الجمهورية الجزائرية الديموقراطية الشعبية

People's Democratic Republic of Algeria

وزارة التعليم العالي و البحث العلمي

Ministry of High Education and Scientific Research

جامعة قاصدي مرباح – ورقلة

Kasdi Merbah University – Ouargla

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Thesis presented in order to obtain Master Degree

in Chemical Engineering

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Entitled:

Valorization of household waste by the bio-drying process assisted by a thermal source

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Academic Year: 2021/2022

Acknowledgement

First of all, we’d like to express our sincere gratitude towards Allah. Due to his will, we were able to implement this project and finish it successfully despite the difficulties we faced.

We extend our most beautiful expressions of love and devotion to the parents in particular, and every family member for standing by our side and providing the necessary support.

Our sincere appreciation goes to our supervisor, Dr. Djamel Mennouch & Mr. Hathat Azzeddine for their endless support and guidance throughout the whole process of this project their valuable advice; support and encouragement have helped us during this semester.

We would like to sincerely thank the members of the jury who honor us by judging our end-of-study dissertation.

Last but not least, special thanks go to our friends who have helped us out with their abilities.

Abstract:
The biological drying experiments were carried out by using two dryers, the first is an oven, the purpose of this step is to improve the ideal sludge ratio and operating temperature and the second is a tunnel dryer that aims to apply the initial application settings with the addition of thermal resistance and air stream.
Experimental studies on biodrying of food waste mixed with sludge based on the preparation of 3 samples (1/3 Sl + FW, 1/5 Sl + FW) and FW without sludge, where it was found that (1/3 Sl + FW) is the optimal sample at 45°C. Where was the result as follows: VSf=62.98%, and this indicates that the bacterial activity contributes the Reduction of moisture content and thus improves bio-drying.
Keywords: Bio-drying, Thermal resistance, Food waste, Moisture content.

ملخص:
تم إجراء التجفيف الحيوي على مرحلتين ،الأولى باستخدام غرفة البخار والغرض من هذه الخطوة تحسين نسبة الحمأة ودرجة الحرارة المثلى ، والثانية باستخدام مجفف نفقي يهدف إلى تطبيق إعدادات المرحلة الأولى مع إضافة المقاومة الحرارية وتدفق الهواء.
قمنا بتحضيرعينتين من نفايات الطعام الممزوجة بالحمأة بنسب مختلفة (3/1 و 5/1) و أخرى بدون حمأة ، حيث وجد أن العينة التي تحتوي على نسبة 3/1 من الحمأة هي العينة المثلى عند 45 درجة مئوية، و كانت النتيجة كالتالي: VSf = 62.98٪ مما يدل على أن النشاط البكتيري ساهم في تقليل محتوى الرطوبة وبالتالي حسن من التجفيف الحيوي.
الكلمات المفتاحية:التجفيف الحيوي، مقاومة حرارية، نفايات الطعام، محتوى الرطوبة.

Résumé :
Le séchage biologique a été réalisé en deux étapes, la première à l'aide d'un étuve et cette étape a pour but d'améliorer le Pourcentage de boues et la température optimale, et la seconde à l'aide d'un séchoire tunnel visant à appliquer les paramétre de la première étape avec l'ajout de la résistance thermique et du débit d'air.
Nous avons préparé deux échantillons de déchets ménagers mélangés avec des boues dans des proportions différentes (1/3 et 1/5) et un autre sans boues, où il a été constaté que l'échantillon contenant 1/3 des boues est l'échantillon optimal à 45C°, et le résultat était le suivant : VSf = 62,98 % indiquant que l'activité bactérienne a contribué à la réduction de la teneur en humidité et a ainsi amélioré le bio-séchage.
Mots clés :Séchage biologique, Résistance thermique, Déchets ménagers, Humidité.

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Chapter II: Experimental procedure

Chapter III: Results & Discussion

Abbreviation

BA	Bulking Agent
BDD	Bio-Drying Duration
d.b	dry base
DM	Dry Mass
FW	Food Waste
MCs	Moisture Contents
MSW	Municipal Solid Waste
VS	Volatile Solid
Sl	Sludge
SR	Sludge Ratio
SRF	Solid Recovered Fuel
TS	Total Solid
w.b	wet base
Wdry	Weight dry
WTE	Waste To Energie
Wwet	Weight wet

Contents

General Introduction

In fact**,** the massive production of household waste in Algeria, will gradually taking us to a catastrophic turn, unless a sustainable strategy and an organized system of management of this type of waste were previously adopted.

Several treatment methods are practiced all over the world, such as recycling, land filling, composting and incineration. In recent years a new alternative has been implemented, allowing the recovery of energy from the organic fraction of waste. It is the bio-drying process which is a modern method for the recovery of household and similar waste.

In this context the objective of this work is the valorization of household waste by a bio-drying process in order to obtain a final product (SRF) in one hand and protecting the environment in the other hand, that can be stored for future use to produce energy (heat, electricity….etc.), in addition we seek to optimize the operating parameters of our drying process by using the Stat graphics software based on the experimental design method.

The work plan is as follows:

Chapter I: Bibliographic study on the bio-drying process.

Chapter Ⅱ: Experimental procedure.

Chapter III: Result and Discussion.

Finally, we ended this work with a conclusion that includes a general interpretation of the results of the study.

Chapter I: Bibliographic study on the bio-drying process

Chapter I: Bibliographic study on the bio-drying process

I.1. Introduction:

In this chapter, we will conduct a general study to provide an overview of waste characteristics and the various techniques used to combat this phenomenon, with a focus on bio-drying and the factors that influence it.

I.2. Definition of waste:

According to article 3 of the Law of December 12, 2001, it is any residue of a process of production, transformation or use. And more generally any substance, or product and any movable property which the owner or holder gets rid of, plans to get rid of, or which he has the obligation to get rid of or eliminate. However, the term waste can be the subject of many definitions, depending on the aspect considered. From a sociological, environmental and systemic, legal and economic point of view, “waste” takes on deferent meanings [1].

I.3. Household waste:

According to article 3 of the Law of December 12, 2001, all waste from households as well as similar waste from industrial, commercial, craft and other activities which, by their nature and composition, are similar to household waste [1]. Household waste consists of:

• A recyclable part: glass, cardboard, paper, etc.

