Æ. Utilization of sewage sludge in EU application of old and new methods – A review. **Renewable and Sustainable Energy Reviews**, v.12, p.116-140, 2008.
- Ghugare, S. B.; Tiwary, S.; Elangovan, V.; Tambe, S. S. Prediction of higher heating value of solid biomass fuels using artificial intelligence formalisms. **Bioenergy Research**, v.7, n.2, p.681-692, 2014.
- Haykiri-Açma, H. Combustion characteristics of different biomass materials. **Energy Conversion and Management**, v.44, n.1, p.155-162, 2003.
- Herbert, G. M. J.; Krishnan, A. U. Quantifying environmental performance of biomass energy. **Renewable and Sustainable Energy Reviews**, v.59, p.292-308, 2016.
- Hippinen, I.; Ahtila, P. Drying of activated sludge under partial vacuum conditions – an experimental study. **Drying Technology**, v.22, p.2119-2134, 2004.
- Hohenstein, W. G.; Wright, L. L. Biomass energy production in the United States: an overview. **Biomass and Bioenergy**, v.6, n.3, p.161-173, 1994.
- Huiliñir, C.; Villegas, M. Biodrying of pulp and paper secondary sludge: Kinetics of volatile solids biodegradation. **Bioresource Technology**, v.157, p.206-213, 2014.
- Jang, H. N.; Kim, J. H.; Back, S. K.; Sung, J. H.; Yoo, H. M.; Choi, H. S.; Seo, Y. C. Combustion characteristics of waste sludge at air and oxy-fuel combustion conditions in a circulating fluidized bed reactor. **Fuel**, v.170, p.92-99, 2016.

- Jenkins, B.; Baxter, L.; Miles, T. Combustion properties of biomass. **Fuel Processing Technology**, v.54, n.1-3, p.17-46, 1998.
- Kemp, I. C.; Fyhr, B. C.; Laurent, S.; Roque, M. A.; Groenewold, C. E.; Tsotsas, E.; Sereno, A. A.; Bonazzi, C. B.; Bimbenet, J. Kind, M. Experimental drying kinetics data. **Drying Technology**, v.19, n.1, p.15-34, 2001.
- Khan, A. A.; de Jong, W.; Jansens, P. J.; Spliethoff, H. Biomass combustion in fluidized bed boilers: Potential problems and remedies. **Fuel Processing Technology**, v.90, n.1, p.21-50, 2009.
- Kijo-Kleczkowska, A.; Sroda, K.; Kosowska-Golachowska, M.; Musial, T.; Wolski, K. Mechanisms and kinetics of granulated sewage sludge combustion. **Waste Management**, v.46, p.459–471, 2015.
- Kraft, D. L.; Orender, H. C. Considerations for using sludge as a fuel. **Tappi Journal**, v.76, n.3, p.175–183, 1993.
- Kudra, T.; Gawrzynski, Z.; Glaser, R.; Stanislawski, J.; Poirier, M. Drying of pulp and paper sludge in a pulsed fluid bed dryer. **Drying Technology**, v.20, p.917-933, 2002.
- Lee, J. E.; Choo, E. M. A study on air jet drying for water content reduction of sludges. **Korean Journal of Chemical Engineering**, v.27, n.6, p.1822-1828, 2010.
- Lähdeniemi, A.; Mäkelä, M.; Dahl, O. Drying/fractionation of deinking sludge with a high-velocity cyclone. **Drying Technology**, v.31, p.378-384, 2013.
- Léonard, A.; Blacher, S.; Marchot, P.; Pirard, J. P., Crine, M. Convective drying of wastewater sludges: influence of air temperature, superficial velocity, and humidity on the kinetics. **Drying Technology**, v.23, p.1667-1679, 2005.
- Léonard, A.; Meneses, E.; Le Trong, E.; Salmon, T.; Marchot, P.; Toye, D.; Crine, M. Influence of back mixing on the convective drying of residual sludges in a fixed bed. **Water Research**, v.42, n.10-11, p.2671-2677, 2008.
- Li, X.; Dai, X.; Yuan, S.; Li, N.; Liu, Z.; Jin, J. Thermal analysis and 454 pyrosequencing to evaluate the performance and mechanisms for deep stabilization and reduction of high-solid anaerobically digested sludge using biodrying process. **Bioresource Technology**, v.175, p.245–253, 2015.

- Mäkelä, M.; Geladi, P.; Larsson, S. H.; Finell, M. Pretreatment of recycled paper sludge with a novel high-velocity pilot cyclone: effect of process parameters on convective drying efficiency. **Applied Energy**, v.131, p.490-498, 2014.
- Manara, P.; Zabaniotou, A. Towards sewage sludge based biofuels via thermochemical conversion – A review. **Renewable and Sustainable Energy Reviews**, v.16, n.5, p.2566-2582, 2012.
- Mathioudakis, V. L.; Kapagiannidis, A. G.; Athanasoulia, E.; Diamantis, V. I.; Melidis, P.; Aivasidis, A. Extended dewatering of sewage sludge in solar drying plants. **Desalination**, v.248, p.733-739, 2009.
- Mendiara, T.; Abad, A.; Diego, L. F. de; Gayán, P.; Adánez, J. Biomass combustion in a CLC system using an iron ore as an oxygen carrier. **International Journal of Greenhouse Gas Control**, v.19, p.322-330, 2013.
- Metcalf & Eddy. **Wastewater engineering: treatment, disposal, reuse**. 4. ed. New York: McGraw-Hill, 2004. 1819 p.
- Nakomcic-Smaragdakis, B.; Cepic, Z.; Dragutinovic, N. Analysis of solid biomass energy potential in Autonomous Province of Vojvodina. **Renewable and Sustainable Energy Reviews**, v.57, p.186-191, 2016.
- Nanda, S.; Mohanty, P.; Pant, K. K.; Naik, S.; Kozinski, J. A.; Dalai, A. K. Characterization of north american lignocellulosic biomass and biochars in terms of their candidacy for alternate renewable fuels. **Bioenergy Research**, v.6, p.663-677, 2013.
- Navaee-Ardeh, S.; Bertrand, F.; Stuart, P. R. Key variables analysis of a novel continuous biodrying process for drying mixed sludges. **Bioresource Technology**, v.101, p.3379-3387, 2010.
- Neyens, E.; Baeyens, J. A review of thermal sludge pre-treatment processes to improve dewaterability. **Journal of Hazardous Materials**, v.98, n.1-3, p.51-67, 2003.
- Novak, J. T. Dewatering of sewage sludge. **Drying Technology**, v.24, p.1257-1262, 2006.

- Nunes, L. J. R.; Matias, J. C. O.; Catalão, J. P. S. Mixed biomass pellets for thermal energy production: A review of combustion models. **Applied Energy**, v.127, p.135-140, 2014.
- Obernberger, I.; Brunner, T.; Bärnthaler, G. Chemical properties of solid biofuels-significance and impact. **Biomass and Bioenergy**, v.30, n.11, p.973-982, 2006.
- Ohm, T. I.; Chae, J. S.; Kim, J. E.; Kim, H. K.; Moon, S. H. A study on the dewatering of industrial waste sludge by fry-drying technology. **Journal of Hazardous Materials**, v.168, p.445-450, 2009.
- Ohm, T. I.; Chae, J. S.; Kim, J. E.; Kim, H. K.; Moon, S. H. The evaporative drying of sludge by immersion in hot oil: Effects of oil type and temperature. **Journal of Hazardous Materials**, v.178, p.483-488, 2010.
- Park, K. J.; Antonio, G. C.; Oliveira, R. A. de; Park, K. J. B. **Conceitos de processo e equipamentos de secagem**. Campinas: UNICAMP, 2007. 121 p.
- Peregrina, C.; Rudolph, V.; Lecomte, D.; Arlabosse, P. Immersion frying for the thermal drying of sewage sludge: An economic assessment. **Journal of Environmental Management**, v.86, p.246-261, 2008.
- Pronobis, M. The influence of biomass co-combustion on boiler fouling and efficiency. **Fuel**, v.85, n.4, p.474-480, 2006.
- Reyes, A.; Eckholt, M.; Troncoso, F.; Efremov, G. drying kinetics of sludge from a wastewater treatment plant. **Drying Technology**, v.22, n.9, p.2135-2150, 2004.
- Rodrigues, V. A. J.; Silva, C. M.; Carneiro, A. O. C.; Rezende, A. A. P.; Santos, L. S.; Ikawa, G. A. The Use of Pulp Mill Solid Wastes for Energy Production. In: Third International Symposium on Energy from Biomass and Waste Venice, 2010, Venice, Italy. Proceedings Venice 2010, Third International Symposium on Energy from Biomass and Waste Venice, Italy; 8-11 November 2010, 2010. p. 1-11.
- Saidur, R.; Abdelaziz, E. A.; Demirbas, A.; Hossain, M. S.; Mekhilef, S. A review on biomass as a fuel for boilers. **Renewable and Sustainable Energy Reviews**, v.15, n.5, p.2262-2289, 2011.

Salihoglu, N. K.; Pinarli, V.; Salihoglu, G. Solar drying in sludge management in Turkey. **Renewable Energy**, v.32, p.1661-1675, 2007.

Schneider, H. Arrangement for reducing the moisture content of sludge. U.S. Patent 5480539, 1996.

Slim, R.; Zoughaib, A.; Clodic, D. Modeling of a solar and heat pump sludge drying system. **International Journal of Refrigeration**, v.31, p.1156-1168, 2008.

Spinosa, L.; Ayol, A.; Baudez, J.; Canziani, R.; Jenicek, P.; Léonard, A.; Rulkens, W.; Xu, G.; Dijk, L.V. Sustainable and innovative solutions for sewage sludge management. **Water**, v.3, n.2, p.702-717, 2011.

Strezov, V.; Evans, T. J. Thermal processing of paper sludge and characterisation of its pyrolysis products. **Waste Management**, v.29, n.5, p.1644-1648, 2009.

Tao, T.; Peng, X. F.; Lee, D. J. Thermal drying of wastewater sludge: change in drying area owing to volume shrinkage and crack development. **Drying Technology**, v.23, p.669-682, 2005.

Vamvuka, D.; Salpigidou, N.; Kastanaki, E.; Sfakiotakis, S. Possibility of using paper sludge in co-firing applications. **Fuel**, v.88, n.4, p.637-643, 2009.

Vaxelaire, J.; Cézac, P. Moisture distribution in activated sludges: a review. **Water Research**, v.38, p.2215-2230, 2004.

Virmond, E.; Schacker, R. L.; Albrecht, W.; Althoff, C. A.; de Souza, M.; Moreira, R. F. P. M.; José, H. J. Organic solid waste originating from the meat processing industry as an alternative energy source. **Energy**, v.36, n.6, p.3897-3906, 2011.

Virmond, E.; De Sena, R. F.; Albrecht, W.; Althoff, C. A.; Moreira, R. F. P. M.; José, H. J. Characterisation of agroindustrial solid residues as biofuels and potential application application in thermochemical processes. **Waste Management**, v.32, p.1952-1961, 2012.

WEF – Water Environment Federation; ASCE/EWRI – American Society of Civil Engineers/Environmental and Water Resources Institute. Design of municipal wastewater treatment plants. WEF Manual of practice No. 8, ASCE Manuals and Reports on Engineering Practice No. 76, 5 ed., Alexandria, 2010.

- Werther, J.; Ogada, T. Sewage sludge combustion. **Progress in Energy and Combustion Science**, v.25, p.55-116, 1999.
- Werther, J.; Saenger, M.; Hartge, E. U.; Ogada, T.; Siagi, Z. Combustion of agricultural residues. **Progress in Energy and Combustion Science**, v.26, n.1, p.1-27, 2000.
- Williams, A.; Jones, J. M.; Ma, L.; Pourkashanian, M. Pollutants from the combustion of solid biomass fuels. **Progress in Energy and Combustion Science**, v.38, n.2, p.113-137, 2012.
- Williams, A.; Pourkashanian, M.; Jones, J. M. Combustion of pulverised coal and biomass. **Progress in Energy and Combustion Science**, v.27, p.587-610, 2001.
- Winkler, M. K. H.; Bennenbroek, M. H.; Horstink, F. H.; van Loosdrecht, M. C. M.; van de Pol, G. J. The biodrying concept: An innovative technology creating energy from sewage sludges. **Bioresource Technology**, v.147, p.124-129, 2013.
- Wu, Z.; Zhang, J.; Li, Z.; Xie, J.; Mujumdar, A. S. Production of a solid fuel using sewage sludge and spent cooking oil by immersion frying. **Journal of Hazardous Materials**, v.243, p.357-363, 2012.
- Xie, Z.; Ma, X. The thermal behaviour of the co-combustion between paper sludge and rice straw. **Bioresource Technology**, v.146, p.611-618, 2013.
- Yanfen, L.; Xiaoqian, M. Thermogravimetric analysis of the co-combustion of coal and paper mill sludge. **Applied Energy**, v.87, n.11, p.3526-3532, 2010.
- Ye, W.; Han, J.; Qin, L.; Li, Y.; Masami, F.; Yao, H. Emission characteristics of PM₁₀ during sewage sludge combustion. **Aerosol and Air Quality Research**, v.12, p.420-425, 2012,
- Zhao, L.; Gu, W.; He, P.; Shao, L. Effect of air-flow rate and turning frequency on bio-drying of dewatered sludge. **Water Research**, v.44, p.6144-652, 2010.

CHAPTER II

EVALUATION OF PHYSICAL AND THERMOCHEMICAL CHARACTERISTICS OF BIOSLUDGE AS A POTENTIAL ENERGY SOURCE

Abstract

The aim of the present paper is to study the physical and thermochemical characteristics of biosludge and in mixtures with eucalyptus chips or eucalyptus bark in two different proportions (15% and 25%). The biosludge, eucalyptus chips and bark and their respective mixtures were characterized by elementary analysis (CHONS), volatile material content, fixed carbon, ash content, high heating value and thermogravimetric analysis (TGA). The characterization demonstrated that biosludge has potential for energy production, when eucalyptus chips or bark are added at a proportion of 25%, because this percentage increased the heating value, volatile matter, fixed carbon, carbon and hydrogen contents, and decreased nitrogen, sulfur and ash content. According to the TGA results, the addition of eucalyptus chips and bark increased the total mass loss of the biosludge mixtures and, consequently, reduced the residual mass. It was possible to conclude that biosludge mixtures with either 25% eucalyptus chips or eucalyptus bark can be considered as fuels in the combustion process for energy generation.

Keywords: biomass, biosludge, combustion, thermogravimetry.

1. Introduction

World-wide increases in energy demands and costs have created a need for considerable research into renewable energy sources (Fournel *et al.*, 2015), such as biomass, which is the most promising, most publicized and most heavily subsidized renewable energy sources (Aslan, 2016).

Biomass is any organic matter derived from biological organisms, animals or plants (Nakomcic-Smaragdakis *et al.*, 2016), including wood and wood wastes, agricultural residues, food crops, aquatic plants and algae (Demirbas *et al.*, 2009; Abbasi and Abbasi, 2010), industrial wastes, paper residues, food wastes, sewage and industrial sludge and municipal solid wastes (Pronobis, 2006).

Recently, the use of biomass, especially sludge, has been attracting more and more attention, due to its large-scale production and difficulties related to its management and disposal. The high water content of this material makes it difficult to dehydrate, and various types of pollutants, such as heavy metals, poorly biodegradable organic compounds, bacteria and dioxins, make managing its disposal a challenge (Jiang *et al.*, 2010; Seggiani *et al.*, 2012; Bianchini *et al.*, 2015). However, in its dry form, it can be considered a special type of renewable fuel, due to the significant organic fraction (García *et al.*, 2013). Therefore, thermal conversion appears to be the most promising alternative to manage this waste.

Pyrolysis, gasification and combustion are the main thermal treatment technologies for biosludge. The advantages of these processes include volume reduction, thermal destruction of organic toxins and energy recovery from organic sources in the sludge (Magdziarz and Werle, 2014; Seggiani *et al.*, 2012; Chen *et al.*, 2015). Furthermore, according to Kim and Lee (2010) and Winkler *et al.* (2013), the caloric value of dry sludge corresponds to that of brown coal (12 MJ.kg^{-1}).

Before any attempt to utilize the biosludge for energy production through thermochemical processes, it is essential to understand its behavior during pyrolysis and combustion processes, which can be determined by using thermogravimetric analyses (TGA). Thermal analysis provides means for the preliminary assessment of fuel values in wastes (Li *et al.*, 2011; Font *et al.*, 2001; Otero *et al.*, 2002). This information can then be used to forecast combustion efficiency, residence time, excess air, and boiler

design as well as to establish optimal operational conditions for combustion (Otero *et al.*, 2002; Li *et al.*, 2011). Therefore, thermal analysis could make an important contribution to knowledge of biomass thermal behavior (Maiti *et al.*, 2006).

The aim of this paper was to evaluate the physical and thermochemical characteristics of biosludge and biosludge mixtures with either eucalyptus chips or eucalyptus bark in two different proportions, 15% and 25%.

2. Materials and methods

2.1. Materials and characterization

Biosludge was obtained from an activated sludge system in a paper mill effluent treatment plant, with the capacity to treat $720 \text{ m}^3 \cdot \text{d}^{-1}$ and generate $5 \text{ t} \cdot \text{d}^{-1}$ of biosludge with a solids content of 15% after dewatering in a centrifuge. The Eucalyptus (*Eucalyptus* sp.) chips (2-3 cm length) and bark (0.5-1.5 cm length) were collected from a pulp and paper mill.

The samples were dried in the open air to reduce their initial moisture, after which they were milled and sieved to obtain particles with a size smaller than 0.42 mm and larger than 0.25 mm. From these materials, biosludge mixtures with either eucalyptus chips or eucalyptus bark were prepared in two different proportions, 15% and 25%.

