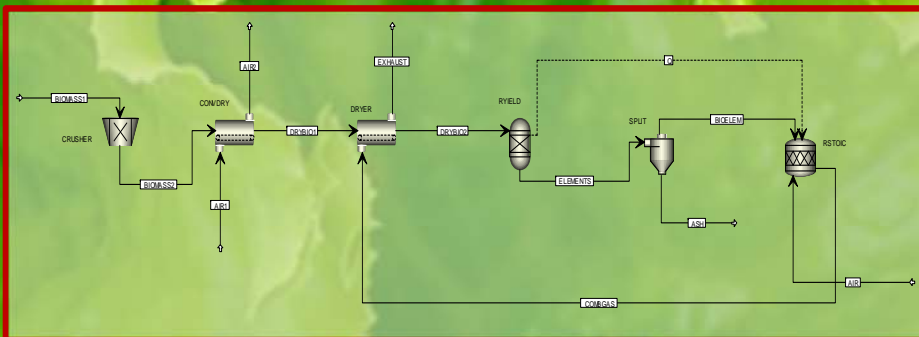


# Disposal and energy recovery from agri-food industry waste

Disposal and energy recovery from agri-food industry waste



Maria Chiara Amoroso

**Maria Chiara Amoroso**



UNIVERSITY OF SALERNO

**Department of Industrial Engineering**

Master Degree in Food Engineering

# **Disposal and energy recovery from agri-food industry waste**

Master thesis in

**Transport Phenomena in Food Processes**

Supervisors:

Prof. Ing. Gaetano Lamberti

Ing. Sara Cascone

Candidate:

Maria Chiara Amoroso

badge number 0622800234

**Academic Year 2017/2018**



*To my family*

This text was printed in Times New Roman

The expected data for the thesis discussion is the 26/7/2018  
Fisciano, 18/7/2018

# Summary

|   |            |
|---|------------|
| <b>Summary.....</b>                             | <b>I</b>   |
| <b>Figure index.....</b>                        | <b>III</b> |
| <b>Table index .....</b>                        | <b>V</b>   |
| <b>Abstract .....</b>                           | <b>VII</b> |
| <b>Abstract .....</b>                           | <b>IX</b>  |
| <b>Introduction.....</b>                        | <b>1</b>   |
| 1.1 The global energy scenario _____            | 2          |
| 1.2 Biomass classification and properties _____ | 3          |
| 1.2.1 Biomass classification                    | 3          |
| 1.2.2 Biomass composition                       | 5          |
| 1.2.3 Biomass properties                        | 5          |
| 1.2.4 Advantages and disadvantages of biomass   | 8          |
| 1.3 Landfilling _____                           | 9          |
| 1.4 Biomass conversion technologies _____       | 10         |
| 1.4.1 Aerobic digestion or composting           | 12         |
| 1.4.2 Anaerobic digestion                       | 13         |
| 1.4.3 Combustion                                | 15         |
| 1.4.4 Pyrolysis                                 | 16         |
| 1.4.5 Torrefaction                              | 18         |

|   |           |
|---|-----------|
| 1.4.6 Gasification  | 20        |
| 1.4.7 Liquefaction  | 23        |
| 1.4.8 Plasma technology   | 23        |
| 1.7 Aims _____  | 24        |
| <b>Biomass and process preliminary analyses .....</b>           | <b>25</b> |
| 2.1 Combustion of solid biomass _____                           | 26        |
| 2.1.1 Combustion technologies                                   | 26        |
| 2.1.2 Biomass characteristics that affecting combustion process | 30        |
| 2.2 Biomass analysis _____                                      | 31        |
| 2.3 Biomass combustion model _____                              | 35        |
| 2.3.1 Integrated drying/combustion system                       | 35        |
| 2.4 Biomass pretreatments _____                                 | 41        |
| 2.4.1 Solar drying  | 41        |
| 2.4.2 Pretreatments analysis                                    | 42        |
| <b>Process simulation .....</b>                                 | <b>45</b> |
| 3.1 Aspen Plus simulation model _____                           | 46        |
| 3.2 Model description _____                                     | 46        |
| 3.2.1 Crusher   | 50        |
| 3.2.2 Convective dryer  | 51        |
| 3.2.3 Dryer   | 57        |
| 3.2.4 Combustion block  | 58        |
| 3.2.5 Sensitivity analysis                                      | 61        |
| 3.4 Model validation _____                                      | 67        |
| <b>Conclusions .....</b>  | <b>71</b> |
| 4.1 Conclusions and future works _____                          | 72        |
| <b>References .....</b>   | <b>75</b> |