• A non-recyclable so-called ultimate part: destined for landfill.

Figure I. 1 Non-recyclable household waste.

Figure I. 2 Recyclable household waste.

I.4. Characterization of household waste:

I.4.1. Density:

Density highlights the relationship between the mass of garbage and the volume it occupies. It is one of the important parameters both in the choice and the design of the means of transportation of urban waste. However, as household waste is essentially compressible, but also subject to a certain expansion, its density can vary widely during the handling it undergoes.

I.4.2. Humidity:

Household waste contains a quantity of water which is that contained in its components, so that the overall water content varies essentially with the respective proportions of these components. , the humidity of household waste in DCs (Developing Countries) is often very high, around 60 to 80%, due to the large putrescible organic fraction that composes them.

I.4.3. Calorific value:

The Net Calorific Value (NCV) of household waste is the amount of heat released by the combustion of a unit weight of raw waste. In general, the higher the water content, the lower the PCI.

I.4.4. The ratio of carbon and nitrogen content:

The C/N ratio was chosen as a quality criterion for the products obtained by composting waste. It is of great importance for the biological treatment of waste, because the evolution of waste in fermentation can be followed by theregular determination of this ratio.

I.5. Different waste treatment process:

I.5.1. Incineration:

Incineration is a thermal treatment method where the controlled burning of waste materials at a temperature of 870 C°–1200 C° for a sufficient time will oxidize about 99% of the organic matter to produce high pressure steam for power generation. Waste incineration reduces the volume and weight of the waste by 90% and 70% respectively [2]. Incineration is the primary approach of waste treatment technology that converts biomass to electricity.

I.5.2. Composting:

Composting is a biological method where the organic component of MSW is aerobically treated to create a product called compost, at relatively low-cost, which is suitable for agricultural purposes [3, 4]. During composting, readily degradable substrates are rapidly consumed and the heating process releases significant energy. Depending on the degradability of the organic substrate, the oxygen supply and heat loss, the temperature of the material can rise up to 70 °C or more which eliminate the pathogens from the material [5] .

I.5.3. Land-filling:

The landfill is a land that is built up from deposits of solid refuse in layers covered by soil. It consists of a random mixture of food scraps and other kitchen waste, paper, plastic, metals, and glass. Organic waste dumped in a landfill site will decompose with time, but the inorganic constituents will be remaining for a long time. Since each landfill has its own particular constituents and the leachate quality of a particular landfill also changes over time. The main environmental problem associated with the landfill is the pollution of ground water.

I.5.4. Recycling:

It is possible to recover and reuse many materials found in waste to make new products of the same type or a different type [6].

I.6. Bio-drying process:

Biodrying is an aerobic convective evaporation process which reduces the moisture content of the waste, with minimum aerobic degradation[7].This process is different from composting in that the output of the composting process is stabilized organic matter, but the output of the biodrying process is only partially stabilized, which is useful for energy production [8].

This mechanism is accomplished by relying on microorganisms, both bacteria and fungi to biologically degrade the organic component [9]. According to the general global reaction of biodegradation:

$$COHN + O2 + Microorganism \rightarrow CO2 + NH3 + Energy$$

Mixed sludge usually contains mesophilic and thermophilic organisms. The growth and mortality rate of different types of microorganisms are highly dependent on temperature.

The microorganisms role in biodrying is divided as (1) Psychrophile micro-organisms reach their maximum growth rates below 20°C; (2) Mesophilic microorganisms between 20°C and 42°C and (3) Thermophilic organisms above 40 °C with a growth limit at 70 °C [10] .

Mesophilic microorganisms cannot withstand temperatures above 45 ºC. As for thermophilic microorganisms, they die at temperatures above 70 ºC. This type of bacteria grows weakly when the temperature is below 40 ºC; the growth of mesophilic organisms is therefore essential to reach temperatures acceptable to thermophiles. Hyperthermophilic microorganisms cannot survive at temperatures below 60°C and are generally not present in the sludge when it is loaded into the dryer. The maximum temperature of the bio-dryer is therefore limited to 70 ºC by thermophilic microorganisms. As shown in the ***Figure I.3***:

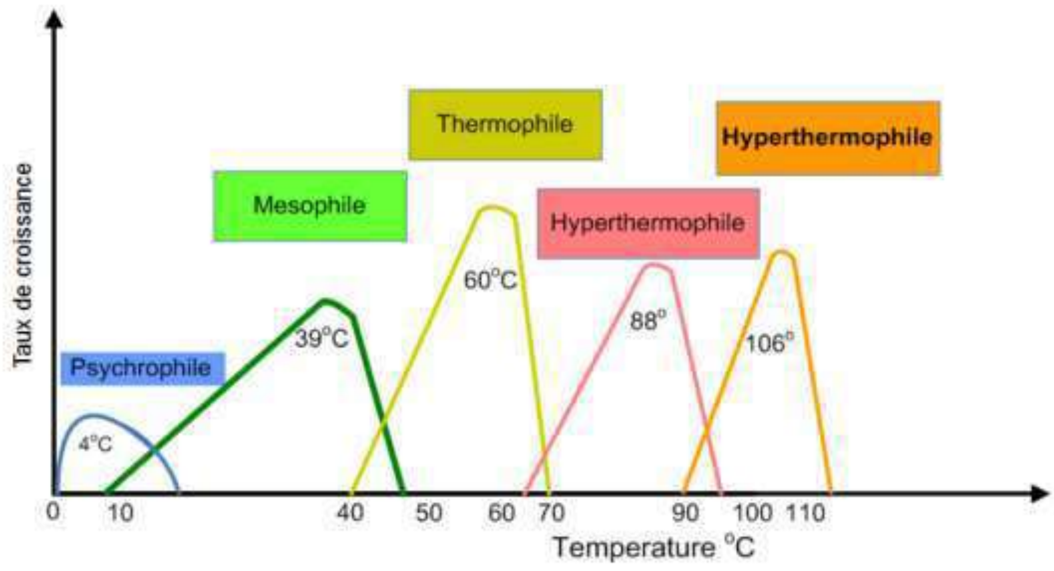


Figure I.3 Growth rates of different organisms [11].