The characterization of the biosludge, eucalyptus chips and bark and their respective mixtures was performed using the following analyses: elementary chemical composition, including carbon, hydrogen, nitrogen and sulfur in accordance with EN 15104 (CEN, 2011a) and EN 15289 (CEN, 2011b), and oxygen, measured by the difference of C, H, N, S and ash from 100; immediate chemical analysis, especially, moisture content, volatile matter and ash content based on EN 15148 (CEN, 2009a), N 156 (CEN, 2007) and EN 14775 (CEN, 2009b), respectively, and fixed carbon, calculated from the difference of moisture, ash and volatile matter; and higher heating value, according to EN 14918 (CEN, 2009c).

2.2. Thermal analysis

The thermogravimetric analysis of biosludge, eucalyptus chips and bark, and their respective mixtures was determined in an Automatic Multiple Sample

Thermogravimetric Analyzer TGA-1000. The experiments were conducted at atmospheric pressure and temperature ranging from 50 to 700°C under nitrogen atmosphere using a heating rate of 10°C.min⁻¹. The thermogravimetric curve (TG) was recorded to analyze the mass loss as a function of temperature and the first derivative curve of mass loss (DTG). The results of total mass loss were evaluated statistically by comparing the two-sample variance using the F test.

3. Results and discussion

3.1. Thermal characterization

The characteristics of the materials are presented in Table 1. The results observed in this study were in accordance with the characterization of paper sludge obtained in other studies (Vamvuka *et al.*, 2009; Xie and Ma, 2013; Areeprasert *et al.*, 2015; Mäkelä *et al.*, 2014).

Table 1 – Immediate analysis, elementary composition and heating value of the materials and mixtures.

	BS	EC	EB	15% EC	25% EC	15% EB	25% EB
Immediate analysis (% , d.b.)							
W	10.4 ± 0.85	14.5 ± 0.51	12.3 ± 0.25	12.5 ± 0.29	13.8 ± 0.32	11.6 ± 0.36	12.6 ± 0.96
VM	65.1 ± 1.32	87.3 ± 0.01	81.2 ± 0.22	67.8 ± 0.06	69.5 ± 0.54	67.6 ± 0.55	69.2 ± 0.50
CF	0.62 ± 0.63	12.5 ± 0.03	15.2 ± 0.30	2.14 ± 1.12	4.42 ± 0.61	1.28 ± 0.70	2.23 ± 0.38
AC	34.3 ± 0.69	0.22 ± 0.04	3.56 ± 0.08	28.6 ± 0.62	26.1 ± 1.15	31.1 ± 1.25	29.9 ± 0.44
Elementary composition (% , d.b.)							
C	22.8 ± 0.21	49.5 ± 0.21	46.3 ± 0.21	30.6 ± 1.13	31.1 ± 0.35	32.2 ± 0.14	36.4 ± 0.28
H	2.33 ± 0.08	6.00 ± 0.01	5.30 ± 0.03	3.32 ± 0.16	3.38 ± 0.07	3.52 ± 0.06	4.24 ± 0.06
O	37.1 ± 0.37	43.0 ± 0.24	43.7 ± 0.15	34.9 ± 0.60	36.6 ± 0.81	30.6 ± 1.55	27.5 ± 0.13
N	2.20 ± 0.06	0.44 ± 0.001	0.36 ± 0.01	1.72 ± 0.07	1.57 ± 0.04	1.62 ± 0.09	1.12 ± 0.10
S	1.21 ± 0.03	0.76 ± 0.005	0.77 ± 0.003	0.84 ± 0.01	1.21 ± 0.05	0.92 ± 0.02	0.84 ± 0.01
HHV (MJ.kg ⁻¹ , d.b.)							
	10.3 ± 0.06	19.4 ± 0.05	18.5 ± 0.28	11.5 ± 0.06	12.0 ± 0.01	11.4 ± 0.05	11.4 ± 0.17

BS = biosludge; EC= eucalyptus chips; EB = eucalyptus bark; W = moisture content; VM = volatile matter; FC = fixed carbon; AC = ash content; HHV = high heating value; d.b. = dry basis.

The moisture content of dried biosludge was 10.4% (dry basis); however, the amount of moisture after the dewatering process was significantly higher than 80% (wet basis). Therefore, according to Strezov and Evans (2009), pre-drying biosludge is important for improvement of the overall energy efficiency of the thermal process, such as combustion. The moisture content considered adequate for combustion in biomass boilers is 50% (w.b.) (Kraft and Orender, 1993; Werther and Ogada, 1999; Kudra *et al.*, 2002; Frei *et al.*, 2004). Biosludge with 50% moisture can have a heating value similar

to some woods species and peat, and can also generate in significant economic benefits for boiler operations (Navaee-Ardeh *et al.*, 2006).

The volatile matter was greater than 80% for eucalyptus chips and bark, and above 60% for biosludge and mixtures. Since biosludge from paper mills consists of cells, cellulose and inorganic materials, such as additives (limestone) used in the biological treatment (Hippinen and Ahtila, 2002; Sutcu and Akkurt, 2009; Frías *et al.*, 2015), the high levels of volatile material found in biosludge is, according to Méndez *et al.* (2009) due to its elevated organic matter content and/or due to CaCO₃ that decomposes at temperatures below 900°C.

In comparison with eucalyptus chips and bark, the biosludge had very high ash content and lower carbon and hydrogen content, which resulted in a lower HHV. Additionally, the percentage of nitrogen and sulfur is rather high, which may be a problem when only taking into account the combustion of this fuel.

According to Hippinen and Ahtila (2002), the high ash content found in biosludge could be due to the amount of inorganic matter passing through primary treatment, the additive feeding in biological treatment and/or the age of the microbes in aeration.

The addition of eucalyptus chips and bark improved biosludge characteristic, increasing the heating value, volatile matter, fixed carbon, carbon and hydrogen contents, and decreasing the ash, nitrogen and sulfur contents. Therefore, the mixture of dried sludge and eucalyptus chips or bark can be potential fuel for biomass boilers.

3.2. Thermal analysis

The TG and DTG curves for biosludge, eucalyptus chips and bark are presented in Figure 1, and for the mixtures, in Figure 2. It can be observed that the thermal degradation of mixtures showed an intermediate profile between those obtained for the biosludge, eucalyptus chips and bark.

The mass loss as a function of the temperature for the biosludge, eucalyptus chips and bark and their respective mixtures are presented in Table 2. The first temperature range (100-200°C) was characterized by a small loss of moisture. According to Chen *et al.* (2015), this small loss can be attributed to the thermal decomposition of intracellular and chemically bound water.

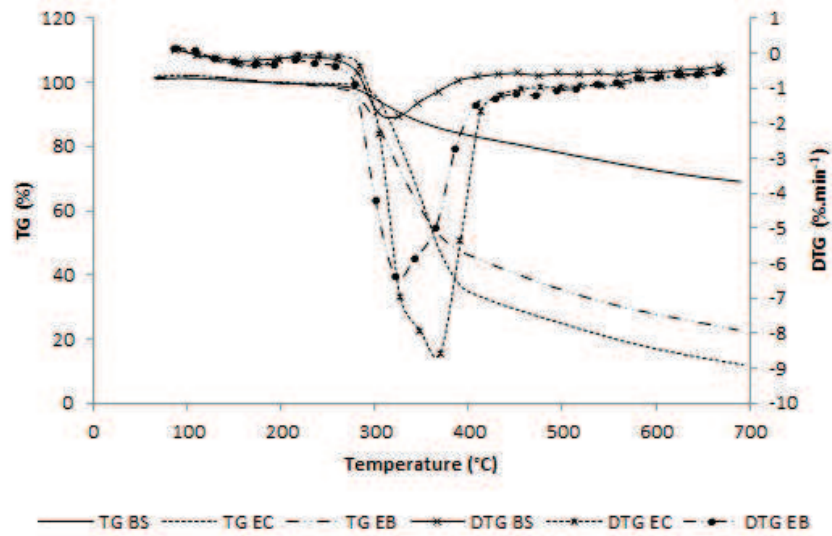


Figure 14 – TG-DTG curves of biosludge (BS), eucalyptus chips (EC) and eucalyptus bark (EB).

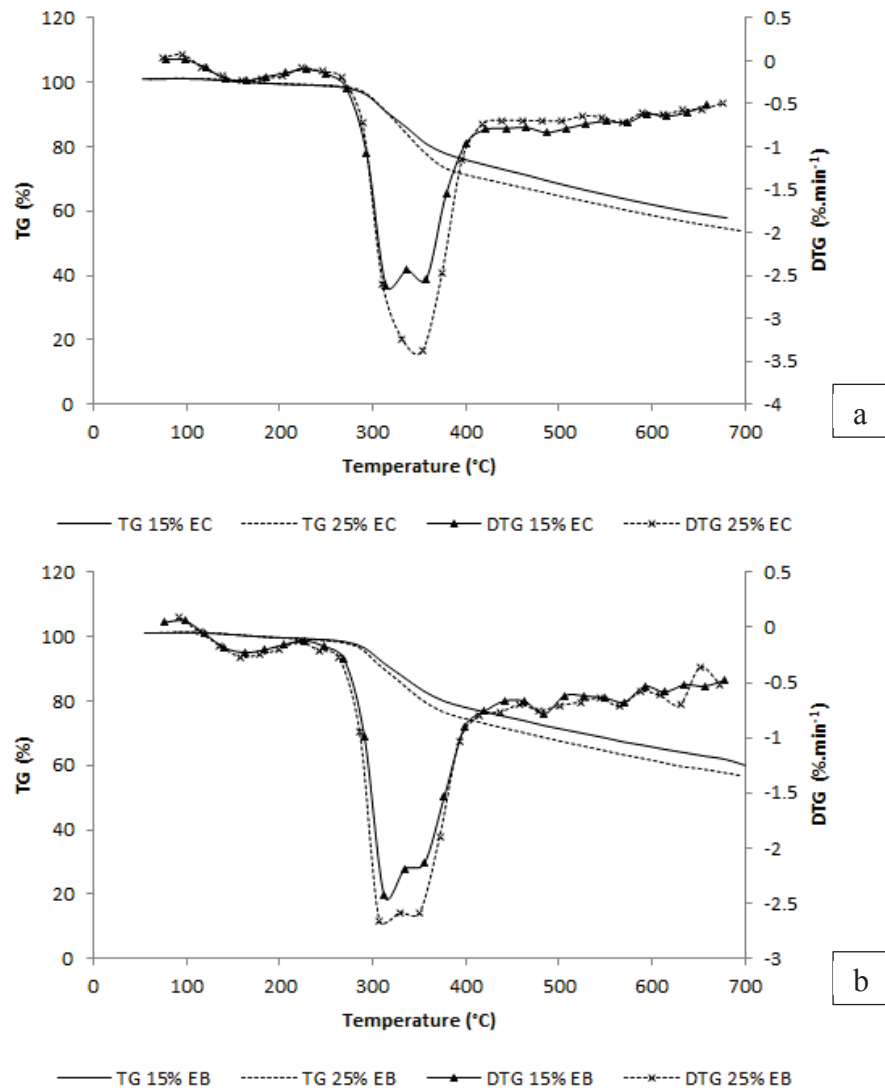


Figure 2 – TG-DTG curves of mixtures of biosludge with (a) eucalyptus chips and (b) eucalyptus bark.

Table 2 – Mass loss (%) of the materials as a function of temperature.

Material	Temperature range (°C)						Total mass loss
	100-200	200-300	300-400	400-500	500-600	600-700	
BS	1.50 ± 0.99	5.36 ± 0.62	11.5 ± 0.16	7.65 ± 0.08	5.77 ± 0.02	3.32 ± 0.21	32.0 c
EC	2.22 ± 0.11	5.68 ± 0.93	57.7 ± 0.88	11.7 ± 0.22	8.36 ± 0.07	4.62 ± 0.01	89.9 a
EB	1.91 ± 0.05	11.8 ± 0.46	42.8 ± 0.60	9.37 ± 0.11	8.26 ± 0.01	4.83 ± 0.11	78.6 b
15% EC	1.72 ± 0.21	3.28 ± 0.35	20.2 ± 0.29	7.97 ± 1.80	5.55 ± 0.57	4.51 ± 0.40	43.2 c
25% EC	1.75 ± 0.14	2.27 ± 0.21	25.6 ± 2.72	7.05 ± 0.16	6.49 ± 0.06	4.27 ± 0.01	47.3 c
15% EB	1.65 ± 0.01	8.00 ± 0.16	13.5 ± 1.18	7.00 ± 0.11	4.93 ± 0.04	4.23 ± 0.06	41.0 c
25% EB	1.82 ± 0.01	8.43 ± 0.01	16.2 ± 1.04	7.43 ± 0.16	6.45 ± 0.07	4.27 ± 0.21	44.4 c

BS = biosludge; EC= eucalyptus chips; EB = eucalyptus bark.

The values followed by one letter in the column did not differ from each other at 5% of probability by the F test.

The temperature range of 200-300°C can be attributed to the beginning of hemicellulose decomposition, since this component decomposes between 230-390°C (Vamvuka *et al.*, 2009). The highest mass loss observed for EB could be due to the presence of extractives in wood bark that degrade within this temperature range.

The higher thermal degradation occurred in the temperature range of 300-400°C, being characterized by the degradation of hemicellulose and, especially, cellulose, that decomposes between 320°C and 380°C (Park *et al.*, 2009). It can be seen that the mass loss was higher for EC, than for EB or BS due to the higher volatile matter and lower ash content of EC and EB. Therefore, the addition of these materials in BS increased the mass loss, being greater for 25%.

According to Xie and Ma (2013), mass loss detected for BS within the temperature range of 300-400°C corresponded to the release and combustion of volatile matter and biodegradable organics present in cells and produced during stabilization or the biological treatment of biosludge. Since the major components of BS are paper pulp and wood fiber, the temperature peaks can represent the decomposition of hemicellulose and cellulose, according to Yanfen and Xiaoqian (2010) and Vamvuka *et al.* (2009).

Decomposition of inorganic matter mainly took place from 400°C to 700°C. Although the mass loss of all materials decreases, according to Heikkinen *et al.* (2004), the slow decomposition of lignin can be observed.

The lower mass loss observed for BS was expected due to the high inorganic matter (34%) present in this material, due to which, its residual mass was about 69%.

As shown in Table 2, the addition of either eucalyptus chips or bark increased the total mass loss of the biosludge mixtures and, consequently, reduced residual mass. Although, the mass loss was higher for the mixtures with EC due to the lower ash content of this material, it did not differ significantly from EB.

4. Conclusions

The TGA results and characterization showed that the addition of either eucalyptus chips or bark at a proportion of 25% increased mass loss, heating value, volatile matter, fixed carbon, carbon and hydrogen contents, and decreased the ash, nitrogen and sulfur contents. Therefore, the combustion of biosludge mixtures with either 25% eucalyptus chips or eucalyptus bark may provide an attractive option for the utilization of industrial sludge as a renewable energy source.

References

Abbasi, T.; Abbasi, S. A. Biomass energy and the environmental impacts associated with its production and utilization. **Renewable and Sustainable Energy Reviews**, v.14, n.3, p.919-937, 2010.

Areprasert, C.; Coppola, A.; Urciuolo, M.; Chirone, R.; Yoshikawa, K.; Scala, F. The effect of hydrothermal treatment on attrition during the fluidized bed combustion of paper sludge. **Fuel Processing Technology**, v.140, p.57-66, 2015.

Aslan, A. The causal relationship between biomass energy use and economic growth in the United States. **Renewable and Sustainable Energy Reviews**, v.57, p.362-366, 2016.

Bianchini, A.; Bonfiglioli, L.; Pellegrini, M.; Saccani, C. Sewage sludge drying process integration with a waste-to-energy power plant. **Waste Management**, v.42, p.159-165, 2015.

CEN, European Committee for Standardization: **EN 15148**: Solid biofuels – Determination of volatile matter content. Brussels, Belgium, 2009a.

CEN, European Committee for Standardization: **EN 14775**: Solid biofuels – Determination of ash content. Brussels, Belgium, 2009b.

CEN, European Committee for Standardization: **EN 14918**: Solid biofuels – Determination of calorific value. Brussels, Belgium, 2009c.

CEN, European Committee for Standardization: **EN 15104**: Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen - Instrumental methods. Brussels, Belgium, 2011a.

CEN, European Committee for Standardization: **EN 15289**: Solid biofuels – Determination of total content of sulfur and chlorine. Brussels, Belgium, 2011b.

Chen, J.; Mu, L.; Cai, J.; Yao, P.; Song, X.; Yin, H.; Li, A. Pyrolysis and oxy-fuel combustion characteristics and kinetics of petrochemical wastewater sludge using thermogravimetric analysis. **Bioresource Technology**, v.198, p.115-123, 2015.

Demirbas, M. F.; Balat, M.; Balat, H. Potential contribution of biomass to the sustainable energy development. **Energy Conversion and Management**, v.50, n.7, p.1746-1760, 2009.

Font, R.; Fullana, A.; Conesa, J. A.; Llavador, F. Analysis of the pyrolysis and combustion of different sewage sludges by TG. **Journal of Analytical and Applied Pyrolysis**, v.58-59, p.927-941, 2001.

Fournel, S.; Palacios, J. H.; Morissette, R.; Villeneuve, J.; Godbout, S.; Heitz, M.; Savoie, P. Influence of biomass properties on technical and environmental performance of a multi-fuel boiler during on-farm combustion of energy crops. **Applied Energy**, v.141, p.247-259, 2015.

Frei, K. M.; Cameron, D.; Stuart, P. R. Novel drying process using forced aeration through a porous biomass matrix. **Drying Technology**, v.22, n.5, p.1191-1215, 2004.

Frías, M.; Rodríguez, O.; Sánchez De Rojas, M. I. Paper sludge, an environmentally sound alternative source of MK-based cementitious materials. A review. **Construction and Building Materials**, v.74, p.37-48, 2015.

García, G.; Arauzo, J.; Gonzalo, A.; Sánchez, J. L.; Ábrego, J. Influence of feedstock composition in fluidised bed co-gasification of mixtures of lignite, bituminous coal and sewage sludge. **Chemical Engineering Journal**, v.222, p.345-352, 2013.