---

## Figure index

|   |    |
|---|----|
| Figure 1. World marketed energy consumption. [1].                                     | 2  |
| Figure 2. Carbon cycle [3].   | 4  |
| Figure 3. Bases for expressing fuel composition [8].                                  | 7  |
| Figure 4. Potential biomass conversion processes [12].                                | 11 |
| Figure 5. Anaerobic digestion process.  | 14 |
| Figure 6. Pyrolysis in a biomass particle [8].  | 16 |
| Figure 7. Simplified layout of a pyrolysis plant [8].                                 | 17 |
| Figure 8. Potential paths for gasification.   | 22 |
| Figure 9. Plasma gasifier.  | 24 |
| Figure 10. Classification of grate furnace technologies [25].                         | 27 |
| Figure 11. Underfeed stoker [25].   | 27 |
| Figure 12. Example of fluidized bed combustion [25].                                  | 28 |
| Figure 13. From the left: biomass sample A and sample B before drying.                | 33 |
| Figure 14. Drying curve of sample A.  | 33 |
| Figure 15. Drying curve of sample B.  | 34 |
| Figure 16. Simplified process flowsheet of biomass combustion system.                 | 35 |
| Figure 17. Excess heat by the system versus moisture content of the starting biomass. | 40 |
| Figure 18. Example of passive dryer [28].   | 42 |
| Figure 19. Example of active solar dryer [28].  | 42 |
| Figure 20. Press used for experimental tests.   | 43 |
| Figure 21. Results of the experimental tests.   | 43 |
| Figure 22. Substances selected for the simulation.                                    | 47 |
| Figure 23. Selection of simulation PSD in terms of its parameters.                    | 48 |

---



---

|   |    |
|---|----|
| Figure 24. Selection of water as moisture component. ....                         | 48 |
| Figure 25. Biomass stream.....  | 48 |
| Figure 26. Cumulative PSD curve as a function of particle size. ....              | 50 |
| Figure 27. Solids crusher. ....   | 50 |
| Figure 28. Convective dryer. ....   | 51 |
| Figure 29. Simultaneous heat and mass transfer. ....                              | 52 |
| Figure 30. Selection of drying conditions. ....                                   | 56 |
| Figure 31. Implementation of mass and heat transfer coefficients. ....            | 57 |
| Figure 32. Shortcut dryer.....  | 57 |
| Figure 33. Selection of operating conditions. ....                                | 58 |
| Figure 34. Combustion unit. ....  | 58 |
| Figure 35. Operating conditions of RYield.....                                    | 60 |
| Figure 36. Operating conditions of RStoic. ....                                   | 61 |
| Figure 37. Sensitivity results curve. ....  | 62 |
| Figure 38. Operating conditions of AIR1 stream entering the convective dryer..... | 62 |
| Figure 39. Sensitivity results curves.....  | 63 |
| Figure 40. Operating conditions of AIR stream entering the RStoic reactor. ....   | 64 |
| Figure 41. Process flowsheet. ....  | 65 |
| Figure 42. Sensitivity results curve. ....  | 68 |
| Figure 43. Sensitivity results curves.....  | 69 |