The principle of biodrying process is that effective utilization of the heat energy produced during the self heating reaction of municipal solid waste can be used for evaporation of water from the same. The source of energy for the self heating reaction is the easily biodegradable ingredients and the heat released during aerobic degradation of the same can be used for drying. In another view point in the biodrying process the transition of the substrate takes place, when the required heat is generated on the biochemical path [12]. The basic process flow during the biodrying process is shown in ***Figure I.4***:

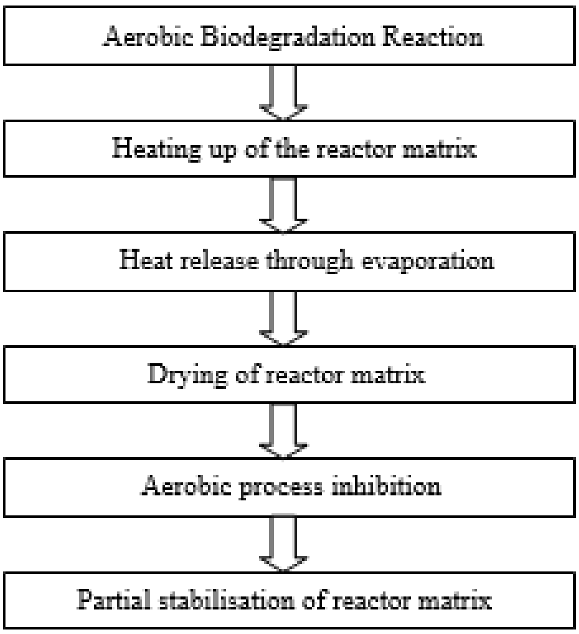


Figure I. 3 The Process Flow Diagram of Biodrying.

I.6.1. Factors affecting bio-drying process:

I.6.1.1. Moisture content:

Moisture content of the waste is considered as a single critical parameter for evaluating the efficiency of bio-drying process. The moisture content influences microbial activity and biodegradation of the organic component during bio-drying process. Most organic wastes like dewatered sewage sludge, food waste and garden waste contain abundant water with a typical moisture content around 80% or higher, and this excessive moisture affects particle aggregation, causes packing and reduces void space, which all prevents efficient air movement throughout the matrix and limits aerobic decomposition [13,14].

I.6.1.2. Air-flow rate:

According to literature, it has been established that air-flow rate is the main operational parameter used both in laboratory and commercial applications for process control in bio-drying process. The air-flow rate has a direct influence on the matrix temperature and drying efficiency.

Skourides et al.[15] investigated the agitated bio-drying of the organic fraction of municipal solid and the results showed maximum drying rate achieved for the highest aeration rates used (120 m3/h), leading to lower final moisture content levels (20% w/w from an initial 40% w/w) with a short retention time of less than 7 days. In a similar study to investigate the effect of air-flow on the bio-drying of gardening wastes, it was found that higher air-flow rate corresponds to greater weight loss (40–57% weight loss) and leachate production at low air-flow.

I.6.1.3. Temperature:

Frei et al. [16] and Navaee-Ardeh et al [17] indicated that high temperatures (>55°C) during biodrying process enhance the conversion of moisture to vapor and also facilitate the vapor pressure of the air-flow passing through the matrix to carry more moisture out. Accordingly, the biodegradation potential of a bulking agent (BA) would significantly influence the bio-drying process by the bio generated heat.

I.6.1.4. Bulking agents:

The use of bulking agent (BA) plays a crucial role in bio-drying process. The use of BA adjusts the initial moisture content and facilitates air movement due to the increase in voids ratio. It effects on bio-drying has been demonstrated by some authors. A number of different materials as bulking agents have been used by different researches including bark to bio-dry sewage sludge [16], and sawdust and/or straw [18,19] .

Moreover, BA is important for regulating the matrix porosity and enabling air flow to carry away the water vapor passing through the matrix. For effective bio-drying, it is important to consider the physical structure as well as biodegradability of the bulking agent. In another study, rice straw of different sizes as BA was used in sludge bio-drying and it was reported that small-particle size BA reduced the water content by 0.3% more compared to the large particle size BA [20] .It is revealed that straw has substantial biodegradation potential in bio-drying process while sawdust has poor capacity to be degraded [19] . In order to improve the efficiency of bio-drying, it is important to consider the physical structure as well as the biodegradability when selecting a material as BA.

I.7. Previous Studies on Biodrying Processes:

Beilin and Sevket Tulun have studied the process ofbio-drying and the results were as follows:

The waste was placed in a reactor with a constant air flow of 50 L/h and initial moisture contents between 48.49 and 50.00%. Experiments were conducted on a laboratory scale using a 36-liter bio-drying reactor. To determine the effect of temperature on bio-drying, the process was repeated at different temperatures between 30°C and 50°C. After 13 days, the result was that bio-drying reduced the waste volume content by 32% and the final product had a high calorific value (4680) Kcal/kg) [21].

As reported by Frei and al.[22] and Roy and al.[23]**,**the typical temperature range in the biodrying process is 15–55 °C, although temperatures of up to 65 °C have been observed. These bacteria are sensitive to the temperature of the matrix in which they grow. Too high temperatures kill mesophilic bacteria while favoring the growth of thermophiles.

Works of Adani et al. [24] have indicated that appropriate management of the processing parameters (airflow rate and biomass temperatures) could achieve biomass drying in very short times (8–9 days). This biomass can be very heterogeneous, such as sludge, MSW and harvest wastes [25,24].

I.8. Waste to Energy Technologies:

Technologies for the recovery of energy from the waste materials into useable heat, electricity, or fuel are generally called waste to energy technologies (WTE). Waste to energy (WTE) technology has the potential to reduce the volume of the original waste by 90%, depending on the composition by recovering the energy [26, 27]. In the hierarchy of solid waste management, WTE is ranked before the final disposal, indicating the limitations of this option regarding the economic and environmental benefits [28] .Waste to energy (WTE) processes recover the energy from the waste through either direct combustion (e.g., incineration, pyrolysis and gasification) or production of combustible fuels in the form of methane, hydrogen and other synthetic fuels (e.g., anaerobic digestion, mechanical biological treatment and refuse derived fuel) [29] .

I.9. The advantages and disadvantages of biodrying:

I.9.1. Advantages:

Drying this type of waste reduces its total weight and makes it easier to handle, which also reduces handling and transport costs [18].