- Heikkinen, J. M.; Hordijk, J. C.; De Jong, W.; Spliethoff, H. Thermogravimetry as a tool to classify waste components to be used for energy generation. **Journal of Analytical and Applied Pyrolysis**, v.71, n.2, p.883-900, 2004.
- Hippinen, I.; Ahtila, P. Drying of activated sludge under partial vacuum conditions – an experimental study. **Drying Technology**, v.22, p.2119-2134, 2004.
- Jiang, J.; Du, X.; Yang, S. Analysis of the combustion of sewage sludge-derived fuel by thermogravimetric method in China. **Waste Management**, v.30, n.7, p.1407-1413, 2010.
- Kim, J. K.; Lee, H. D. Investigation on the combustion possibility of dry sewage sludge as a pulverized fuel of thermal power plant. **Journal of Industrial and Engineering Chemistry**, v.16, n.4, p.510-516, 2010.
- Kraft, D. L.; Orender, H. C. Considerations for using sludge as a fuel. **Tappi Journal**, v.76, n.3, p.175–183, 1993.
- Kudra, T.; Gawrzynski, Z.; Glaser, R.; Stanislawski, J.; Poirier, M. Drying of pulp and paper sludge in a pulsed fluid bed dryer. **Drying Technology**, v.20, p.917-933, 2002.
- Li, X. G.; Lv, Y.; Ma, B. G.; Jian, S. W.; Tan, H. B. Thermogravimetric investigation on co-combustion characteristics of tobacco residue and high-ash anthracite coal. **Bioresource Technology**, v.102, n.20, p.9783-9787, 2011.
- Magdziarz, A.; Werle, S. Analysis of the combustion and pyrolysis of dried sewage sludge by TGA and MS. **Waste Management**, v.34, n.1, p.174-179, 2014.
- Maiti, S.; Dey, S.; Purakayastha, S.; Ghosh, B. Physical and thermochemical characterization of rice husk char as a potential biomass energy source. **Bioresource Technology**, v.97, n.16, p.2065-2070, 2006.
- Mäkelä, M.; Geladi, P.; Larsson, S. H.; Finell, M. Pretreatment of recycled paper sludge with a novel high-velocity pilot cyclone: effect of process parameters on convective drying efficiency. **Applied Energy**, v.131, p.490-498, 2014.
- Méndez, A.; Fidalgo, J. M.; Guerrero, F.; Gascó, G. Characterization and pyrolysis behaviour of different paper mill waste materials. **Journal of Analytical and Applied Pyrolysis**, v.86, n.1, p.66-73, 2009.

Nakomcic-Smaragdakis, B.; Cepic, Z.; Dragutinovic, N. Analysis of solid biomass energy potential in Autonomous Province of Vojvodina. **Renewable and Sustainable Energy Reviews**, v.57, p.186-191, 2016.

Navaee-Ardeh, S.; Bertrand, F.; Stuart, P. R. Emerging biodrying technology for the drying of pulp and paper mixed sludges. **Drying Technology**, v.24, p.863-878, 2006.

Niu, S.; Chen, M.; Li, Y.; Xue, F. Evaluation on the oxy-fuel combustion behavior of dried sewage sludge. **Fuel**, v.178, p.129-138, 2016.

Otero, M.; Calvo, L. F.; Gil, M. V.; García, A. I.; Morán, A. Co-combustion of different sewage sludge and coal: A non-isothermal thermogravimetric kinetic analysis. **Bioresource Technology**, v.99, n.14, p.6311-6319, 2008.

Otero, M.; Díez, C.; Calvo, L. F.; García, A. I.; Morán, A. Analysis of the co-combustion of sewage sludge and coal by TG-MS. **Biomass and Bioenergy**, v.22, n.4, p. 319-329, 2002.

Park, Y. H.; Kim, J.; Kim, S. S.; Park, Y. K. Pyrolysis characteristics and kinetics of oak trees using thermogravimetric analyzer and micro-tubing reactor. **Bioresource Technology**, v.100, n.1, p.400-405, 2009.

Pronobis, M. The influence of biomass co-combustion on boiler fouling and efficiency. **Fuel**, v.85, n.4, p.474-480, 2006.

Seggiani, M.; Puccini, M.; Raggio, G.; Vitolo, S. Effect of sewage sludge content on gas quality and solid residues produced by cogasification in an updraft gasifier. **Waste Management**, v. 32, n.10, p.1826-1834, 2012.

Strezov, V.; Evans, T. J. Thermal processing of paper sludge and characterisation of its pyrolysis products. **Waste Management**, v.29, n.5, p.1644-1648, 2009.

Sutcu, M.; Akkurt, S. The use of recycled paper processing residues in making porous brick with reduced thermal conductivity. **Ceramics International**, v.35, n.7, p.2625-2631, 2009.

Vamvuka, D.; Salpigidou, N.; Kastanaki, E.; Sfakiotakis, S. Possibility of using paper sludge in co-firing applications. **Fuel**, v.88, n.4, p.637-643, 2009.

Werther, J.; Ogada, T. Sewage sludge combustion. **Progress in Energy and Combustion Science**, v.25, p.55-116, 1999.

Xie, Z.; Ma, X. The thermal behaviour of the co-combustion between paper sludge and rice straw. **Bioresource Technology**, v.146, p.611-618, 2013.

Yanfen, L.; Xiaoqian, M. Thermogravimetric analysis of the co-combustion of coal and paper mill sludge. **Applied Energy**, v.87, n.11, p.3526-3532, 2010.

Yu, Y. H.; Kim, S. D.; Lee, J. M.; Lee, K. H. Kinetic studies of dehydration, pyrolysis and combustion of paper sludge. **Energy**, v.27, n.5, p.457-469, 2002.

CHAPTER III

THERMAL DRYING OF INDUSTRIAL SLUDGE USING FORCED AERATION

Abstract

This study investigated an industrial biosludge drying system using hot gases from a coal furnace, aimed increasing the solids content of the biosludge to above 50% (w.b.), considered suitable for combustion in biomass boilers. Biosludge was collected from a paper mill activated sludge plant. Mixtures of biosludge with eucalyptus chips and with eucalyptus bark in two different proportions (15% and 25%), were pile up, on a drying chamber. Hot gases generated by the furnace, with a flowrate of $0.64 \pm 0.02 \text{ m}^3 \cdot \text{s}^{-1}$ at $100 \pm 20^\circ\text{C}$, were applied to the piles through a blowing system. The results demonstrated that the mixture of 75% biosludge and 25% eucalyptus bark achieved the best drying ratio, increasing the total solids content from 31 to 72%, in a 5 hour drying interval. Nevertheless, all other treatments with addition of bulking agent reached solids content above 50%, confirming the positive effect of adding dried material to the sludge. These results indicate a potential use of hot gases that are currently available and released into the atmosphere by paper mills.

Keywords: biomass, biosludge, energy recovery, moisture reduction, sludge drying.

1. Introduction

The generation of large amounts of sewage and industrial sludge from wastewater treatment plants (WTP) is becoming a worldwide environmental problem. Management practices and the appropriate final disposal of the sludge should minimize odor, chemical and biological contamination, as well as energy and transportation costs. Above all, it should be environmentally and economically feasible. The highest operational costs of WTP are related to sludge treatment and disposal (Ruiz and Wisniewski, 2008; Wei *et al.*, 2013). In sludge treatment, the dewatering and drying processes play a major role, since the sludge volume reduction facilitates handling and decreases transportation and final disposal costs (Léonard *et al.*, 2004; Chai, 2007; Bennamoun *et al.*, 2013).

In general, the behavior of a water molecule during the sludge drying process is widely dependent on its proximity to the solid (Vaxelaire and Cézac, 2004). Water within the sludge can be classified into four groups: (i) free water that is not attached to the sludge particles and can be removed by gravitational settling (Bennamoun, 2012; Vaxelaire and Cézac, 2004); (ii) interstitial water that is trapped within the flocs or occurs in the capillaries of the dewatered cake (Bennamoun, 2012; Vaxelaire and Cézac, 2004) and can be removed by strong mechanical dewatering (Novak, 2006); (iii) surface water that is held on the surface of the solid particles by adsorption and adhesion (Vaxelaire and Cézac, 2004), and can only be removed through drying mechanisms (Novak, 2006); and (d) intracellular and chemically bounded water that can be removed only at high temperature drying processes (Novak, 2006).

The amount of water that can be removed depends on the dewatering and drying processes and also how the water is available into the sludge. Mechanical dewatering processes are generally accomplished by centrifuges, filters or pressing devices and enable the removal of free, interstitial and some of the surface water present in the sludge (Chen *et al.*, 2002). Depending on the sludge type and dewatering unit conditions, it can reach maximum dry solids contents of 18-50% (Mäkelä *et al.*, 2014; Stoica *et al.*, 2009). On the other hand, thermal drying processes can achieve solids contents above 95% (Bennamoun, 2012), and enable the removal of intracellular and chemically bounded water from sludge suspensions, but may result in an exponential

increase of energy consumption (Mäkelä *et al.*, 2014; Chen *et al.*, 2002; Leonard *et al.*, 2002).

In recent years, several studies have been reported to find a more efficient, sustainable and low cost method for sludge drying. Some examples are fry-drying technology, immersion of wet sludge in a hot oil bath (Ohm *et al.*, 2009; Ohm *et al.*, 2010; Wu *et al.*, 2012; Chang *et al.*, 2013; Chae *et al.*, 2016); bio-drying, alternative composting method for reduction of moisture content (Frei *et al.*, 2004; Navaee-Ardeh *et al.*, 2006; Navaee-Ardeh *et al.*, 2010; Zhao *et al.*, 2010; Cai *et al.*, 2012; Winkler *et al.*, 2013); application of solar energy as heat source (Salihoglu *et al.*, 2007; Slim *et al.*, 2008; Mathioudakis *et al.*, 2009 e Ferreira *et al.*, 2014), convective drying under high airflow (Hayashi and Shimada, 2006; Lee and Cho, 2010; Lähdeniemi *et al.*, 2013; Mäkelä *et al.*, 2014).

Other studies have investigated processes for converting sludge into energy source through integrated techniques of drying and thermochemical processes such as combustion, incineration and pyrolysis (Han *et al.*, 2012; Li *et al.*, 2014b; Bianchini *et al.*, 2015).

The present study proposed and investigated a biosludge drying system using hot gases from a direct coal-fired furnace as the drying energy source, with the objective of increasing the solids content of the biosludge to above 50% (w.b.), considered adequate for combustion in biomass boilers (Kraft and Orender, 1993; Werther and Ogada, 1999; Kudra *et al.*, 2002; Frei *et al.*, 2004).

2. Material and methods

The experimental setup is illustrated in Figure 1 and consists of four stages: (i) sampling and characterization of the biosludge and bulking agents (eucalyptus chips and bark); (ii) setup of the drying system; (iii) process operation; and (iv) sampling and analysis.

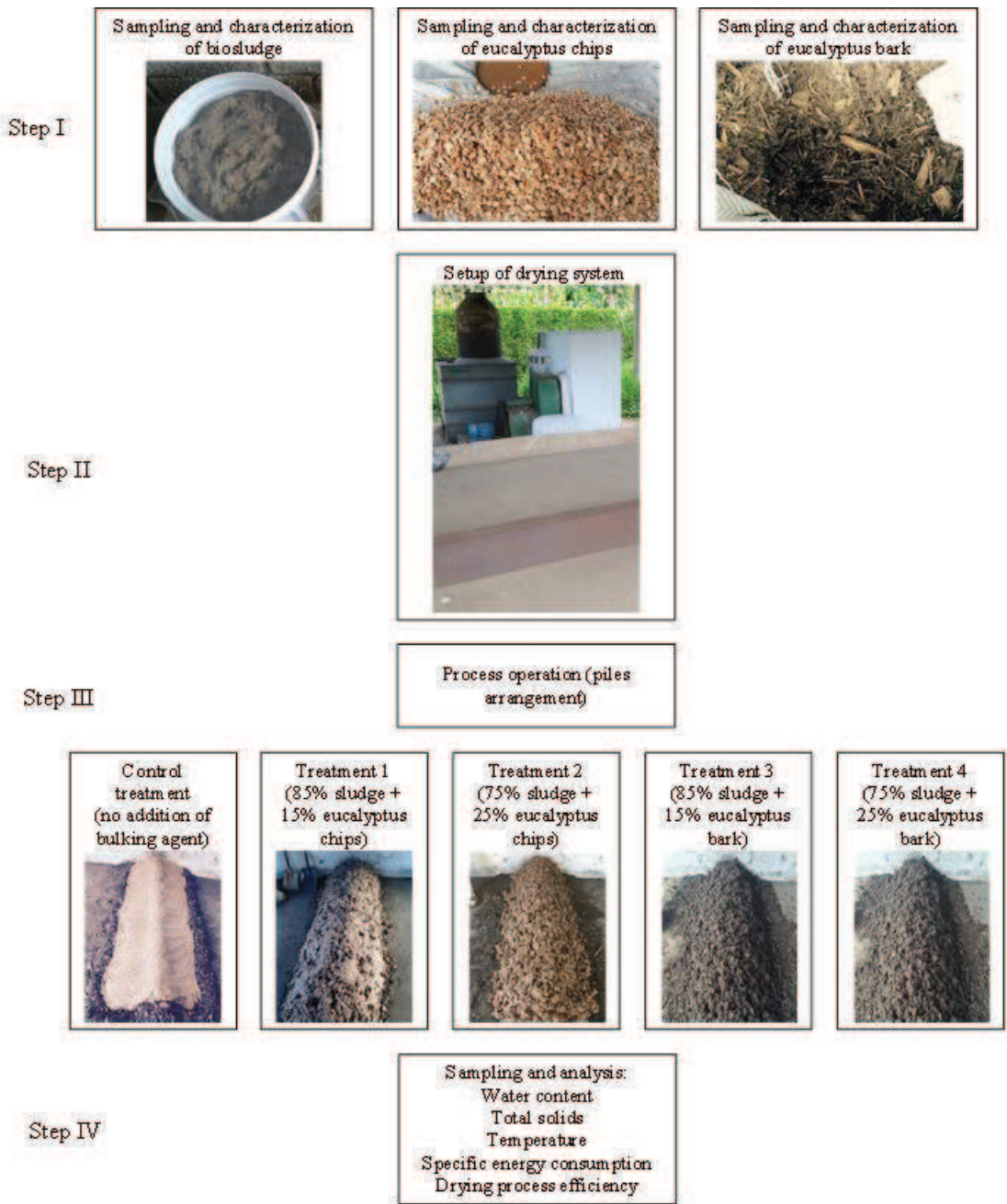


Figure 1 – Experimental setup.

2.1. Biosludge, eucalyptus chips and bark

The biosludge was obtained from an activated sludge system in a paper mill effluent treatment, with the capacity to treat $720 \text{ m}^3 \cdot \text{d}^{-1}$ and generate $5 \text{ t} \cdot \text{d}^{-1}$ of biosludge with a solids content of 15% after dewatering in a centrifuge.

Eucalyptus (*Eucalyptus* sp.) chips and bark were used as bulking agents to confer structure and porosity to the sludge, each one in the proportions of 15% and 25% of the

total mass of sludge to be dried (150 kg). Four treatments and a control with three replicates each were carried out (Table 1).

Table 1 – Treatments performed for biosludge drying.

Treatments	Bulking agent	Biosludge proportion (%)	Bulking agent proportion (%)
Control	-	100	0
Treatment 1	Eucalyptus chips	85	15
Treatment 2	Eucalyptus chips	75	25
Treatment 3	Eucalyptus bark	85	15
Treatment 4	Eucalyptus bark	75	25

The characterization of the biosludge and eucalyptus chips and bark was performed through the following analyses: moisture and total solids contents (APHA *et al.*, 2012); bulk density according to EN 15103 (CEN, 2009a); bulk porosity (Embrapa, 2011); elementary chemical composition, including carbon, hydrogen, nitrogen and sulfur in accordance to EN 15104 (CEN, 2011a) and EN 15289 (CEN, 2011b), and oxygen, measured by the difference of C, H, N, S and ash from 100; immediate chemical analysis, specially, volatile matter and ash content based on EN 15148 (CEN, 2009b) and EN 14775 (CEN, 2009c), and fixed carbon, calculated from the difference of moisture, ash and volatile matter; higher heating value, according to EN 14918 (CEN, 2009d), and lower and net heating values, calculated using the Equations 1 and 2, respectively.

$$LHV = HHV - \left[600 \left(\frac{9H}{100} \right) \right] \quad (1)$$

$$NHV = LHV \left(\frac{100-W}{100} \right) - (6W) \quad (2)$$

Where:

HHV = higher heating value (kcal.kg⁻¹);

LHV = lower heating value (kcal.kg⁻¹);

NHV = net heating value (kcal.kg⁻¹);

H = hydrogen content (%);

W = moisture content (% w.b.).

2.2. Drying apparatus and process operation

The drying experiments were carried out in a method that uses a ventilation system with gas heated by a charcoal furnace. The system consisted of a direct coal-fired coal, a cyclone, a fan coupled to an electric engine, and a drying chamber composed of a terrace (5.0 x 2.0 m), a distribution duct and an aeration diffuser (Figure 2).