---

## Table index

|   |    |
|---|----|
| Table 1. Main renewable energy sources and their usage forms [2].                           | 3  |
| Table 2. Ultimate analysis and ash content of coal and biomass samples (wt% dry basis) [2]. | 5  |
| Table 3. Standard methods for biomass ultimate analysis [8].                                | 6  |
| Table 4. Standard methods for biomass proximate analysis [8].                               | 6  |
| Table 5. Physical, chemical and fuel properties of biomass and coal fuels [3].              | 8  |
| Table 6. Major advantages and disadvantages of biomass fuels [10].                          | 9  |
| Table 7. Comparison of major thermochemical conversion processes [13].                      | 11 |
| Table 8. Operating values for composting.   | 13 |
| Table 9. Advantages and disadvantages of biomass pyrolysis system [16].                     | 18 |
| Table 10. Advantages and challenges for DT and WT [19].                                     | 20 |
| Table 11. Principal constituents in product gases from biomass gasification.                | 21 |
| Table 12. Heating values for product gas based on gasifying medium [8].                     | 21 |
| Table 13. Advantages and disadvantages of combustion technologies [25].                     | 29 |
| Table 14. Ultimate and proximate analysis for biomass.                                      | 32 |
| Table 15. Biomass characteristics.  | 36 |
| Table 16. Results of mass balances.   | 39 |
| Table 17. Results of energy balances.   | 39 |
| Table 18. Biomass operating conditions and chemical composition [31].                       | 49 |
| Table 19. Ash attributes.   | 59 |
| Table 20. Yield distribution.   | 60 |
| Table 21. Stream table of the laboratory scale process simulation.                          | 66 |
| Table 22. Ortomad biomass production.   | 67 |
| Table 23. Stream table of the industrial scale process simulation.                          | 70 |

---



# Abstract

This work has been focused on the study of plant configurations for the disposal and energy recovery from agri-food industry wastes.

Starting from an overview of the global actual situation in the use of renewable energy sources, the attention has been focused on the use of biomass as a renewable source of industrial interest. A general description of the main biomass properties in terms of ultimate and proximate analyses has been presented, and the advantages and disadvantages in its use as a fuel are listed.

Furthermore, the main industrial processes used to the exploitation of biomass fuels have been analyzed; the thermochemical and biochemical conversion technologies have been examined describing the processes, the operating conditions and the main advantages and disadvantages of their use. Then, the attention has been focused on the biomass combustion process, describing the main technologies used in industrial-scale plants and the biomass characteristics affecting this process.

Once the compositions of the biomass under study (lettuce residues) have been identified in literatures, in terms of ultimate and proximate analysis, its higher heating value has been evaluated by the Dulong's formula and its moisture content has been determined through drying tests. The integrated biomass drying/combustion model has been developed by performing the mass and energy balances that made it possible to determine the operating conditions to make the process self-sufficient. From the results of process analysis, the need to subject the biomass to pretreatments to bring it to optimal conditions for the process yields has been deduced.

The biomass conversion process has been implemented in Aspen Plus, a software useful to simulate the behavior of the plant and to analyze its performance. The blocks available in the software used to simulate

the unit operations and their operating conditions have been described, and the streams fed to the plants have been characterized. The simulation results confirmed the possibility to dispose the biomass under study by recovering the heat from the flue gases produced during the combustion process. Finally, a process on a production scale has been simulated using data from a company that works agricultural products.

Further studies may be conducted on the disposal of exhausted gases leaving the dryer, taking into account a cleaning treatment before the emission into the atmosphere. In addition, it will be also necessary to consider a treatment process for combustion ash. Finally, an economic analysis of the process can be performed to evaluate its cost effectiveness in comparison with other technologies.

---

# Abstract

L'obiettivo del lavoro di tesi è stato lo studio delle configurazioni impiantistiche per lo smaltimento e il recupero energetico da scarti dell'industria agroalimentare.

Partendo da una panoramica sulla situazione attuale nell'utilizzo delle fonti di energia rinnovabili, l'attenzione è stata posta sull'uso della biomassa come fonte rinnovabile di interesse industriale. Sono state descritte le principali proprietà della biomassa utili per la sua caratterizzazione come combustibile ed elencati i vantaggi e gli svantaggi legati al suo utilizzo.