It can be used to produce certain biofuels from waste. Bio-drying is a source of energy savings because it limits the use of fossil fuels and/or electricity**.**

I.9.2. Limits or disadvantages:

It is more effective in hot regions. It takes longer than techniques using a conventional electrical or thermal source (or solar in sunny regions).

It has no real disinfectant power and does not stabilize bio-waste (if it is still biodegradable). Such waste stored in a landfill or in wet conditions will continue to degrade and eventually produce methane (greenhouse gas, which contributes to climate change).

I.10. Conclusion:

By reducing the moisture content in the waste matrix and preserving the majority of the calorific value or energy content of the organic matter present, the bio-drying process tends to increase the energy content of the bio-dried material.

Chapter Ⅱ: Experimental procedure

Chapter Ⅱ: Experimental procedure

II.1. Introduction:

This study is intended to evaluate the role of melting dewatered sludge with FW in favor of biodrying process promoting the bacterial activity; the process will be thermally assisted to enhance the moisture content using two experimental setups:

The 1st one, we expose FW to convective heat in oven temperature the operation focused in optimization of the ideal sludge ratio and the operating temperature.

The second aims to apply the first experimental setup's optimum biodrying paramaters using dryer tunnel to enhance the quality of final biodryed product using forced air stream.

II.2. Materials and methods:

II.2.1.Step 1:

The waste is composed as the following: 80% of the total weight is vegetables, 15% of it is fruits and 5% bread, as shown in ***Table II.1*** .The whole prepared quantity of FW is shredded into small pieces (slices) of about 20*5mm area, after that we mix it all together.

Table II. 1:Waste compositions.

Type	Name	Weight (kg)	Percentage of each item	%(From total waste)
Vegetables	Potato	0.1	3.1	80
	Carrots	0.4	12.5	
	Tomatoes	0.3	9.37	
	Turnip leaf	0.4	12.5	
	Courgette	0.3	9.37	
	Salad	0.3	9.37	
	Beetroot	0.3	9.37	
	Beetroot leaves	0.8	25	
	Spring onions	0.3	9.37	
	Total:3.2kg			
Fruits	Lemon	0.3	50	15
	Orange	0.3	50	
	Total:0.6kg			
Others	Bread	0.2	100	5
	Total:0.2kg			
Total	**4kg**			**100%**

3 trials have to be prepared: the 1st is FW without sludge, the 2nd with 1/5 sludge ratio, the 3rd with 1/3 sludge ratio as follows:

Table II. 2: 3 Trials composition setup.

Trials	FW	1/3 Sludge + FW	1/5 Sludge + FW
Weight (g)	600	200(Sludge)+400(FW)	120(Sludge)+480(FW)

The three trials are placed in a programmed temperature drying oven (type: MEMMERT UFB 400 UNIVERSAL OVEN) two times to conduct two experiences: the 1st 45C° and the 2nd at 35C°.

The results in six samples have to be prepared from the same recipient that held the whole quantity of six samples; the whole prepared quantity of FW is melted with previously indicated quantities of sludge and then introduced in equal quantities in three metallic mesh supports of 5mm*5mm square holes and placed into the drying oven.

The initial three trials are prepared synthetically for the second time in small quantities of 60 to 50 g to conduct Total Solid test at 105°C for 24h into a drying oven and TS of sludge is also tested as well. The remained quantities resulted from TS test are introduced in a muffle oven at 550°C in presence of oxygen for 1 hour according to Volatile Solid Standard Test, and this term that express, in this scale the consumed organic matter during ignition (△VS)is considered as biodegradability index.

In the same manner final products results from two experiences respect the same procedure to conduct TS and VS.

The results are introduced in software program called experience plan in the objective of optimizing two key factors: ΔVS & BDD and is intended to find the adequate trial or FW – Sludge Melting Ratio that guaranty the best bio-drying product SRF and to assess in which trial micro-organisms are obviously played its role in bio heat generation.

Figure II. 1: Balance (Denver instrument MXX-2001).

Figure II. 2: Programmed temperature drying oven (type: MEMMERT UFB 400 UNIVERSAL OVEN) for Total Solid Test.

Figure II. 3: Humidity Analyzer IR35 Denver Instrument for initial moisture measurement.

Figure II. 4: Compact Muffle Furnace, Model: LE6/11/B150, Marque: Nabertherm for Volatile Solids Test.

Figure II. 5: Product Preparation.

II.2.1.1. Bio-Drying End Point Determination:

✓ *FW without Sludge:*

MCs (w.b) = (Wwet –Wdry)/Wwet = (1- Wdry)/Wwet then Wdry = (1- MCs w.b) * Wwet

MCs (w.b) as 5g measured by IR35 Denver Instrument equal to **87%**

So Wdry = (1- 0,87) *599,6 = 77,95 g

The bio-dyring final product (SRF) MCs standard for storing objective impose MCs (d.b.) ≤ **25 %** And MCs (d.b) = (Wwet –Wdry)/Wdry.

Then Wdry (final weight) = (1+ MCs d.b) *Wdry= (1+ 0,25) *77,95 = 97,4 g (without metallic mesh support as its weight equal to 170,5g) so 97,4 + 170,5 = **267,9 g**

✓ *FW with 1/5 Sludge ratio:*

MCs (w.b.) equal to **65%**

Drying End Point **=437,23 g**

✓ *FW with 1/3 Sludge ratio:*

MCs (w.b.) equal to **76%**

Drying End Point **=354,43 g.**

II.2.2.Step 2:

II.2.2.1. Description of the drying system:

Drying experiments were performed on tunnel dryer ***Figure II.7*** installed in the mechanical engineering laboratory, Ouargla University, Algeria. The dryer is a forced convection dryer intended for the drying of food products. Four removable stainless steel plates that can be placed in a channel (drying chamber) of dimension (250 cm x 50 cm x 50c m). The drying chamber is thermally insulated with polystyrene (thickness = 3cm), the outer part of which is covered by four galvanized sheets. A mixture of 1/3 Sl +FW deposited on a drying rack is exposed to airflow. The mass loss of the product is controlled by a digital scale .The temperature and relative humidity of the air (before and after the drying rack) are detected by a combined temperature and humidity sensor. An additional sensor serves to measure the air velocity.