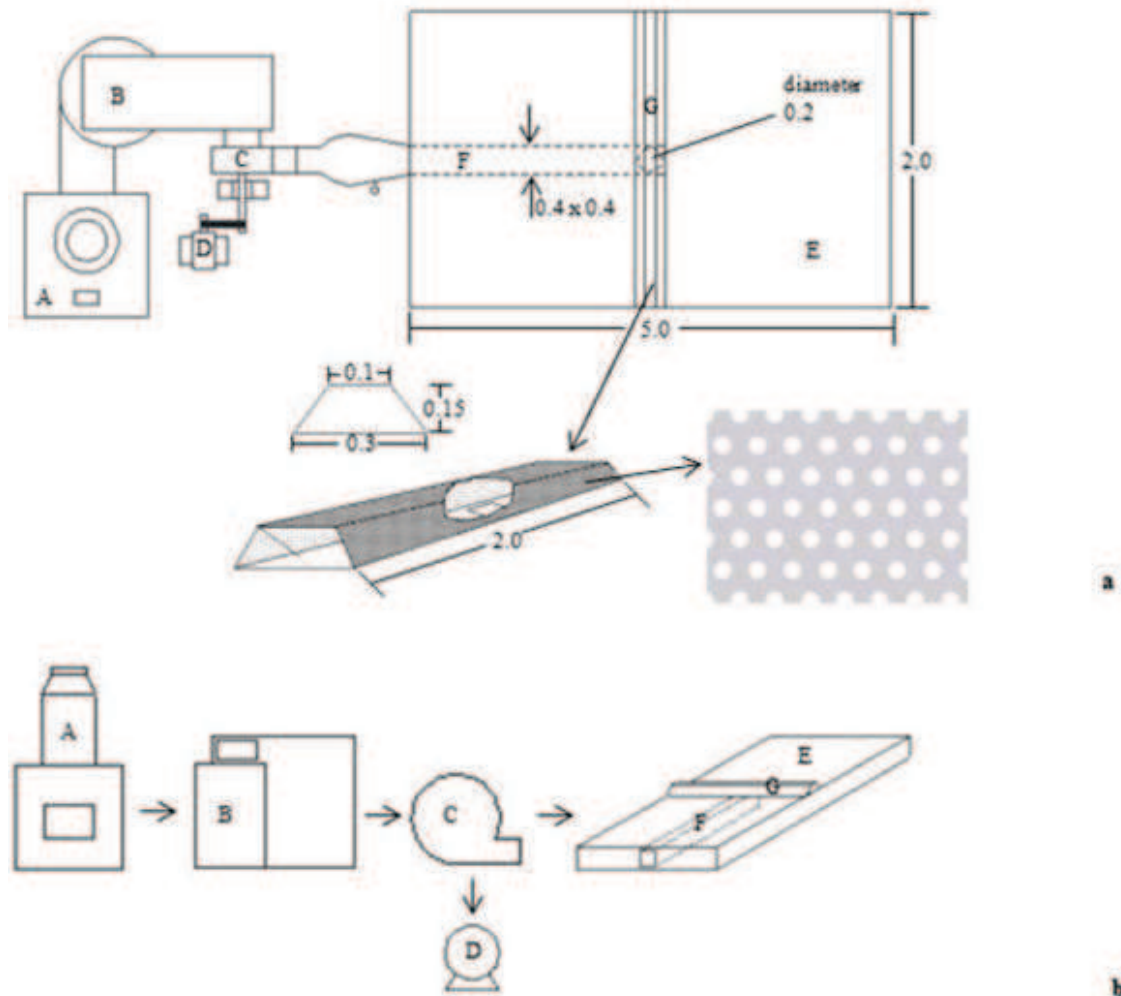


Figure 2 – Drying system. (a) Plant and (b) flowchart: (A) direct fired coal furnace; (B) cyclone; (C) fan; (D) electric engine; (E) terrace; (F) distribution duct; (G) aeration diffuser.

The heated gas distribution was carried out in a duct installed in the center of the terrace with a circular exit of 200 mm in diameter. Above the circular exit there was a trapezoidal shaped metal aeration diffuser (300 mm base, 100 mm top and 150 mm height) as showed in Figure 2G. The diffuser had 23% of its area perforated with 2 mm diameter holes. The piles were built over the gas diffusers.

Coupled to the distribution duct there was a centrifugal fan driven by an electric engine with a power of 5 hp (3.7 kW) and working at 1,780 rpm, which provided a hot gas flow of $0.64 \pm 0.02 \text{ m}^3 \cdot \text{s}^{-1}$. This centrifugal fan withdrew the hot gas from a duct of a coal furnace at the coal furnace at a temperature of $100 \pm 20^\circ\text{C}$ and forced its passage through the piles of biosludge and bulking agents. In all treatments, the system operated during 5 hours.

The initial mass and length of the piles were set to 150 kg and 2.0 m, respectively. Their height and superficial area varied depending on the type of treatment, due to the difference of bulk density and mixture proportion of the eucalyptus chips and bark. Table 2 and Figure 3 present the major physical characteristics of the piles.

Table 2 – Initial mass and piles dimension for biosludge drying.

Parameter	Control Treatment	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Initial mass of mixture (kg)	151.2 ± 0.7	150.2 ± 0.3	150.2 ± 0.1	150.5 ± 0.3	150.5 ± 0.3
Initial pile length (m)	2.00 ± 0.00	2.00 ± 0.00	2.00 ± 0.00	2.00 ± 0.00	2.00 ± 0.00
Initial pile height (cm)	20.3 ± 0.76	25.7 ± 1.53	37.5 ± 2.50	26.6 ± 0.12	28.9 ± 1.21
Initial pile area (m^2)	2.93 ± 0.02	2.92 ± 0.02	3.60 ± 0.08	2.98 ± 0.06	3.17 ± 0.05

Note: Control treatment: no addition of bulking agent; Treatment 1: 15% eucalyptus chips; Treatment 2: 25% eucalyptus chips; Treatment 3: 15% eucalyptus bark; Treatment 4: 25% eucalyptus bark.

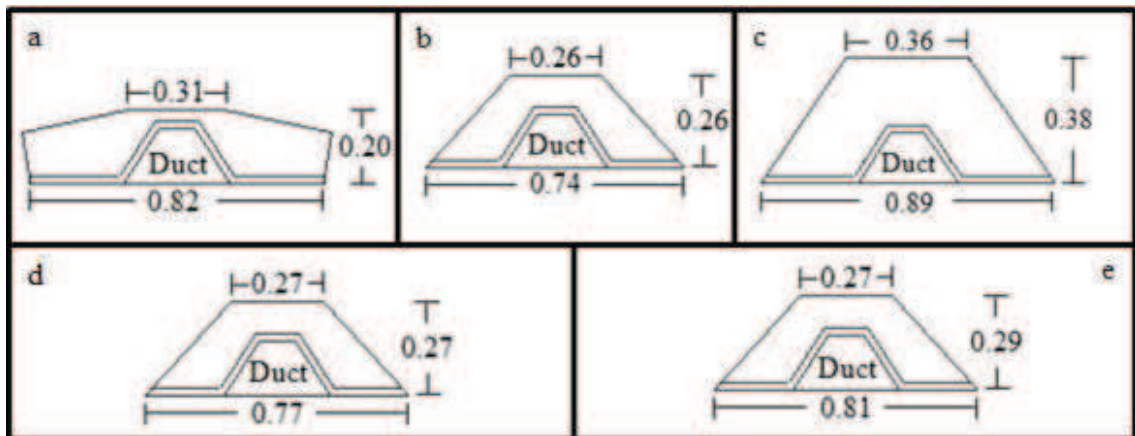


Figure 3 – Transverse view of each pile: (a) Control treatment; (b) Treatment 1; (c) Treatment 2; (d) Treatment 3; (e) Treatment 4.

Figure 4 shows the piles of each treatment arranged on the drying chamber. The control pile (Figure 4a) was involved with an eucalyptus bark border, in order to retain the sludge in the drying chamber.

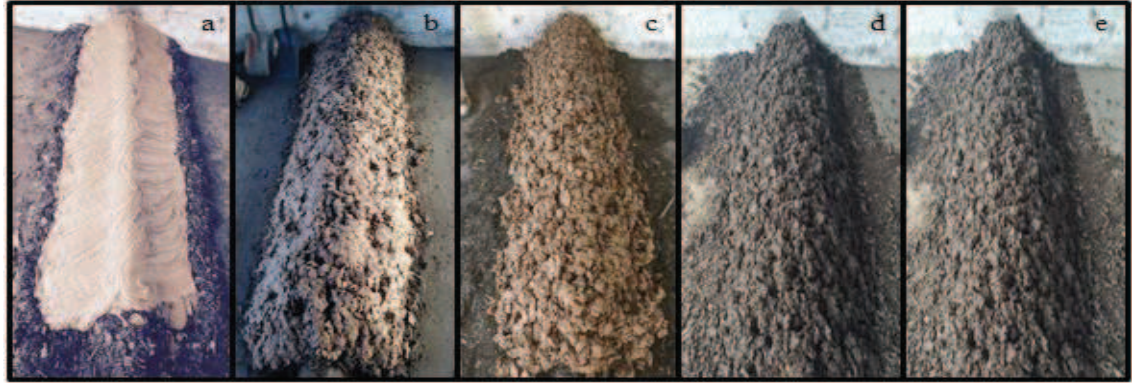


Figure 4 – Photos of each pile: (a) Control treatment; (b) Treatment 1; (c) Treatment 2; (d) Treatment 3; (e) Treatment 4.

2.3. Sampling and analysis

During the drying system operation, the ambient and the drying fluid and piles temperatures were measured every 30 minutes, using HIGHMED HM-600 thermometers. The piles temperatures were measured at 15 points, with the thermometers located 5cm deep at the top, middle and bottom of the piles. The water content, before and after drying, as well as the final total solids content of the biosludge mixtures were determined by drying the samples at 105°C for 24h (APHA *et al.*, 2012). The consumption of charcoal used in each treatment was determined by a platform scale with capacity of 100kg and precision of 0.1kg. For the determination of the electric energy consumption, the three-phase clock electric meter Nansen Model PN5D-G was used. The specific energy consumption and the drying process efficiency were calculated through the Equations 3 and 4, respectively (Lopes *et al.*, 2008).

$$SEC = \frac{EE + (CC \times HHV)}{M_{evap}} \quad (3)$$

$$DE = \frac{M_{evap} \times h_{ev}}{EE + (CC \times HHV)} \times 100 \quad (4)$$

Where:

SEC = specific energy consumption (kJ.kg⁻¹);

EE = electricity consumption (kJ);

CC = charcoal consumption (kg);

HHV = higher heating value (kJ.kg⁻¹);

M_{evap} = mass of water evaporated inform the sludge (kg);

h_{ev} = vaporization latent heat of water (kJ.kg⁻¹);

DE = drying efficiency (%).

2.4. Statistical analysis

The experiments were carried out in a completely randomized design, where the treatments were arranged in a factorial scheme with additional treatment [(2x2) + 1] with three replicates: two types of bulking agents (eucalyptus chips and eucalyptus bark), two proportions of bulking agents (15% and 25%), and a control treatment without addition of bulking agent. The parameters analyzed statistically were moisture reduction, final total solids content in the biosludge mixture pile, specific energy consumption and drying efficiency. The data were submitted to variance analysis for all parameters, using the F test. The analysis included the contrast of the control treatment with the others, as well as the study of the interaction between the two types of bulking agents and their different proportion by using the Dunnett and Tukey tests, respectively. All analyzes were performed using the statistical software Statistica®, at the significance level of 5%.

3. Results and discussion

3.1. Biosludge, eucalyptus chips and bark

The characteristics of the biosludge, eucalyptus chips and bark and mixtures are shown in Table 3. All parameters were measured on dried materials with a moisture level of 10% (w.b.), except for moisture and total solids contents, bulk density and net heating value.

The biosludge and mixtures of treatments 1, 2, 3 and 4 had high moisture content; therefore the pre-drying of these materials was essential to enable their energetic use because of the effect of this parameter on the heating value. The combustion reaction is exothermic and the evaporation of water is strongly endothermic, so the autothermal limit (self-supporting combustion) (Jenkins *et al.*, 1998) for sludge is around 50% moisture content (w.b.) (Kraft e Orender, 1993; Werther e Ogada, 1999; Kudra *et al.*, 2002; Frei *et al.*, 2004). Above this critical moisture content, there is not sufficient energy from combustion to evaporate the water and heat the product, requiring a supplemental fuel, such as natural gas, and as consequence, CO and other products from incomplete combustion may be emitted in greater quantities (Jenkins *et al.*, 1998).

Table 3 – Characteristics of materials and mixtures.

Parameters	Biosludge	Eucalyptus chips	Eucalyptus bark	Mixture Treatment 1	Mixture Treatment 2	Mixture Treatment 3	Mixture Treatment 4
Moisture (% w.b.)	86.62 ± 0.74	14.54 ± 0.51	12.26 ± 0.25	74.24 ± 1.67	69.26 ± 0.29	74.16 ± 1.58	65.34 ± 2.80
Moisture (% d.b.)	735.9 ± 58.3	17.25 ± 0.29	13.97 ± 0.32	289.4 ± 26.2	225.3 ± 3.02	287.5 ± 24.7	189.7 ± 22.4
Total solids (%)	12.00 ± 0.85	85.46 ± 0.51	87.74 ± 0.25	25.76 ± 1.67	30.74 ± 0.29	25.87 ± 1.60	34.66 ± 2.80
Bulk density (kg.m ⁻³)	1089 ± 8.17	151.0 ± 4.72	149.4 ± 7.20	930.8 ± 7.20	647.0 ± 3.60	823.9 ± 2.72	540.9 ± 10.9
Porosity (%)	42.92 ± 0.06	73.03 ± 0.01	74.07 ± 0.05	47.43 ± 0.06	50.45 ± 0.04	47.59 ± 0.06	50.70 ± 0.05
Volatile matter (%)	65.06 ± 1.32	87.32 ± 0.01	81.21 ± 0.22	67.84 ± 0.06	69.49 ± 0.54	67.61 ± 0.55	69.21 ± 0.50
Fixed carbon (%)	0.623 ± 0.63	12.46 ± 0.03	15.23 ± 0.30	2.143 ± 1.12	4.424 ± 0.61	1.283 ± 0.70	2.230 ± 0.38
Ash content (%)	34.32 ± 0.69	0.219 ± 0.04	3.563 ± 0.08	29.93 ± 0.44	26.09 ± 1.15	31.11 ± 1.25	28.65 ± 0.62
C (%)	22.85 ± 0.21	49.55 ± 0.21	46.35 ± 0.21	30.60 ± 1.13	31.15 ± 0.35	32.20 ± 0.14	36.40 ± 0.28
H (%)	2.330 ± 0.08	6.000 ± 0.01	5.300 ± 0.03	3.320 ± 0.16	3.380 ± 0.07	3.520 ± 0.06	4.245 ± 0.06
O (%)	37.09 ± 0.37	43.03 ± 0.24	43.66 ± 0.15	34.88 ± 0.60	36.60 ± 0.81	30.62 ± 1.55	27.46 ± 0.13
N (%)	2.200 ± 0.06	0.439 ± 0.00	0.360 ± 0.01	1.720 ± 0.07	1.570 ± 0.04	1.625 ± 0.09	1.120 ± 0.10
S (%)	1.210 ± 0.03	0.759 ± 0.01	0.769 ± 0.00	0.836 ± 0.01	1.215 ± 0.05	0.923 ± 0.02	0.840 ± 0.01
HHV (MJ.kg ⁻¹)	10.34 ± 0.05	19.41 ± 0.05	18.46 ± 0.28	11.51 ± 0.06	12.04 ± 0.01	11.36 ± 0.05	11.44 ± 0.17
LHV (MJ.kg ⁻¹)	9.808 ± 0.70	18.05 ± 0.44	17.26 ± 0.28	10.76 ± 0.09	11.28 ± 0.00	10.57 ± 0.03	10.48 ± 0.15
NHV (MJ.kg ⁻¹)	0.347 ± 0.02	15.06 ± 0.04	14.83 ± 0.24	3.548 ± 0.04	5.403 ± 0.00	6.836 ± 0.02	6.828 ± 0.11

Note: Treatment 1: 15% wood chips; Treatment 2: 25% wood chips; Treatment 3: 15% eucalyptus husks; Treatment 4: 25% eucalyptus husks.

HHV = higher heating value; LHV = lower heating value; NHV = net heating value.

The material density is inversely proportional to its porosity, i.e., the higher the material density, the lower its porosity and, therefore, the lower its drying capacity.

The higher volatile matter was found for the eucalyptus chips and bark, which presented average over 80%, indicating that those materials are easier to ignite and burn, although their combustion is expected to be fast and difficult to control (Werther *et al.*, 2000). Although the volatile matter contents of the biosludge and mixtures of treatments 1, 2, 3 and 4 were lower than those found for the eucalyptus chips and bark, they were similar to values obtained for other biomasses used for combustion, such as sunflower husk (69.1%), mustard husk (68.6%), soya husk (69.6%), groundnut shell (68.1%), coffee husk (64.6%) (Werther *et al.*, 2000), rice hulls (63.5%), rice straw (65.5%) (Jenkins *et al.*, 1998), and wheat straw (68.3%) (Kijo-Kleczkowska *et al.*, 2016).

The ash is an inert material and does not contribute to the total heat released by combustion, i.e., it reduces the heating value of the material (Avelar *et al.*, 2016). It was observed that the biosludge and the mixtures had high ash content, which can cause, according to Costa *et al.* (2016), problems during combustion and in equipment maintenance, increase particle emission, and decrease process efficiency.

The carbon and hydrogen contents were higher for the mixtures of treatments 1, 2, 3 and 4, and the oxygen content was lower, compared to the biosludge. According to Obernberger *et al.* (2006) carbon and hydrogen are elements that positively contribute to heating value, while the oxygen contributes negatively as a fuel component; however, the presence of oxygen contributes to oxidation reactions, acting as a combustive. The hydrogen content can also influence the LHV due to the formation of water (Batistella *et al.*, 2015; Virmond *et al.*, 2011).

The nitrogen and sulfur contents are very important for evaluating possible polluting gas emissions. Both N and S contents were higher for the biosludge and the mixtures, which could mainly form, during combustion, gaseous N₂ and nitric oxides (NO, NO₂), and gaseous SO₂ and alkali or earth-alkali sulfates (Obernberger *et al.*, 2006).

It was observed that the heating values were higher for the bulking agents, compared to the biosludge and mixtures. This occurs because the C and H contents tend to increase the heating value while the ash and moisture contents decrease it. The heating values of the biosludge and mixtures were similar to sewage sludge, which is commonly used in

energy conversions (Calvo *et al.*, 2013; Chirone *et al.*, 2008; Jiang *et al.*, 2010; Kijokleczkowska *et al.*, 2015; Bianchini *et al.*, 2015).

According to the results presented in Table 3, the addition of bulking agents improved the physical and chemical characteristics of the biosludge, increasing the porosity, heating values, volatile matter, fixed carbon, carbon and hydrogen contents, and decreasing the ash, nitrogen and sulfur contents. Therefore, the mixture of dried sludge and a bulking agent are potential fuel for biomass boilers.