Inoltre, sono stati esaminati i processi industriali principalmente impiegati nello sfruttamento della biomassa come combustibile. Le tecnologie di conversione termochimica e biochimica sono state analizzate descrivendone il processo, le condizioni operative e i principali vantaggi e svantaggi del loro utilizzo. A seguire, l'attenzione è stata focalizzata sul processo di combustione della biomassa con la descrizione delle tecnologie impiegate in ambito industriale e le caratteristiche della biomassa che influenzano tale processo.

Della biomassa oggetto di studio (residui di lattuga), una volta individuate, in letteratura, le composizioni, in termini di analisi elementare e prossimale, sono stati valutati il potere calorifico superiore, attraverso la formula di Dulong, e il contenuto di umidità, attraverso prove sperimentali di essiccamento. È stato sviluppato il modello integrato essiccamento/combustione della biomassa e, attraverso la risoluzione di bilanci di materia ed energia, è stato possibile determinare le condizioni operative necessarie per rendere il sistema autosufficiente. Dai risultati ottenuti analizzando il processo è stato dedotto che fosse necessario sottoporre la biomassa a dei

pretrattamenti per portarla alle condizioni ottimali per le rese del processo.

Il processo di conversione della biomassa è stato implementato in Aspen Plus, un software utilizzato per simulare il comportamento di un impianto e valutarne la performance. Sono stati descritti i blocchi disponibili nel software, utilizzati per simulare le unità operative, e le loro condizioni di processo e, inoltre, sono state caratterizzate le correnti che alimentano l'impianto. I risultati ottenuti dal modello di simulazione hanno confermato la possibilità di smaltire la biomassa oggetto di studio recuperando il calore dai fumi prodotti durante il processo di combustione. Infine, è stato simulato un processo su scala produttiva utilizzando i dati di un'azienda che si occupa della lavorazione di prodotti agricoli di IV gamma.

Potranno essere condotti ulteriori studi sullo smaltimento dei fumi esausti in uscita dall'essiccatore, tenendo conto della necessità di un trattamento di pulizia degli stessi prima della loro emissione in atmosfera. In aggiunta, sarà necessario considerare anche un processo di trattamento per lo smaltimento delle ceneri da combustione. Infine, potrà essere eseguita un'analisi economica del processo per valutarne la sua convenienza in confronto alle altre tecnologie.

---

# References

1. Khan A.A. et al., *Biomass combustion in fluidized bed boilers: potential problems and remedies*, Fuel Process Technol **90** 21-50 (2009).
2. 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 **31** 171-192 (2005).
3. Saidur R. et al., *A review on biomass as a fuel for boilers*, Renewable and Sustainable Energy Reviews **15** 2262-2289 (2011).
4. Nikoo M.B., Mahinpey N., *Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS*, Biomass and Bioenergy **32** 1245-1254 (2008).
5. Jenkins B.M. et al., *Combustion properties of biomass*, Fuel Processing Technology **54** 17-46 (1998).
6. Faaij A.P.C., *Biomass combustion*, Encyclopedia of Energy **1** 175-191 (2004).
7. Demirbas A., *Combustion characteristics of different biomass fuels*, Progress in Energy and Combustion Science **30** 219-230 (2004).
8. Basu P., *Biomass gasification and pyrolysis: practical design and theory*, Elsevier (2010).
9. Demirbas A., *Relationships between heating value and lignin, moisture, ash and extractive contents of biomass fuels*, Energy Exploration & Exploitation **20** 105-111 (2002).
10. Vassilev S.V. et al., *An overview of the chemical composition of biomass*, Fuel **89** 913-33 (2010).
11. Di Ciaula A. et al., *Il trattamento della frazione organica dei rifiuti urbani (FORSU)*, ISDE Italia (2015).
12. Tsukahara K., Sawayama, S., *Liquid fuel production using microalgae*, Journal of the Japan Petroleum Institute **48** 251-259 (2005).
13. Demirbas A., *Biorefineries: Current activities and future developments*, Energy Conversion and Management **50** 2782-2801 (2009).