The air coming from the external environment is preheated by electrical resistance.

Under the effect of a fan with adjustable speed, drying air circulates in the drying room, passes through the sample where the biodegradation happens at a constant drying temperature (45C°), and comes out at a lower temperature and high humidity.

The dryer used ***Figure II.6*** consists of the following elements :

1- Drying channel, 2- Drying racks, 3- Door, 4- Process schematic, 5- Air velocity sensor, 6- Measuring point for Temperature and humidity , 7- Digital balance, 8- Bracket for drying plates , 9- Measuring point with humidity andt emperature sensor, 10- Switch cabinet with digital displays, 11- Fan

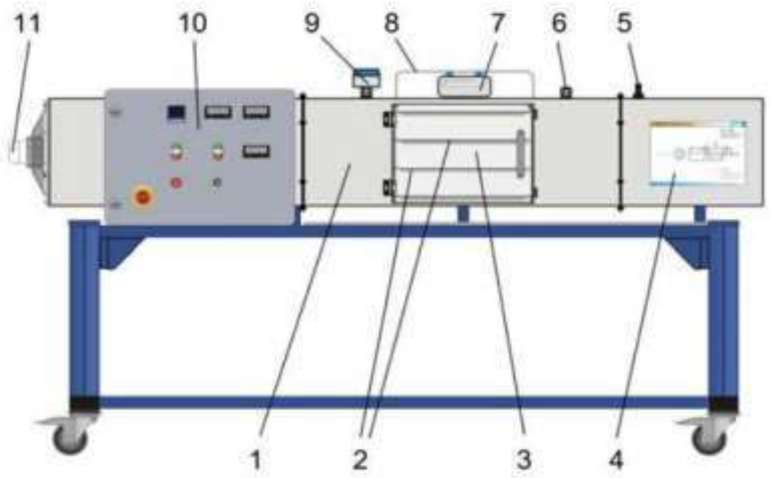


Figure II. 6: Descriptive Diagram of Convection Electric Tunnel Dryer.

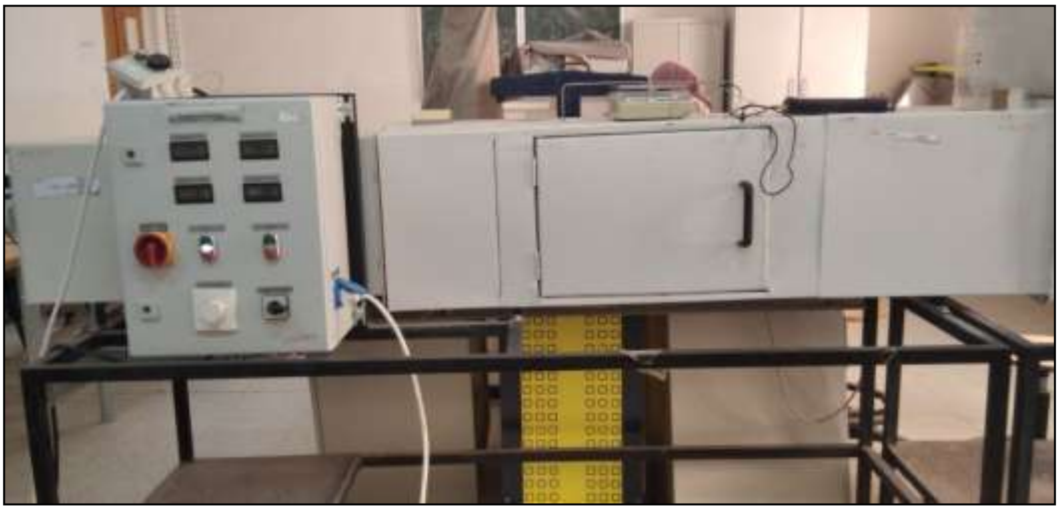


Figure II. 7: Real picture of Tunnel Dryer.

II.2.2.2. Preparing the dryer:

In order to ensure proper operation of the tunnel dryer, it is necessary to follow the following steps:

✓ Switching on the dryer.

✓ Adjustment of the ventilation to have the speed of the desired drying air (0.45 m/s) with an airflow of 28m^3/h.

✓ Resistance adjustment according to the desired drying temperature.

✓ The installation of different measuring devices ***Figure II.8***

Thermocouple Balance Anemometer

Figure II. 8: The different measuring parameters.

II.2.2.3. Sampling and product preparation:

After results which show that 1/3 Sl + FW is the optimal sample, 4 kg of the same previous composition were prepared The whole prepared quantity of FW is shredded into small pieces (slices) of about 20*5mm area, after that we mix it all together, and put it in the tunnel dryer .

We took 15 g from the composition to conduct Total Solid test at 105°C for 24h into a drying oven. The remained quantities resulted from TS test are introduced in a muffle oven at 550°C for 1h to conduct the initial volatile solid. After the experiment is finished, we calculate the final TS and VS.

II.2.2.4. Bio-Drying End Point Determination:

MCs (w.b) = (Wwet –Wdry)/Wwet = (1- Wdry)/Wwet then Wdry = (1- MCs w.b) * Wwet.

MCs (w.b) as 15g measured by IR35 Denver Instrument equal to **73%.**

So Wdry = (1- 0,73) *3893.30 = 1051.191 g.

The bio-dyring final product (SRF) MCs stds for storing objective impose MCs (d.b.) ≤ **25 %** [30]. And MCs (d.b) = (Wwet –Wdry)/Wdry.