3.2. Temperature distribution

Figure 5 shows the temperature variation of the ambient air, hot gas and into the piles. The temperature profiles were generally even, and the temperature differences were slight among the treatments. The hot gas temperature in each treatment varied from 80°C to 120°C, considering that the water in sludge can be removed by drying at temperatures around the water evaporation temperature (between 100°C and 105°C) (Bianchini *et al.*, 2015). The piles temperatures were not influenced by ambient temperature.

As the pile was placed in the drying chamber, heat from hot gas was rapidly directly transferred into sludge raising sludge sample temperature and evaporating water content, as well reported by Deng *et al.* (2015). The temperatures of the piles increased in the beginning of the drying process and tended to a steady value, as observed by Huang *et al.* (2016) during hot air forced convective drying of sewage sludge, and Deng *et al.* (2009) evaluating sewage sludge in a paddle dryer.

The temperature of the control treatment pile was the lowest among all treatments, due to the high density (1089 kg.m⁻³) and low porosity (42.92%) of the sludge, which hampered the passage of the hot gas. As bulking agents were added to the sludge, the pile temperature increased, i.e., the bulking agents increased the sludge porosity, permitting the gas flow to diffuse easily in the gaps and macropores, as verified by Han *et al.* (2012). The positive effect of adding dried material to the sludge was also observed by Léonard *et al.* (2008) during the sewage sludge drying in discontinuous pilot-scale dryer with drying air temperature of 105°C.

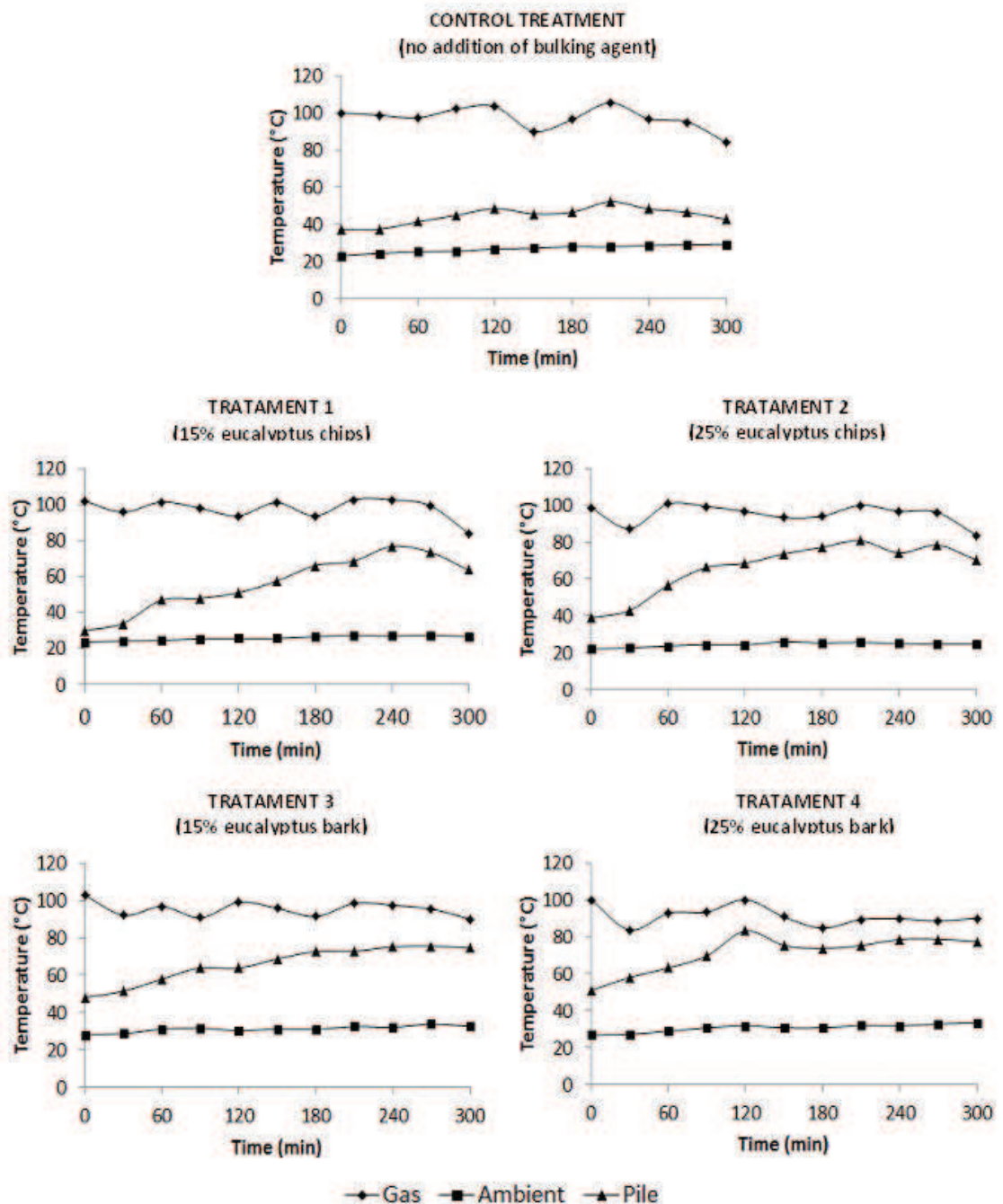


Figure 5 – Temperature profiles of Control treatment, Treatment 1, Treatment 2, Treatment 3 and Treatment 4.

3.3. Biosludge mixture drying

Table 4 presents the average values of moisture reduction during biosludge drying. The variance analysis shows that there is an effect of the interaction between the type of bulking agent and its proportion. The moisture reduction reflects the amount of water evaporated during the biosludge drying and depends on the pile temperature. As shown in Fig. 5, the pile temperatures varied from 37 to 52°C for the control treatment (no

addition of bulking agent); 30 to 77°C for Treatment 1 (15% eucalyptus chips); 39 to 81°C for Treatment 2 (25% eucalyptus chips); 48 to 76°C for Treatment 3 (15% eucalyptus bark) and 51 to 83°C for Treatment 4 (25% eucalyptus bark). Higher temperatures in the piles with a higher proportion of bulking agents were observed, and thus there was higher moisture reduction in those piles were therefore obtained. Treatments 2 and 4 seem to have higher heating rate, according to the pile temperature, that can be explained by the higher bulk porosity, which allow a higher gas flowrate. Also, only Treatment 1 was statistically similar to the control treatment.

Table 4 – Average values of the moisture reduction (%) of biosludge as a function of the bulking agent and proportion of bulking agent.

Proportion of bulking agent (%)	Bulking agent	
	Eucalyptus chips	Eucalyptus bark
15	19,90 Ab	31,52* Bb
25	40,76* Ba	58,78* Aa
Control treatment ¹	10,63	

Note: The mean values followed by at least one capital letter in the column and one lowercase letter in the line did not differ from each other at 5% of probability by the “Tukey” Test.

*They differ from the control treatment, at 5% of probability by the “Dunnett” test.

¹Biosludge pile without addition of bulking agent.

These results were somehow expected once the bulking agents increase the porosity of the piles and allow a broader distribution of the hot gases and also help the evaporation of the water within the biosludge. As stated by Léonard *et al.* (2008), the addition of dry products gives a sludge bed with higher permeability. Indeed, according to the classical permeability-porosity relation, Kozeny-Carman equation, describing the pressure drop of fluid flowing through a porous media, permeability is an increasing function of porosity (Léonard *et al.*, 2008).

Nevertheless, a moisture reduction was two-fold higher when 25% of bulking agents were mixed to the biosludge, which supports the importance of the incorporation of these materials to the sludge drying system. The reduction of sludge moisture decreases the costs associated with sludge transportation and treatment and mostly increases significantly the low heating value of the sludge, turning it into a much better fuel.

Li *et al.* (2014a) studied the convective drying of wastewater sludges and sawdust/sludge mixtures, and observed that higher sawdust addition increased moisture reduction.

The incorporation of eucalyptus bark into the sludge improved moisture reduction when compared to the addition of eucalyptus chips. A possible explanation for this fact is that eucalyptus bark has smaller particles and greater porosity than the eucalyptus chips. According to Lee and Cho (2010), the water content decreases with decreasing particle size due to the higher surface area to volume ratio.

The results found for the treatments with incorporation of eucalyptus bark were similar to those obtained in other studies using different types of sludge and drying systems. Lee and Cho (2010) studied sewage sludge drying through hot air injection (80°C), with initial moisture content in the range of 80-85%, and obtained a moisture reduction of 33.5%. Adamiec (2002) evaluated the drying of malt and beer industry sludge with initial moisture content of 76%, in a fluidized bed drier and drying temperature of 80-100°C, and obtained moisture reduction of 50-60%.

The average values of final total solids content of the biosludge mixture pile, specific energy consumption and dryer efficiency are presented in Table 5. According to the variance analysis, the interaction between the type of bulking agent and the amount incorporated to the biosludge had no effect on these parameters. The type of bulking agent did not significantly affect the final total solids content of the sludge mixture, although greater content was found in the piles with eucalyptus bark.

Table 5 – Average values of the final total solids content (FTS), specific energy consumption (SEC) and drying efficiency (DE) of biosludge mixtures, as a function of the bulking agent and proportion of bulking agent.

Effect	Variable	FTS (%)	SEC (kWh.kg ⁻¹)	DE (%)
Bulking agent	Eucalyptus chips	58.56* a	1.17 a	61.79 a
	Eucalyptus bark	64.63* a	1.14 a	62.69 a
Proportion of bulking agent	15%	51.52* a	1.21 a	59.63 a
	25%	71.76* b	1.11 a	64.85 a
Control treatment ¹	---	23.21	1.33	55.27

Note: The mean values followed by at least one capital letter in the column and one lowercase letter in the line did not differ from each other at 5% of probability by the “Tukey” Test.

*They differ from the control treatment, at 5% of probability by the “Dunnett” test.

¹Biosludge pile without addition of bulking agent.

On the other hand, the proportion of bulking agent incorporated to the biosludge significantly affected the total solids content after drying. A higher solids content was observed for the proportion of 25%, when compared to 15% and to the control treatment (0%). Hippinen and Ahtila (2004) also achieved a final solids content of 70% when drying pulp and paper sludge in a rotary evaporator at temperatures of 70 to 90°C.

The final total solids content of control was statistically different from all other treatments and did not reach the minimum solids content of 50% appropriated for combustion (Kraft and Orender, 1993; Werther and Ogada, 1999; Kudra *et al.*, 2002; Frei *et al.*, 2004). The other treatments reached solids content above 50%, with values similar to those found by Mäkelä *et al.* (2014) for the drying of recycled paper sludge using a high-velocity cyclone with air drying temperature of 90°C.

The specific energy consumption is an intensive parameter (i.e. per unit mass) which represents the amount of energy from fuel (charcoal) required for heating the drying gas, and the electricity required to drive the fan, required to remove the water in the biosludge mixture. The dryer process efficiency is the ratio between the amount of energy required to remove water and the total energy used by the dryer. In this study, both parameters were not affected by the proportion and type of bulking agent used.

According to Table 5, the energy consumption between 1.11 and 1.33 kWh.kg⁻¹ was required to remove the water content from the piles. According to Bennamoun *et al.* (2013), convective belt dryers operate at a specific energy consumption of 0.70 to 1.14 kWh.kg⁻¹, whereas consumptions of as 0.90 to 1.10 kWh.kg⁻¹ and 1.20 to 1.40 kWh.kg⁻¹ are usual for drum and flash dryers, respectively. Mäkelä *et al.* (2014) found a total specific energy consumption of 1.50 to 3.10 kWh.kg⁻¹ to obtain a dried sludge with solids content above 50%. For all treatments, the drying process efficiency was higher than 50%. Krawczyk and Badyda (2011) also found efficiency higher than 50% for the solar drying wastewater sludge. Lee and Cho (2010) obtained 60% of efficiency during the heat-drying sewage sludge.

In general, the type of bulking agent used did not affect the parameters analyzed; however, mixtures of biosludge and eucalyptus bark presented higher moisture reduction and final total solids content. The addition of a bulking agent to the biosludge mixture increased the moisture reduction, the final solids content in the mixture and the drying process efficiency, and reduced the specific energy consumption, with better results found for the proportion of 25%.

4. Conclusions

The proposed drying system has been proved to be very promising when a bulking agent was added to the biosludge, since the addition of eucalyptus chips and bark raised

the piles temperature and consequently increased the drying rate and water evaporation. The bulking agents also increased the organic matter content and the heating value, which is useful for further combustion processes.

During the drying process, the mixture of biosludge with 25% of eucalyptus bark presented higher moisture reduction, final total solids content and drying process efficiency, as well as lower specific energy consumption.

The great advantages of using this drying system to dry sludge is the easy operation, low maintenance and operating costs, in contrast verified in many mechanical dryers. Furthermore, the sludge moisture reduction to values considered adequate for combustion it is possible.

The attained results are a significant step in the development of drying methods capable of utilizing secondary energy (gases released from boilers), potentially available in industrial environments.

A study of the technical and feasibility of the implementation of the biosludge drying system in paper and packing industries is a suggestion for future work.

References

Adamiec, J. Drying of waste sludges in a fluidized bed dryer with a mixer. **Drying Technology**, v.20, n.4-5, p.839-853, 2002.

APHA, American Public Health Association; AWWA, American Water Works Association; WEF, Water Environment Federation. **Standard methods for the examination of water and wastewater**. 22. ed. Baltimore: APHA, 2012.

Avelar, N. V.; Rezende, A. A. P.; Carneiro, A. C. O.; Silva, C. M. Evaluation of briquettes made from textile industry solid waste. **Renewable Energy**, v.91, p.417-424, 2016.

Batistella, L.; Silva, V.; Suzin, R. C.; Virmond, E.; Althoff, C. A.; Moreira, R. F. P. M.; José, H. J. Gaseous emissions from sewage sludge combustion in a moving bed combustor. **Waste Management**, n.46, p.430-439, 2015.

Bennamoun, L. Solar drying of wastewater sludge: A review. **Renewable and Sustainable Energy Reviews**, v.16, p.1061-1073, 2012.

Bennamoun, L.; Arlabosse, P.; Léonard, A. Review on fundamental aspect of application of drying process to wastewater sludge. **Renewable and Sustainable Energy Reviews**, v.28, p.29-43, 2013.

Bianchini, A.; Bonfiglioli, L.; Pellegrini, M.; Saccani, C. Sewage sludge drying process integration with a waste-to-energy power plant. **Waste Management**, v.42, p.159–165, 2015.

Cai, L.; Gao, D.; Che, T.; Liu, H.; Zheng, G.; Yang, Q. Moisture variation associated with water input and evaporation during sewage sludge bio-drying. **Bioresource Technology**, v.117, p.13-19, 2012.

Calvo, A. I.; Tarelho, L. A. C.; Teixeira, E. R.; Alves, C.; Nunes, T.; Duarte, M.; Coz, E.; Custodio, D.; Castro, A.; Artiñano, B.; Fraile, R. Particulate emissions from the co-combustion of forest biomass and sewage sludge in a bubbling fluidised bed reactor. **Fuel Processing Technology**, n.114, p.58-68, 2013.

Chae, J. S.; Choi, S. A.; Kim, Y. H.; Oh, S. C.; Ryu, C. K.; Ohm, T. I. Experimental study of fry-drying and melting system for industrial wastewater sludges. **Journal of Hazardous Materials**, v.313, p.78-84, 2016.

Chang, F. C.; Ko, C. H.; Wu, J. Y.; Wang, H. P.; Chen, W. S. Resource recovery of organic sludge as refuse derived fuel by fry-drying process. **Bioresource Technology**, v.141, p.240-244, 2013.

Chen, G.; Yue, P. L.; Mujumdar, A. S. Sludge dewatering and drying. **Drying Technology**, v.20, n.4-5, p.883-916, 2002.

Chirone, R.; Salatino, P.; Scala, F.; Solimene, R.; Urciuolo, M. Fluidized bed combustion of pelletized biomass and waste-derived fuels. **Combustion and Flame**, n.155, p.21-36, 2008.

CEN, European Committee for Standardization. **Solid biofuels – Determination of bulk density**. Brussels, 2009a.

CEN, European Committee for Standardization. **Solid biofuels – Determination of volatile matter content**. Brussels, 2009b.

CEN, European Committee for Standardization. **Solid biofuels – Determination of volatile ash content**. Brussels, 2009c.

CEN, European Committee for Standardization. **Solid biofuels – Determination of calorific value**. Brussels, 2009d.

CEN, European Committee for Standardization. **Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen – Instrumental methods**. Brussels, 2011a.

CEN, European Committee for Standardization. **Solid biofuels – Determination of total content of sulfur and chlorine**. Brussels, 2011b.

Costa, T. O.; Calijuri, M. L.; Avelar, N. V.; Carneiro, A. C. O.; Assis, L. R. Energetic potential of algal biomass from high rate algal ponds for the production of solid biofuels. **Environmental Technology**, v.1, n.1-34, 2016.

Ferreira, A. G.; Gonçalves, L. M.; Maia, C. B. Solar drying of a solid waste from steel wire industry. **Applied Thermal Engineering**, v.73, p.102-108, 2014.

Frei, K. M.; Cameron, D.; Stuart, P. R. Novel drying process using forced aeration through a porous biomass matrix. **Drying Technology**, v.22, n.5, p.1191-1215, 2004.

Font, R.; Gomez-Rico, M. F.; Fullana, A. Skin effect in the heat and mass transfer model for sewage sludge drying. **Separation and Purification Technology**, v.77, p.146-161, 2011.

Han, R.; Liu, J.; Zhang, Y.; Fan, X.; Lu, W.; Wang, H. Dewatering and granulation of sewage sludge by biophysical drying and thermo-degradation performance of prepared sludge particles during succedent fast pyrolysis. **Bioresource Technology**, v.107, p.429-436, 2012.

Hayashi, N.; Shimada, S. Study on drying organic sludges by thermal jet dryer – Part 1: Drying performance of thermal jet dryer. **Drying Technology**, v.24, p.1601-1607, 2006.