14. Comitato Tecnico-GDL Digestione Anaerobica, *L'integrazione tra la digestione anaerobica e il compostaggio*, C.R.P.A (2006).
15. RENAEL, APAT, *Vademecum fonti rinnovabili – Energia da biomasse*, (2005).
16. Vamvuka D., *Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes - An overview*, International Journal of Energy Research **35** 835-862 (2011).
17. Van der Stelt M.J.C. et al., *Biomass upgrading by torrefaction for the production of biofuels: A review*, Biomass and Bioenergy **35** 3748-3762 (2011).
18. Kopczynski M., Plis A., Zuwala J., *Thermogravimetric and kinetic analysis of raw and torrefied biomass combustion*, Chemical and Process Engineering **36** (2) 209-223 (2015).
19. He C. et al., *Wet torrefaction of biomass for high quality solid fuel production: A review*, Renewable and Sustainable Energy Reviews **91** 259-271 (2018).
20. Kaushal P., Tyagi R., *Advanced simulation of biomass gasification in a fluidized bed reactor using Aspen Plus*, Renewable Energy **101** 629-636 (2017).
21. Neubauer Y., *Biomass combustion science, technology and engineering*, Woodhead Publishing Limited (2013).
22. Davis C., *Heat of combustion of algae for use in a diesel engine*, University of Tennessee at Chattanooga (2013).
23. Molino A. et al., *Biomass gasification technology: The state of the art overview*, Journal of Energy Chemistry **25** 10-25 (2016).
24. Favas J. et al., *Hydrogen production using plasma gasification with steam injection*, International Journal of Hydrogen Energy **3** 1-9 (2017).
25. Van Loo S., Koppejan J., *The Handbook of Biomass Combustion and Co-firing*, Earthscan (2008).
26. Gebreegziabher T. et al., *Design and optimization of biomass power plant*, Chemical Engineering Research and Design **92** 1412-1427 (2014).
27. Luk H.T. et al., *Drying of biomass for power generation: A case study on power generation from empty fruit bunch*, Energy **63** 205-215 (2013).
28. Chua K.J., Chou S.K., *Low-cost drying methods for developing countries*, Trends in Food Science and Technology **14** 519-528 (2003).
29. El-Sebaili A.A. et al., *Experimental investigation of an indirect type natural convection solar dryer*, Energy Conversion and Management **43** 2251-2266 (2002).
30. Grover P.D., Mishra S.K., *Biomass Briquetting: Technology and Practices*, Regional Wood Energy Development Programme (1996).

31. Parikh J. et al., *A correlation for calculating HHV from proximate analysis of solid fuels*, Fuel **84** 487-494 (2005).
  32. Pangavhane D.R. et al., *Design, development and performance testing of a new natural convection solar dryer*, Energy **27** 579-590 (2002).
  33. Palma G., *Produzione di microalghe in fotobioreattori: influenza della luce e sfruttamento della biomassa esausta*, Tesi di laurea magistrale in ingegneria chimica e dei processi industriali, Università degli Studi di Padova (2012).
  34. Al-Malah K.I.M., *Aspen Plus: Chemical Engineerign Applications*, Wiley (2016).
-



*“La vita è un insieme di avvenimenti, di cui l’ultimo potrebbe anche cambiare il senso di tutto l’insieme”* (Cit. I. Calvino)

I would like to thank the Prof. Gaetano Lamberti for giving me again the opportunity to work in his group and for making me feel part of what has been my second family in these recent months.

A special thanks goes to my supervisor Ing. Sara Cascone for the great support she gave me in these months. I thank her for the patience, for the precious advices and for the laughs together which made this period pleasant.

Thanks to my family for the support given to me in these years and thanks to Francesco for being present every time, even in my no moments.

Thanks to the guys of the T5a lab. for all the funny moments spent together: R’amen boys! Thank to Vincenzo, with whom I shared these months of laboratory life; his “culture” moments during the lunch break have made him one of a kind.

People to appreciate would be very many, but the time is short so, a collective thanks to all of you who in these years have supported me during this university “adventure”.