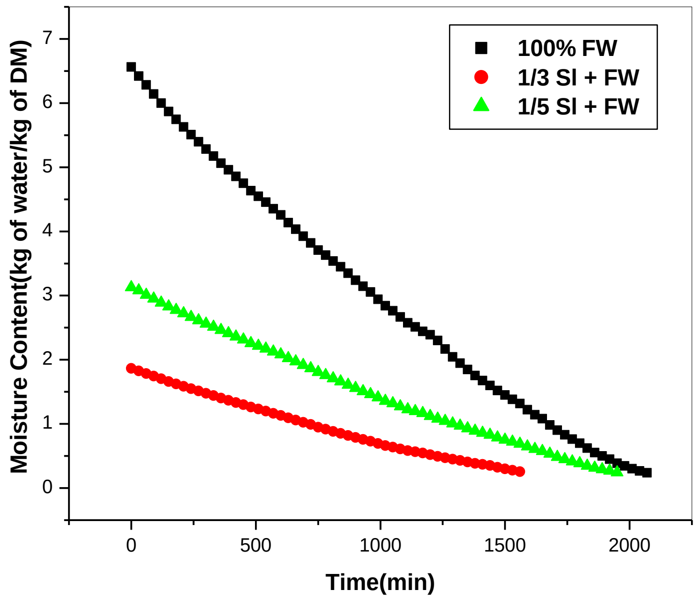
Then Wdry (final weight) = (1+ MCs d.b) *Wdry= (1+ 0,25) *1051.191 = 1313.98 g (without metallic mesh support as its weight equal to 1726.7 g) so 1313.98 + 1726.7= **3040.69g .**

Chapter III:
Results & Discussion

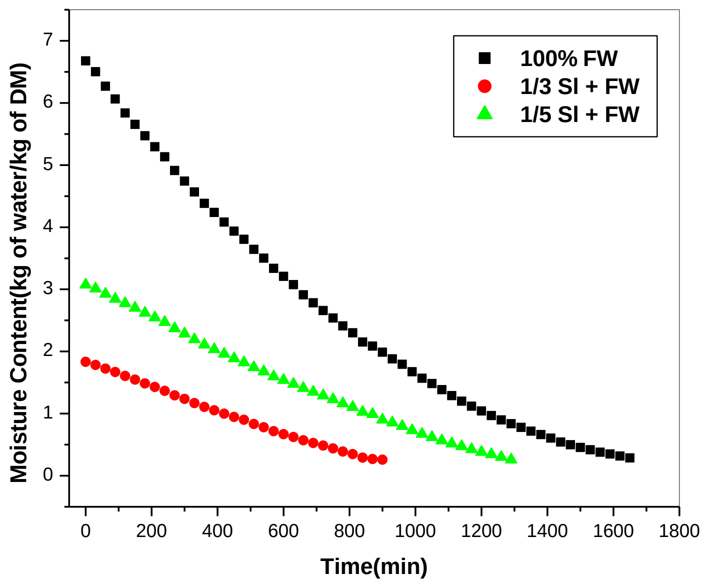
Chapter III: Results & Discussion

III.1.Kinetic Part:

III.1.1. Step 1:



(a)



(b)

Figure III. 1: The effect of sludge ratio on bio drying duration for (a) T=35C°, (b) T=45C°.

The figure represents the effect of sludge ratio on the duration of bio drying for T=45C° and T=35C°, according to this figure we notice a decrease for the 3 cases of sludge ratio in the 2 temperatures .We also note that sludge ratio of 1/3 is the one that took the least time in bio drying then 1/5 and 100% FW. It is obviously noticed that sludge has a positive effect on initial humidity reduction and then on organic matter degradation, also the direct effect of sludge ratio on bio-drying duration.

It is noticed in the ***Figure III.2*** that the temperature T=45C° causes a reduction in the duration of bio drying more than T=35C° in the 3 cases of composition this indicates that the temperature 45C° contributes to the acceleration of bio drying and causes better bacterial activity than that T =35C°.

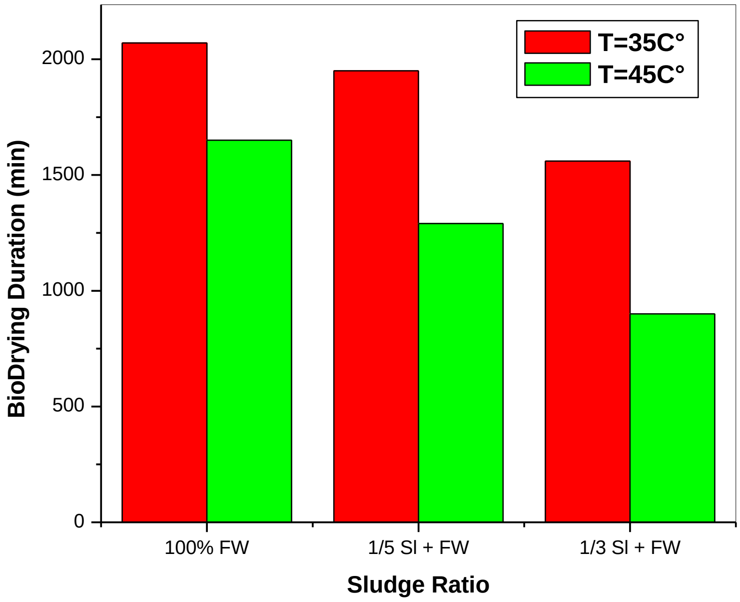


Figure III. 2: The effect of Temperature on bio drying duration.

III.1.1.1. Total Solids & Volatile Solids determination:

✓ ***Total Solids content:***

The total solids content is expressed as a ratio of weights obtained before and after the drying process. The test protocol consists of placing a Waste sample (25 to 50g) in an oven at a temperature of 105 °C until a steady mass is obtained (24hours).

$$\boldsymbol{TS}(\%) = \frac{(\boldsymbol{Wi} - \boldsymbol{Wf})}{\boldsymbol{Wi}} \times \mathbf{100}$$

Wi: Dried residue weight before the drying in the oven at T=105C°.
Wf : Dried residue weight after the drying in the oven at T=105C°.

✓ ***Volatile Solids Content:***

The residue from the 105°C drying process is heated to 550°C for one hour in a muffle oven.

% Volatile Solids = [(Dry sample weight-Ash weight)/ Dry sample weight] ×100

$$\boldsymbol{VS}(\%) = \frac{(\boldsymbol{Wi} - \boldsymbol{Wf})}{\boldsymbol{Wi}} \times \mathbf{100}$$

Wi: Dry sample weight at 105C°.

Wf: Ash Weight at 550C°.

❖ *Initial TS & VS:*

Table III. 1: Initial Total Solids & Volatile Solids determination.