Hippinen, I.; Ahtila, P. Drying of activated sludge under partial vacuum conditions – an experimental study. **Drying Technology**, v.22, p.2119-2134, 2004.

- Huang, Y. W.; Chen, M. Q.; Jia, L. Assessment on thermal behavior of municipal sewage sludges thin-layer during hot air forced convective drying. **Applied Thermal Engineering**, v.96, p.209-216, 2016.
- Jenkins, B. M.; Baxter, L. L.; Miles Jr., T. R.; Miles, T. R. Combustion properties of biomass. **Fuel Processing Technology**, v.54, p.17-46, 1998.
- Jiang, J.; Du, X.; Yang, S. Analysis of the combustion of sewage sludge-derived fuel by a thermogravimetric method in China. **Waste Management**, v.30, p.1407-1413, 2010.
- Kraft, D. L.; Orender, H. C. Considerations for using sludge as a fuel. **Tappi Journal**, v.76, n3, p.175-183, 1993.
- Kijo-Kleczkowska, A.; Sroda, K.; Kosowska-Golachowska, M.; Musial, T.; Wolski, K. Combustion of pelleted sewage sludge with reference to coal and biomass. **Fuel**, v.170, p.141-160, 2016.
- Kijo-Kleczkowska, A.; Sroda, K.; Kosowska-Golachowska, M.; Musial, T.; Wolski, K. Mechanisms and kinetics of granulated sewage sludge combustion. **Waste Management**, v.46, p.459-471, 2015.
- Kudra, T.; Gawrzynski, Z.; Glaser, R.; Stanislawski, J.; Poirier, M. Drying of pulp and paper sludge in a pulsed fluid bed dryer. **Drying Technology**, v.20, p.917-933, 2002.
- Lee, J. E.; Cho, E. M. A study on air jet drying for water content reduction of sludges. **Korean Journal of Chemical Engineering**, v.27, n.6, p.1822-1828, 2010.
- Lähdeniemi, A.; Mäkelä, M.; Dahl, O. Drying/fractionation of deinking sludge with a high-velocity cyclone. **Drying Technology**, v.31, p.378-384, 2013.
- Léonard, A.; Blacher, S.; Marchot, P.; Crine, M. Use of X-ray microtomography to follow the convective heat drying of wastewater sludges. **Drying Technology**, v.20, n.4-5, p.1053-1069, 2002.
- Léonard, A.; Meneses, E.; Le Trong, E.; Salmon, T.; Marchot, P.; Toye, D.; Crine, M. Influence of back mixing on the convective drying of residual sludges in a fixed bed. **Water Research**, v.42, n.10-11, p.2671-2677, 2008.

- Léonard, A.; Vandevenne, P.; Salmon, T.; Marchot, P.; Crine, M. Wastewater sludge convective drying: influence of sludge origin. **Environmental Technology**, v.25, n.9, p.1051-1057, 2004.
- Li, J.; Bennamoun, L.; Fraikin, L.; Salmon, T.; Toye, D.; Schreinemachers, R.; Léonard, A. Analysis of the shrinkage effect on mass transfer during convective drying of sawdust/sludge mixtures. *Drying Technology*, n.32, p.1706-1717, 2014a.
- Li, S.; Li, Y.; Lu, Q.; Zhu, J.; Yao, Y.; Bao, S. Integrated drying and incineration of wet sewage sludge in combined bubbling and circulating fluidized bed units. **Waste Management**, v. 34, p. 2561-2566, 2014b.
- Lopes, R. P.; Afonso, A. D. L.; Silva, J. S. Energia no pré-processamento de produtos agrícolas. In: Silva, J. S. (Ed.). **Secagem e Armazenagem de produtos agrícolas**. Viçosa: Aprenda Fácil, 2008. p.191-219.
- Mäkelä, M.; Geladi, P.; Larsson, S. H.; Finell, M. Pretreatment of recycled paper sludge with a novel high-velocity pilot cyclone: effect of process parameters on convective drying efficiency. **Applied Energy**, v.131, p.490-498, 2014.
- Mathioudakis, V. L.; Kapagiannidis, A. G.; Athanasoulia, E.; Diamantis, V. I.; Melidis, P.; Aivasidis, A. Extended dewatering of sewage sludge in solar drying plants. **Desalination**, v.248, p.733-739, 2009.
- McKendry, P. Energy production from biomass (part 1): overview of biomass. **Bioresource Technology**, n.83, p.37-46, 2002.
- Navae-Ardeh, S.; Bertrand, F.; Stuart, P. R. Emerging biodrying technology for the drying of pulp and paper mixed sludges. **Drying Technology**, v.24, p.863-878, 2006.
- Navae-Ardeh, S.; Bertrand, F.; Stuart, P. R. Key variables analysis of a novel continuous biodrying process for drying mixed sludges. **Bioresource Technology**, v.101, p.3379-3387, 2010.
- Novak, J. T. Dewatering of sewage sludge. **Drying Technology**, v.24, p.1257-1262, 2006.
- Obernberger, I.; Brunner, T.; Bärnthaler, G. Chemical properties of solid biofuels – significance and impact. **Biomass & Bioenergy**, v.30, p.973-982, 2006.

Ohm, T. I.; Chae, J. S.; Kim, J. E.; Kim, H. K.; Moon, S. H. A study on the dewatering of industrial waste sludge by fry-drying technology. **Journal of Hazardous Materials**, v.168, p.445-450, 2009.

Ohm, T. I.; Chae, J. S.; Kim, J. E.; Kim, H. K.; Moon, S. H. The evaporative drying of sludge by immersion in hot oil: Effects of oil type and temperature. **Journal of Hazardous Materials**, v.178, p.483-488, 2010.

Saidur, R.; Abdelaziz, E. A.; Demirbas, A.; Hossain, M. S.; Mekhilef, S. A review on biomass as a fuel for boilers. **Renewable and Sustainable Energy Reviews**, v.15, p.2262-2289, 2011.

Salihoglu, N. K.; Pinarli, V.; Salihoglu, G. Solar drying in sludge management in Turkey. **Renewable Energy**, v.32, p.1661-1675, 2007.

Slim, R.; Zoughaib, A.; Clodic, D. Modeling of a solar and heat pump sludge drying system. **International Journal of Refrigeration**, v.31, p.1156-1168, 2008.

Stoica, A. Sandberg, M.; Holby, O. Energy use and recovery strategies within wastewater treatment and sludge handling at pulp and paper mills. **Bioresource Technology**, v.100, p.3497-3505, 2009.

Tao, T.; Peng, X. F.; Lee, D. J. Skin layer on thermally dried sludge cake. **Drying Technology**, v.24, p.1047-1052, 2006.

Tao, T.; Peng, X. F.; Lee, D. J. Thermal drying of wastewater sludge: change in drying area owing to volume shrinkage and crack development. **Drying Technology**, v.23, p.669-682, 2005.

Vaxelaire, J.; Bongiovanni, J. M.; Mousques, P.; Puiggali, J. R. Thermal drying of residual sludges. **Water Research**, v.34, n.17, p.4318-4323, 2000.

Vaxelaire, J.; Cézac, P. Moisture distribution in activated sludges: a review. **Water Research**, v.38, p.2215-2230, 2004.

Vaxelaire, J.; Puiggali, J. R. Analysis of the drying of residual sludge: from the experiment to the simulation of a belt dryer. **Drying Technology**, v.20, p.989-1008, 2002.

Werther, J.; Ogada, T. Sewage sludge combustion. **Progress in Energy and Combustion Science**, v.25, p.55-116, 1999.

Werther, J.; Saenger, M.; Hartge, E. U.; Ogada, T.; Siagi, Z. Combustion of agricultural residues. **Progress in Energy and Combustion Science**, n.26, p.1-27, 2000.

Winkler, M. K. H.; Bennenbroek, M. H.; Horstink, F. H.; van Loosdrecht, M. C. M.; van de Pol, G. J. The biodrying concept: An innovative technology creating energy from sewage sludges. **Bioresource Technology**, v.147, p.124-129, 2013.

Wu, Z.; Zhang, J.; Li, Z.; Xie, J.; Mujumdar, A. S. Production of a solid fuel using sewage sludge and spent cooking oil by immersion frying. **Journal of Hazardous Materials**, v.243, p.357-363, 2012.

Zhao, L.; Gu, W.; He, P.; Shao, L. Effect of air-flow rate and turning frequency on bio-drying of dewatered sludge. **Water Research**, v.44, p.6144-652, 2010.

CHAPTER IV

COMPUTATIONAL MODELING OF BIOSLUDGE DRYING

Abstract

This research implemented a simulation model for biosludge drying processes to predict the temperature and moisture distribution inside the biosludge, using the COMSOL Multiphysics® simulation program v5.2. A parametric analysis was carried out to determine the effect of initial moisture content on biosludge final temperature and moisture reduction. The simulated temperature and moisture content were experimentally validated and good agreement was observed between the simulation and experimental results. This model is a useful tool to optimize the drying process and develop better strategies for the control of the system.

Keywords: biosludge, drying, heat and mass transfer, modeling.

1. Introduction

Biosludge is a byproduct of industrial wastewater treatment plants usually disposed of in landfills, incinerated, applied in agriculture or incorporated into building materials (Putranto and Chen, 2014; Seggiani *et al.*, 2012; Bennamoun, 2012). Biosludge represents a promising feedstock for energy processes due to its high organic content (Milhé *et al.*, 2016; Otero *et al.*, 2008; Zhou and Jin, 2016). For the treatment, usage and disposal of sludge, a low moisture content is both desirable and necessary (Deng *et al.*, 2009; Stasta *et al.*, 2006; Zhou and Jin, 2016). Mechanical dewatering processes currently employed in industry fails to achieve satisfactory moisture levels, and a drying step is often required. These drying processes are extremely important because a reduction in sludge volume and moisture content facilitates handling and transportation, as well as its use in combustion processes.

Drying implies removing moisture from natural or industrial materials to achieve a specific moisture content, while at the same time ensuring a prime quality product, high quantity and minimal operational costs (Defraeye, 2014).

The drying of sludges is a complex process involving simultaneous and coupled heat and mass transfer which is influenced by many factors such as operational conditions, the degree of hydration and the pore structure and physicochemical properties of the sewage sludge (Huang *et al.*, 2016; Kaya *et al.*, 2006; Salemovic *et al.*, 2015). Such processes can be modeled by taking into account mass and heat balances, and assuming that water diffuses according to kinetic laws (Font *et al.*, 2011).

The modeling principle is based on having a set of mathematical equations, which can adequately characterize the process, and the solution of these equations must allow the prediction of the process and moisture transfer parameters as a function of time (Hussain and Dincer, 2003).

Several drying models were proposed to describe sludge drying. Krawczyk and Badyda (2011) presented the key assumptions for a mathematical model which describes heat and mass transfer phenomena of a solar sewage drying process, as well as techniques used for solving this model with the Fluent computational fluid dynamics (CFD) software. Font *et al.* (2011) developed a mathematical model for the drying process of small sewage sludge spheres and cylindrical tablets, which considers the evaporation of

water from the surface of the particle, the diffusion effects in sewage sludge due to heat and moisture and the formation of a skin layer. Milhé *et al.* (2016) presented the development of a model adapted to a continuous pilot-scale sludge paddle dryer by coupling Markov chains with penetration theory, leading to the simulation of water content and temperature profiles along the dryer during steady-state operations. Putranto and Chen (2014) investigated and evaluated the REA (reaction engineering approach) to model the convective drying of sewage sludge.

The objective of the present study was to implement a simulation model, based on experimental data, for biosludge drying processes using COMSOL Multiphysics® simulation program v5.2. The specific objectives were to predict the temperature and moisture content of the biosludge pile over time, and also provide a visualization of temperature and moisture distribution and evolution inside the biosludge.

2. Material and methods

2.1. Biosludge drying

The biosludge used in this study was obtained from an activated sludge effluent treatment plant of a paper mill, with the capacity to treat $720 \text{ m}^3 \cdot \text{d}^{-1}$ and generate $5 \text{ t} \cdot \text{d}^{-1}$ of biosludge with a solids content of 15% after dewatering in a centrifuge.

Figure 1 shows the experimental apparatus of the sludge drying system. Piles of biosludge were built over the aeration diffuser (Figure 1G), and a hot gas flow of $0.64 \pm 0.02 \text{ m}^3 \cdot \text{s}^{-1}$ at a temperature of $100 \pm 20^\circ\text{C}$, provided by the direct coal-fired furnace, forcing its passage through the piles. The system operated during 5 hours. The initial mass, length and height of the piles were set to 150 kg, 2.0 m and 27 cm respectively.

During the drying system operation, the biosludge pile temperatures were measured at 15 points, every 30 minutes, using HIGHMED HM-600 thermometers, located 5cm deep at the top, middle and bottom of the pile. The moisture content was monitored at 15 points, every 60 minutes, using a moisture analyzer OHAUS MB45. These data were used in a comparison with the simulated results.

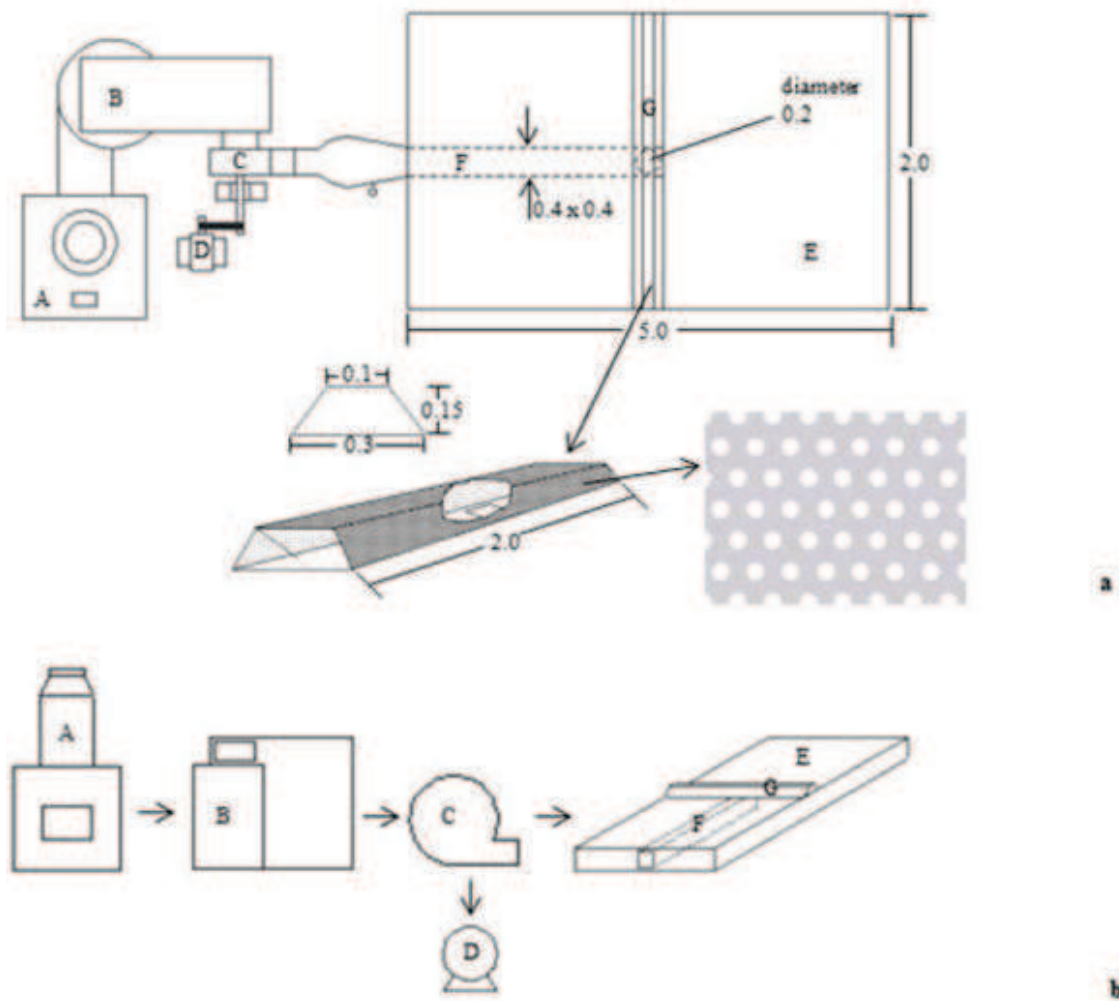


Figure 1 – Drying system. (a) Plant and (b) flowchart: (A) direct fired coal furnace; (B) cyclone; (C) fan; (D) electric engine; (E) terrace; (F) distribution duct; (G) aeration diffuser.

2.2. Model description

The proposed model is based on the heat and mass transfer through the biosludge pile. Both modes of transfer have an effect on each other and occur simultaneously during drying. Heat is transferred from the hot gas toward the pile center and from the pile surface into the atmosphere. Meanwhile, water diffuses outward toward the pile surface, and is evaporated. This model was solved using the Comsol Multiphysics® 5.2.

The geometry used in the simulations represents the biosludge pile, which was considered symmetrical. Figures 2 and 3 present the computational area and the mesh, respectively.

The simulation was carried out in two-dimensions using the following assumptions: (i) constant thermophysical properties; (ii) negligible shrinkage or deformation of object

during drying; (iii) evaporation occurs only at the surface of the pile; (iv) moisture consists of pure water; (v) initial temperature and moisture content distribution in the pile is uniform; (vi) biosludge pile is a solid material; (vii) volume reduction is due to the change of the moisture content, the solid mass remains constant.