Sludge Ratio	Residue at 105C° (full)	The void	(-)
100% FW	12.6216 g	4.9 g	7.7216
1/5 Sl + FW	17.7810 g	4.9 g	12.881
1/3 Sl + FW	20.9340 g	4.9 g	16.034

(a)

Sludge Ratio	Residue at 550C° (full)	The void	(-)
100% FW	101.0354 g	99.8367	1.1987
1/5 Sl + FW	76.1891 g	69.1719	7.0172
1/3 Sl + FW	77.4087 g	66.8035	10.6052

(b)

Sludge Ratio	TS	VS
100% FW	87.13%	84.47%
1/5 Sl+SW	78.53%	45.52%
1/3Sl+FW	73.27%	33.858%

(c)

❖ *TS & VS of experiment T=35C°:*

Table III. 2: Solids & Volatile Solids determination for T=35C°.

Sludge Ratio	Residue at 105C° (full)	The void	(-)
100% FW	110.4590	99.8350	10.6240
1/5 Sl + FW	81.8875	69.1718	12.7157
1/3 Sl + FW	78.2156	66.8043	11.4113

(a)

Sludge Ratio	Residue at 550C° (full)	The void	(-)
100% FW	102.6741	99.8350	2.8391
1/5 Sl + FW	76.8597	69.1718	7.6879
1/3 Sl + FW	75.0817	66.8043	8.2774

(b)

Sludge Ratio	TS	VS
100% FW	82.29%	73.27%
1/5 Sl + FW	78.80%	39.54%
1/3 Sl + FW	80.98%	27.46%

(c)

❖ *TS & VS of experiment T=45C°:*

Table III. 3: Total Solids & Volatile Solids determination for T=45C°.

Sludge Ratio	Residue at 105C° (full)	The void	(-)
100% FW	111.9958	99.8382	12.1608
1/5 Sl + FW	80.5284	69.1738	13.3566
1/3 Sl + FW	75.2723	66.8045	8.468

(a)

Sludge Ratio	Residue at 550C° (full)	The void	(-)
100% FW	102.1425	99.8382	2.3075
1/5 Sl + FW	75.2444	69.1738	6.0726
1/3 Sl + FW	72.0035	66.8045	5.1992

(b)

Sludge Ratio	TS	VS
100% FW	79.73%	81.02%
1/5 Sl + FW	77.73%	46.52%
1/3 Sl + FW	85.88%	38.60%

(c)

Table III. 4: Final result of VS.

Sludge Ratio	VS (initial)	VS of T=35C°	VS of T=45C°	ΔVS of T=35C°	ΔVS of T=45C°
100% FW	84.47%	73.27%	81.02%	11.2%	3.45%
1/5 Sl + FW	45.52%	39.54%	46.52%	5.98%	1%
1/3 Sl + FW	33.858%	27.46%	38.60%	6.398%	4.722%

III.2.Modeling and optimization part:

This part is based on the use of the Stat-Graphic software according to a mixed factorial experimental design (see table III.5).

Table III. 5: The factors and responses of the proposed experimental design.

N°=EXP	SR	T	ΔVS	BDD
			%	Min
1	-1	-1	11.2	2070
2	-1	1	3.45	1650
3	0	-1	5.98	1950
4	0	1	1	1290
5	1	-1	6.398	1560
6	1	1	4.722	900

Level (-1)	100% FW	35C°
Level (0)	1/5 Sl+ FW	/
Level (+1)	1/3 Sl+ FW	45C°

III.2.1 The different answers in the experimental plan:

- Volatile Solid***:***

The analysis result for the volatile solid response gives us the following mathematical model:

$$\Delta VS = 3.49 - 0.8825*SR - 2.401*T + 2.9525*SR^2 + 1.5185*SR*T$$

Or:

SR: The factor of Sludge Ratio.

T: The factor of Temperature.

The different values of the coefficients of the mathematical model are mentioned in ***Table III.6***, of which:

Constant: presents the value of the response at the center of the study area.

A: presents the effect of the state of composition.

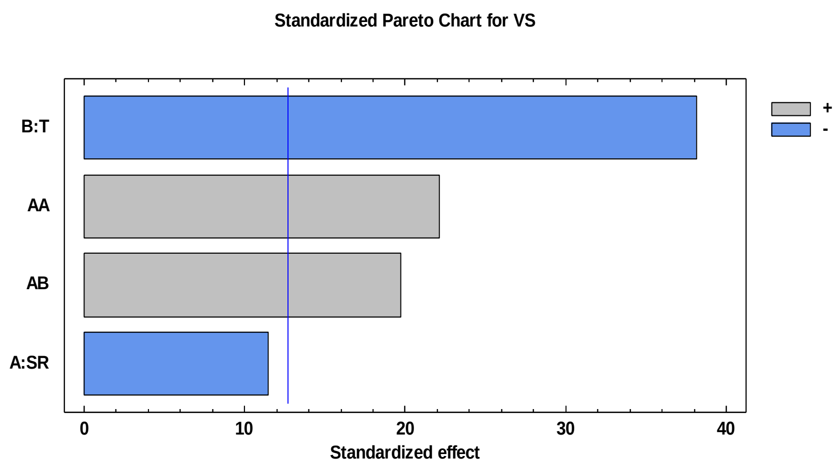
B: presents the temperature effect.

AB: The interaction between the SR and T.

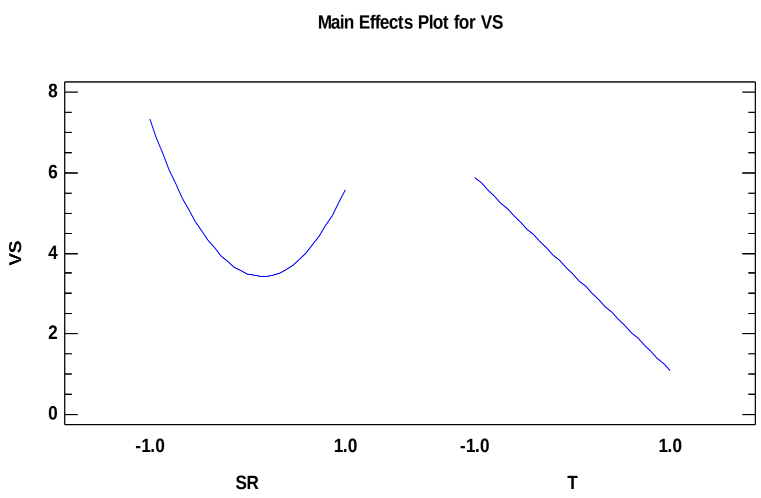
Table III. 6: The values of the coefficients of the mathematical model of volatile solid.