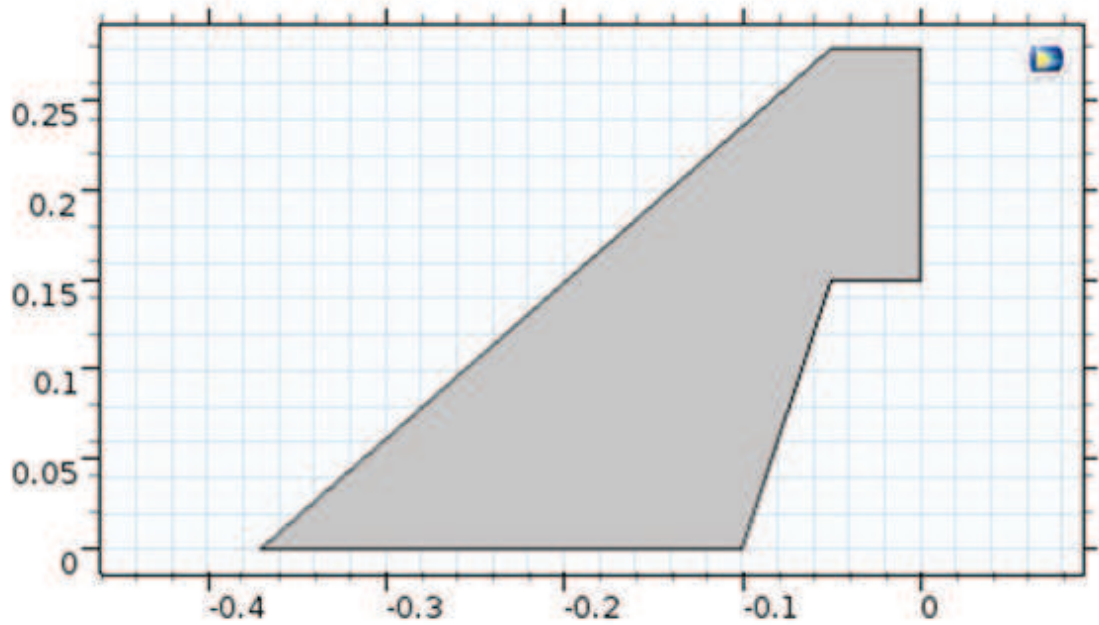


Figure 2 – Geometry used in the simulation of sludge drying process.

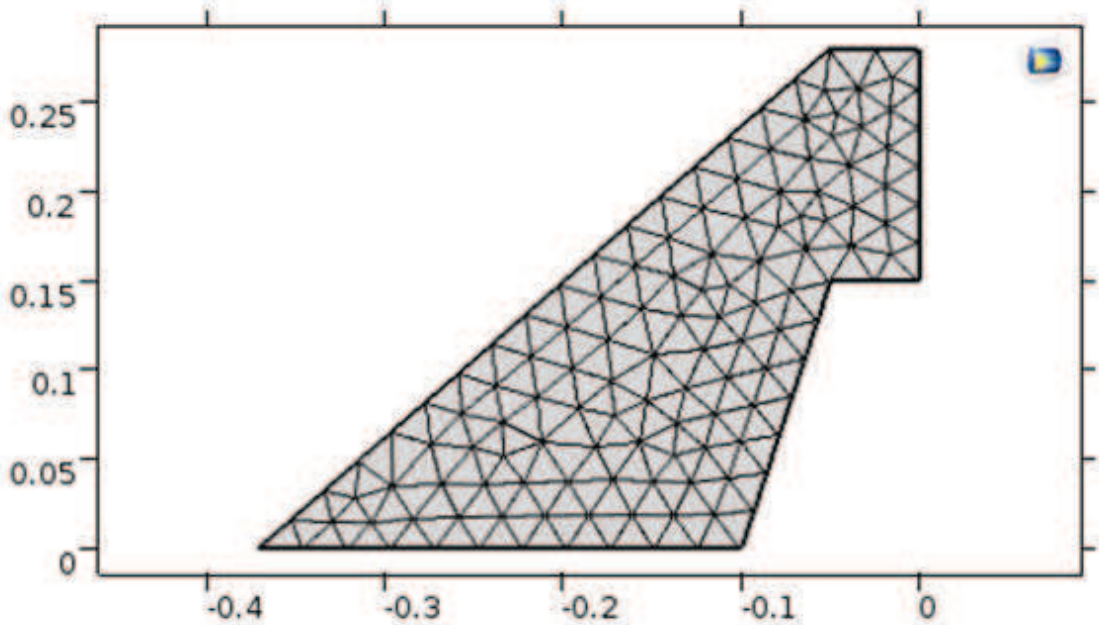


Figure 3 – Mesh used in the simulation of sludge drying process.

The input data is shown in Tables 1 and 2.

Table 1 – Input parameters of the biosludge pile.

Name	Expression	Description
alfa_air	22.5E-6 [m ² /s]	Thermal diffusivity of air
H_calc	Vol_sludge/m_water	
A_layer	W_layer*L_layer	Exposed area of sludge layer
c_b	0.02*ro_sludge/m_water	Molar concentration of water in air, constant
c_m	0.003	
c0	W_wet0*ro_sludge/m_water	Initial molar concentration of water
L_layer	2 [m]	Length of sludge layer
cp_water	4200 [J/kg/K]	Specific heat capacity of water
cp_dryair	1010 [J/kg/K]	
D	4E-7 [m ² /s]	Mass diffusivity of water in sludge
D_m	Dab	Mass diffusivity of water in dry air, 5E-10
Dab	5E-10 [m ² /s]	Diffusion coefficient of water in air
h_air1	1.17*(Q_air1*3600)^(0.37) [W/m ² /K]	Heat transfer coefficient 1
h_air2	1.17*(Q_air2*3600)^(0.37) [W/m ² /K]	Heat transfer coefficient 2
h_m	1.67E-6 [kg/m ² /s]	
hmmm	h_air1/ro_air1/cp_dryair/Le^(2/3)	Reynolds analogy – to confer
k_c	h_air1/ro_air1/cp_dryair	Mass transfer coefficient of water in dry air, 6E-7 [m/s]
k_m	1.29E9 [kg/m/s]	
W_layer	0.27 [m]	Width of sludge layer
Le	alfa_air/Dab	Lewis number
m_water	18 [g/mol]	
m_water0	W_wet0*m_sludge0	Initial mass of water
m_sludge0	150.2 [kg]	Mass of wet sludge
m_drysludge	m_sludge0 – m_water0	Mass of dry sludge
p_air	1013E5 [Pa]	Local pressure
Q_air1	ro_air1*v_air [m ² *s/kg]	
Q_air2	ro_air2*v_air [m ² *s/kg]	
R	8.314462 [Pa*m ³ /mol/K]	Universal constant
ro_air1	p_air*m_water/(R*T_air1)	Density of air 1
ro_air2	p_air*m_water/(R*T_air2)	Density of air 2
ro_sludge	930.8 [kg/m ³]	Density of wet sludge
ro_drysludge	286.2 [kg/m ³]	Density of dry sludge
T_air1	25 [degC]	Output gas temperature (above)
T_air2	101 [degC]	Input gas temperature (bellow)
rate_evap	k_c*(c0 – c_b)*m_water*A_layer	Evaporated water rate per second
v_air	20.6 [m/s]	Mean velocity of drying gas
Vol_sludge	m_sludge0/ro_sludge	Sludge volume
W_dry0	2.25	Moisture in dry basis, kg water/kg dry sludge
W_wet0	W_dry0/(1 + W_dry0)	Moisture in wet basis, kg water/kg wet sludge

Table 2 – Input variables of the biosludge pile.

Name	Expression	Description
cp_sludge	cpa*cp_water + cpb*cp_drysludge	Specific heat capacity of sludge
cp_sludge2	(3017.2 + 2.05*dT + 0.24*dT^2 + 0.002*dT^3) [J/kg/K]	Specific heat capacity of sludge
cp_drysludge	(1434 + 3.29*dT) [J/kg/K]	Specific heat capacity of dry sludge
cpa	W_dry/(1+W_dry)	
cpb	(1/(1+W_dry))	
dT	(T-0 [degC]) [1/K]	Delta temperature
H_fg	2502535.259 – 2385.7624*dT [J/kg]	Latent heat, function of T_s
k_sludge	(0.5148*exp(-0.0051*W_dry)) [W/m/K]	Thermal conductivity of sludge
lda	H_fg*m_drysludge	Latent heat, function of T_s
m_water	W_dry*m_drysludge	Mass of water
m_evapwater	Tds.dflux_cy*m_water*180[s]*L_layer*W_layer	Mass of evaporated water
d_sludge	(m_drysludge + m_water)/Vol_sludge	Density of sludge
m_sludge	m_drysludge + m_water	Mass of wet sludge
W_dry	c*m_water/ro_drysludge	Moisture in dry basis, kg water/kg dry sludge
W_wet	W_dry/(1 + W_dry)	Moisture in wet basis, kg water/kg wet sludge

2.2.1. Governing equations

Based on the previous assumptions, the general heat and mass transfer equations (Equations 1 and 2, respectively) are as follow:

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T \quad (1)$$

$$\frac{\partial C}{\partial t} = D \nabla^2 C \quad (2)$$

Where:

ρ = pile density (kg.m⁻³);

c_p = specific heat of biosludge (J.kg⁻¹.K⁻¹);

k = thermal conductivity of biosludge (W.m⁻¹.K⁻¹);

T = pile temperature (K);

C = pile moisture concentration (mol.m⁻³);

D = biosludge diffusivity (m².s⁻¹);

t = time (s).

The boundary conditions for heat transfer at the surfaces (Equation 3), at the symmetry boundary (Equation 4) and at the internal boundaries (Equation 5) are:

$$k\nabla T = h(T_{\infty} - T) + h_{rad}(T_{\infty} - T) + D\lambda\nabla C \quad (3)$$

$$k\nabla T = 0 \quad (4)$$

$$k\nabla T = h(T_{gas} - T) \quad (5)$$

Where:

h = convection transfer coefficient ($\text{W.m}^{-2}.\text{K}$);

h_{rad} = radiation transfer coefficient ($\text{W.m}^{-2}.\text{K}$);

T_{∞} = air temperature (K);

T_{gas} = gas temperature (K);

λ = molar latent heat of vaporization (J.mol^{-1}).

The boundary conditions for mass transfer at the surfaces (Equation 6), at the symmetry boundary and internal boundaries (Equation 7) are:

$$D\nabla C = h_m(C_{air} - C) \quad (6)$$

$$D\nabla C = 0 \quad (7)$$

Where:

h_m = mass transfer coefficient ($\text{kg.m}^{-2}.\text{s}^{-2}$);

C_{air} = air moisture concentration (mol.m^{-3}).

The initial conditions are:

$$T|_{t=0} = T_0 \quad (8)$$

$$C|_{t=0} = C_0 \quad (9)$$

Where:

T_0 = initial pile temperature, equal to ambient temperature (K);

C_0 = initial pile moisture concentration (mol.m^{-3}).

2.3. Model validation

To validate the results of the numerical simulation, the obtained data for temperature and moisture content were compared with the experimental results. The simulation model performance was determined by calculation of root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination (R^2).

$$RMSE = \sqrt{\frac{1}{n} \sum (\hat{Y}_i - Y_i)^2} \quad (10)$$

$$MAE = \frac{1}{n} \left| \frac{Y_i - \hat{Y}_i}{Y_i} \right| \quad (11)$$

$$R^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{\sum (Y_i - \bar{Y}_i)^2} \quad (12)$$

Where:

RMSE = root mean square error;

MAE = mean absolute error;

R^2 = coefficient of determination;

n = number of observations;

Y_i = data obtained from the experiment;

\hat{Y}_i = data predicted by the simulation;

\bar{Y}_i = means of the data predicted by the simulation.

3. Results and discussion

3.1. Computer simulation

Distributions of temperature and moisture concentration in biosludge pile after 5 hours are presented in Figures 4 and 5, respectively. As shown in Figure 4, the biosludge immediately in contact with the drying gas reached the thermal equilibrium with the inlet gas, while the following layers had lower temperatures, since the gas loses enthalpy while ascending through the pile. This behavior was also observed by Pagano and Mascheroni (2013), during the drying of deep-bed amaranth grains. In Figure 5, it can be seen how the moisture concentration decreased near the surface layer where the evaporation took place.

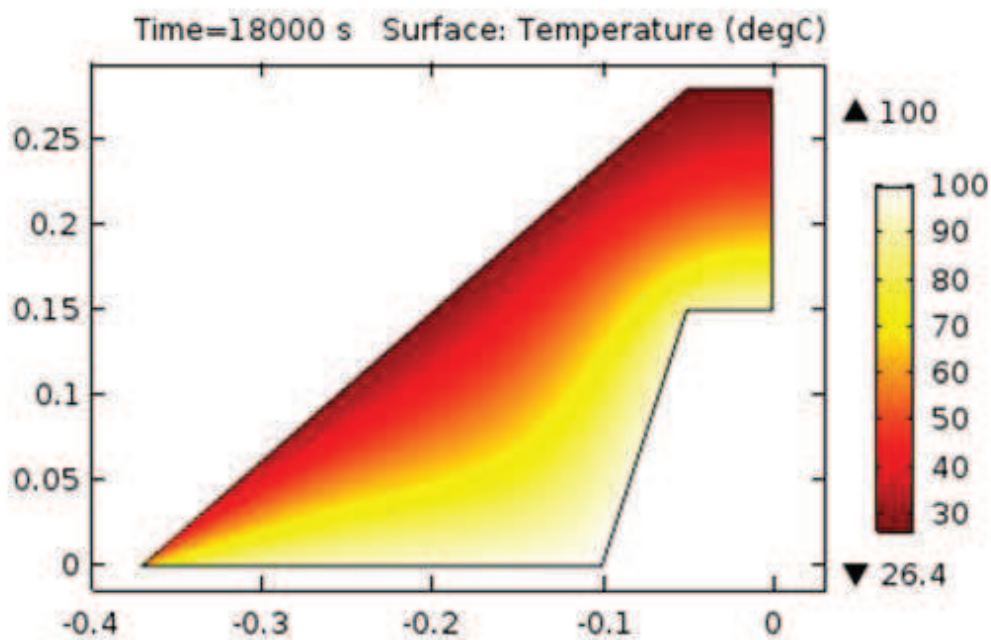


Figure 4 – Temperature distribution in biosludge pile after 5 hours (18,000s) of drying.

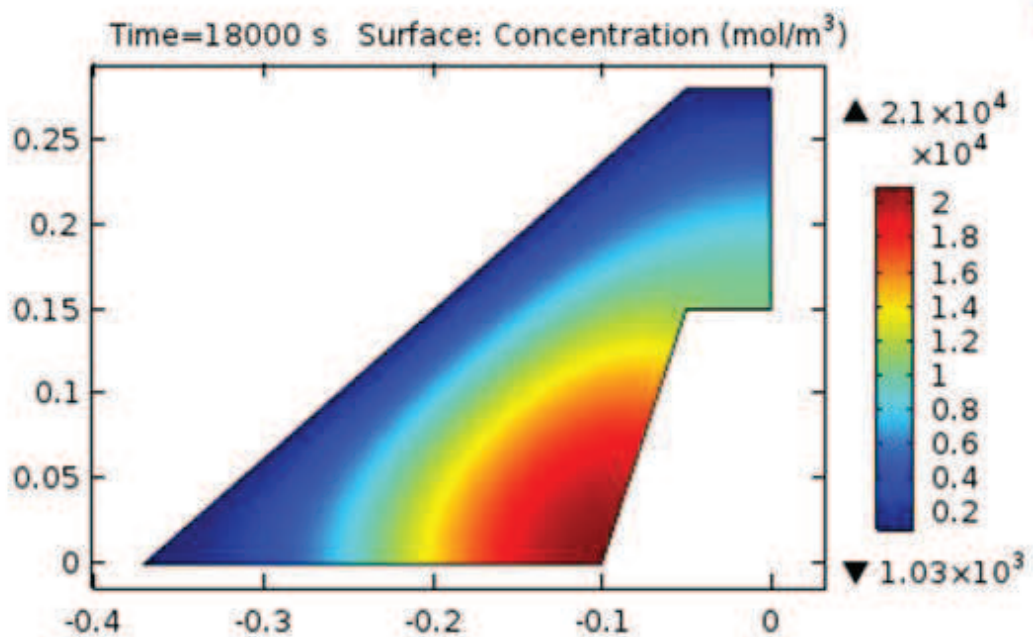


Figure 5 – Moisture concentration distribution in biosludge pile after 5 hours (18,000s) of drying.

Figure 6 presents the temperature profile of the biosludge pile. The temperature increased gradually from ambient temperature to a maximum of 60°C. The temperature did not reach the gas temperature at the final drying period, because the water removal created pores in the biosludge pile, leading, according to Huang *et al.* (2016), to an increase in thermal resistance.

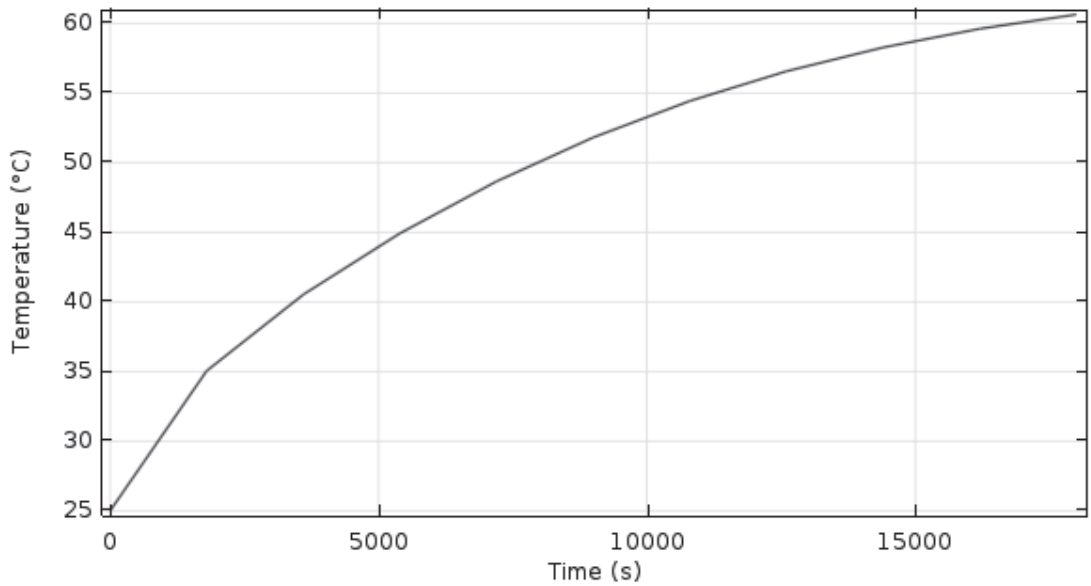


Figure 6 – Temperature profile of biosludge pile.

Variation in the biosludge moisture content over time is shown in Figure 7. The biosludge moisture content decreased from 2.2 kg.kg⁻¹ d.b. to 0.6 kg.kg⁻¹ d.b. (dry basis) in 5 hours.

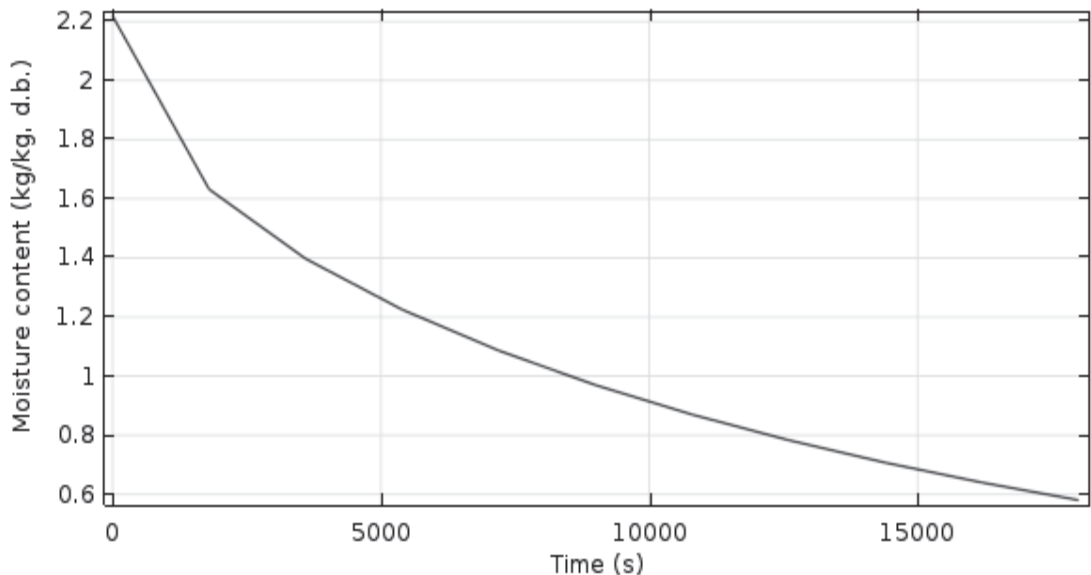


Figure 7 – Moisture content profile of biosludge pile.

Figure 7 is one of the most important elements that give information about product behavior during drying (Bennamoun *et al.*, 2013). It is observed that the drying process began with a short period where the moisture decreased rapidly due to the water

evaporation from the pile surface. This period, known as the constant drying rate, took place in the first 30 minutes (1,800s) of drying, and the water evaporated was free water. During this phase, the evaporation is dominated by the rates of external heat and mass transfer since a film of free water is always available at the surface (Mujumdar and Devahastin, 2007; Li *et al.*, 2016). So, the drying process only depended on the temperature, velocity and humidity of the drying gas, being independent of the biosludge character (Vaxelaire *et al.*, 2000; Léonard *et al.*, 2008).

After 30 minutes of drying, the surface became poor in liquid, since, as explained by Huang *et al.* (2016), the evaporation rate of surface moisture was less than the diffusion rate of inner moisture in the biosludge pile, starting the first falling rate. When water evaporation began to decrease and slow down, after 4 hours (14,400s) of drying, the drying transitioned to the second falling drying rate. This was caused, according to Deng *et al.* (2015), by the diffusion of the moisture inside the biosludge structure. During the falling drying rates, the drying was governed by the rates of internal heat and mass transfer (Mujumdar and Devahastin, 2007; Li *et al.*, 2016), with a decrease of the influence of external variables.

It can be seen in Figure 7 that the drying process occurred mostly in the falling rate periods, as stated by Bennamoun *et al.* (2013). According to Zhou and Jin (2016), this fact occurred because the moisture diffusion during drying was slow and mainly controlled by internal diffusion.

3.2. Comparison of temperature and moisture content profiles of experiment and simulation

Simulation results were compared with experimental data for temperature and moisture content profiles, as shown in Figure 8. According to RMSE (root mean square error), MAE (mean absolute error) and R^2 (coefficient of determination), both simulated temperature and moisture were in strong agreement with experimental data, even though the experimental temperature values were a little scattered. This comparison indicates that the model can predict temperature and moisture content quite accurately.

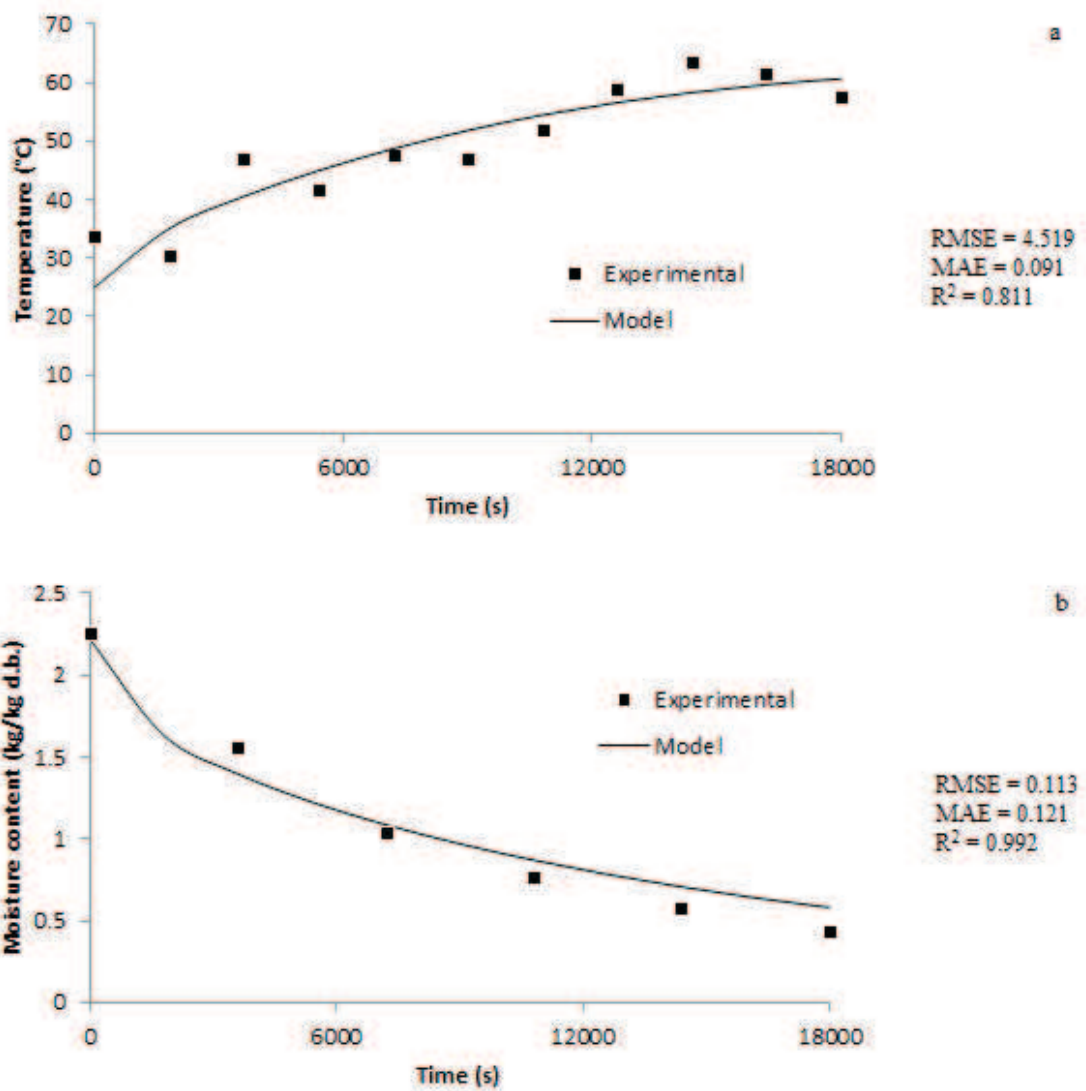


Figure 8 – Temporal average (a) temperature and (b) moisture content profile obtained for experimental and simulation.

3.3. Parametric analysis

The validated model was used to investigate the influence of biosludge initial moisture content on final temperature and moisture reduction. Therefore, a parametric analysis was performed with different initial moisture contents, 9.0, 6.1, 4.6, 3.5, 2.8 and 2.3 kg.kg⁻¹ d.b. The results are presented in Table 3.

Table 3 – Effect of initial moisture on final temperature and moisture reduction.

Initial moisture content (kg.kg ⁻¹ d.b.)	Final temperature (°C)	Final moisture content (kg.kg ⁻¹ d.b.)	Moisture reduction (kg.kg ⁻¹ d.b.)	Moisture reduction (%)
9.0	63.12	0.73	8.26	92
6.1	62.87	0.70	5.40	88
4.6	62.45	0.67	3.92	85
3.5	61.84	0.64	2.86	82
2.8	61.22	0.61	2.19	78
2.3	60.64	0.58	1.72	75

It was observed that the increase in moisture content slightly increased the pile temperature. As verified by Deng *et al.* (2009), the sludge thermal conductivity decreases with moisture reduction and, since, according to Datta (2002) and Çengel (2006), the thermal conductivity is a measure of the efficiency of heat conduction, lower values led to less effective energy transport.

The increase in moisture content also increased the moisture reduction, with this fact being related to the biosludge diffusivity. Mass diffusivity represents the mobility of the water in the biosludge, and, according to Datta (2002) and Bergman *et al.* (2011), generally increases with moisture content. This is because more moisture is available for diffusion, and as the molecules become more mobile at higher temperatures, higher diffusivities also means higher water evaporation and consequent moisture.

4. Conclusions

This study shows that it is possible to describe the thermal behavior of the biosludge during drying by using the simulation model proposed. The model, which takes into account the main phenomena of simultaneous heat and mass transfer, allows the prediction of biosludge temperature and moisture content during the drying period. The comparative study shows good agreement between simulated and experimental values of the biosludge temperature and moisture content during drying. Due to the cost and time involved in experimental studies, the simulation model is of great importance in the effective design and final adjustment and installation of the sludge drying equipment.

References

- Bennamoun, L.; Arlabosse, P.; Léonard, A. Review on fundamental aspect of application of drying process to wastewater sludge. **Renewable and Sustainable Energy Reviews**, v. 28, p. 29-43, 2013.
- Bennamoun, L. Solar drying of wastewater sludge: A review. **Renewable and Sustainable Energy Reviews**, v.16, p.1061-1073, 2012.
- Bergman, T. L.; Lavine, A. S.; Incropera, F. P.; Dewitt, D. P. **Fundamentals of heat and mass transfer**. John Wiley & Sons, Inc., United States of America, 1076 p., 2011
- Çengel, Y. A. **Heat and mass transfer: a practical approach**. McGraw-Hill, New York, 900 p., 2006.
- Datta, A. K. **Biological and bioenvironmental heat and mass transfer**. Marcel Dekker, C., New York, 383p., 2002.
- Defraeye, T. Advanced computational modelling for drying processes - A review. **Applied Energy**, v. 131, p. 323-344, 2014.
- Deng, S.; Wang, X.; Tan, H.; Mikulčić, H.; Li, Z.; Cao, R.; Wang, Z.; Vujanović, M. Experimental and modeling study of the long cylindrical oily sludge drying process. **Applied Thermal Engineering**, v. 91, p. 354-362, 2015.
- Deng, W. Y.; Yan, J. H.; Li, X. D.; Wang, F.; Lu, S. H.; Chi, Y.; Cen, K. F. Measurement and simulation of the contact drying of sewage sludge in a Nara-type paddle dryer. **Chemical Engineering Science**, v. 65, n. 24, p. 5117-5124, 2009.
- Font, R.; Gomez-Rico, M. F.; Fullana, A. Skin effect in the heat and mass transfer model for sewage sludge drying. **Separation and Purification Technology**, v. 77, p. 146-161, 2011.
- Huang, Y. W.; Chen, M. Q.; Jia, L. Assessment on thermal behavior of municipal sewage sludges thin-layer during hot air forced convective drying. **Applied Thermal Engineering**, v. 96, p. 209-216, 2016.

Hussain, M. M.; Dincer, I. Two-dimensional heat and moisture transfer analysis of a cylindrical moist object subjected to drying: A finite-difference approach. **International Journal of Heat and Mass Transfer**, v. 46, p. 4033-4039, 2003.

Kaya, A.; Aydın, O.; Dincer, I. Numerical modeling of heat and mass transfer during forced convection drying of rectangular moist objects. **International Journal of Heat and Mass Transfer**, v. 49, p. 3094-3103, 2006.

Krawczyk, P.; Badyda, K. Two-dimensional CFD modeling of the heat and mass transfer process during sewage sludge drying in a solar dryer. **Archives of Thermodynamics**, v. 32, n. 4, p. 3-16, 2011.

Léonard, A.; Meneses, E.; Le Trong, E.; Salmon, T.; Marchot, P.; Toye, D.; Crine, M. Influence of back mixing on the convective drying of residual sludges in a fixed bed. **Water Research**, v. 42, n. 10-11, p. 2671-2677, 2008.

Li, J.; Liang, Q. C.; Bennamoun, L. Superheated steam drying: Design aspects, energetic performances, and mathematical modeling. **Renewable and Sustainable Energy Reviews**, v. 60, p. 1562-1583, 2016.

Milhé, M.; Sauceau, M.; Arlabosse, P. Modeling of a continuous sewage sludge paddle dryer by coupling Markov chains with penetration theory. **Applied Mathematical Modelling**, v. 40, n. 19-20, p. 8201-8216, 2016.

Mujumdar, A. S.; Devahastin, S. Fundamental principles of drying. In: Mujumdar, A. S. (Ed.) **Handbook of industrial drying**. 3 ed. CRC Press, Boca Raton, p. 1-22, 2007.

Otero, M.; Calvo, L. F.; Gil, M. V.; García, A. I.; Morán, A. Co-combustion of different sewage sludge and coal: A non-isothermal thermogravimetric kinetic analysis. **Bioresource Technology**, v.99, n.14, p.6311-6319, 2008.

Pagano, A. M.; Mascheroni, R. H. Computational modelling of the transport phenomena during low temperature in-bin drying and aeration of amaranth grains. **Mecánica Computacional**, v. XXXII, p. 1321-1345, 2013.

Putranto, A.; Chen, X. A simple and effective model for modeling of convective drying of sewage sludge: the reaction engineering approach (REA). **Procedia Chemistry**, v. 9, p. 77-87, 2014.

Salemović, D. R.; Dedić, A. D.; Čuprić, N. L. A mathematical model and simulation of the drying process of thin layers of potatoes in a conveyor-belt dryer. **Thermal Science**, v. 19, n. 3, p. 1107-1118, 2015.

Seggiani, M.; Puccini, M.; Raggio, G.; Vitolo, S. Effect of sewage sludge content on gas quality and solid residues produced by cogasification in an updraft gasifier. **Waste Management**, v. 32, n. 10, p. 1826-1834, 2012.

Stasta, P.; Boran, J.; Bebar, L.; Stehlik, P.; Oral, J. Thermal processing of sewage sludge. **Applied Thermal Engineering**, v. 26, n. 13, p. 1420-1426, 2006.

Vaxelaire, J.; Bongiovanni, J. M.; Mousques, P.; Puiggali, J. R. Thermal drying of residual sludges. **Water Research**, v. 34, n. 17, p. 4318-4323, 2000.

Zhou, Y.; Jin, Y. Mathematical modeling of thin-layer infrared drying of dewatered municipal sewage sludge (DWMSS). **Procedia Environmental Sciences**, v. 31, n. 86, p. 758-766, 2016.

GENERAL CONCLUSIONS

The sludge drying process is an essential step in wastewater treatment plants that reduces sludge volume and transportation costs, as well as increasing its heating value, transforming the product into an acceptable fuel. However it is an energy intensive process. Therefore, paper mills have been searching for efficient and low energy expenditure drying technologies.

The objective of this research was to propose and investigate a biosludge drying system using hot gases from a direct coal-furnace as the energy source, in order to adapt the biosludge as a fuel for biomass boilers.

According to the results obtained, the proposed drying system has been proved to be very promising when a bulking agent was added to the biosludge, since the addition of either eucalyptus chips or bark raised the piles temperature and consequently increased the drying rate and water evaporation. The bulking agents also increased the mass loss during thermogravimetric analysis, heating value, volatile matter, fixed carbon, carbon and hydrogen contents, and decreased the ash, nitrogen and sulfur contents, which is useful for further combustion processes.

During the drying process, the mixture of 75% biosludge and 25% eucalyptus bark presented the best drying results, with higher moisture reduction, final total solids content and drying process efficiency, as well as lower specific energy consumption.

The great advantages of using this drying system to dry sludge is its easy operation, low maintenance and operating costs, in contrast verified in many mechanical dryers. Furthermore, the reduction of sludge moisture content to values considered viable for combustion was also possible. However, a relatively long drying time is required.

The simulation model proposed in this research can describe the thermal behavior of the biosludge during drying in the system studied. The model allows the prediction of biosludge temperature and moisture content during the drying period and shows good agreement between simulated and experimental results. Due to the cost and time involved in experimental studies, this simulation model is of great importance in the effective design and final adjustment and installation of the sludge drying equipment.

It can be concluded that drying biosludge mixtures through the proposed system is possible, being a significant step in the development of drying methods capable of utilizing secondary energy, such as gases released from boilers, potentially available in industrial environments. Moreover, the dried product can be used as fuel in combustion processes for energy generation.

Studies of the air pollutants emitted during biosludge combustion and of the technical parameters and feasibility of the drying system implementation in paper mills are suggested as questions for future research.