Coefficient	***Value***
Constant	3.49
A: SR	- 0.8825
B: T	- 2.401
AB	1.5185
AA	2.9525

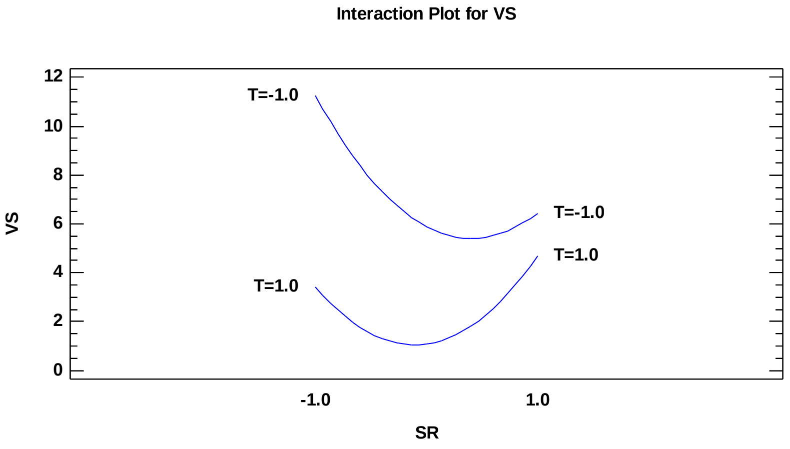
Figure III.3 (a) (b) and (c) shows the different effects and interaction on volatile solid .We note that the sludge ratio (a) and the temperature (b) have negative effects, which drying temperature is the most influential factor than the SR, on the other hand interactions (AA), (AB) presents a positive and less important effect.



(a)



(b)



(c)

Figure III. 3: Pareto chart (a), effects (b) and interaction (c) on volatile solid.

The response surface and the contour of ***Figure III.4*** show that the temperature and sludge ratio have negative effect on volatile solid.

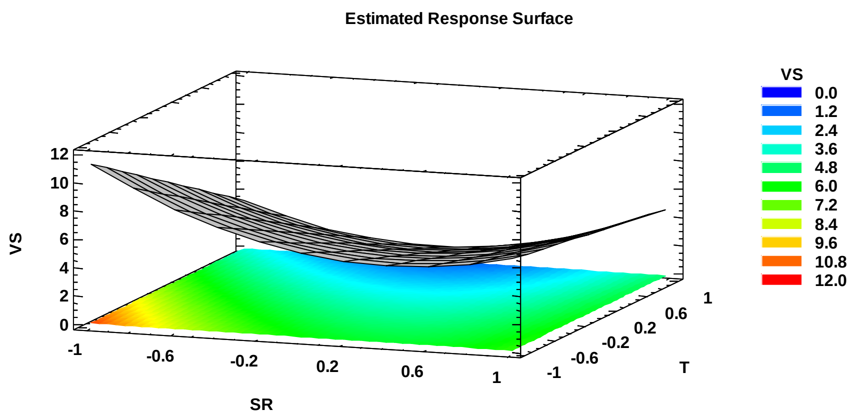


Figure III. 4: Response surface and contour on volatile solid.

➢ ***Bio-Drying Time:***

The analysis results for the drying time response gives us the following mathematical model:

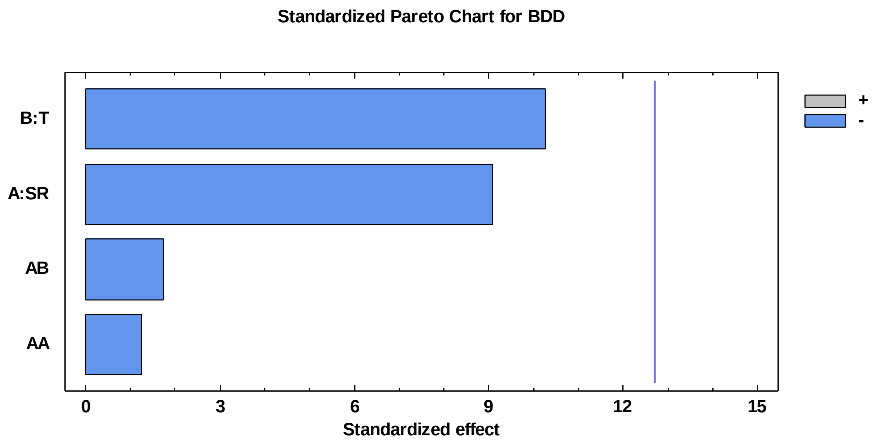
$$BDD = 1620.0 - 315.0*SR - 290.0*T - 75.0*SR^2 - 60.0*SR*T$$

The different values of the coefficients of the mathematical model are mentioned in ***Table III.7.***

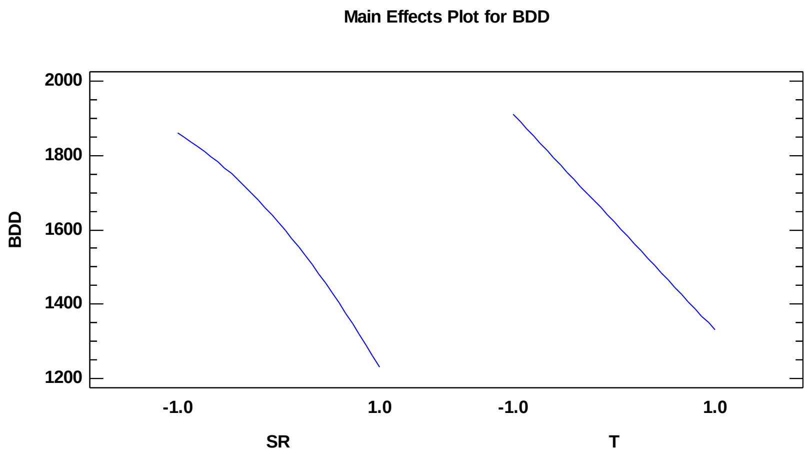
Table III. 7: The values of the coefficients of the mathematical model of drying time.

Coefficient	***Value***
Constant	1620.0
A: SR	- 315.0
B: T	- 290.0
AB	- 75.0
AA	- 60.0

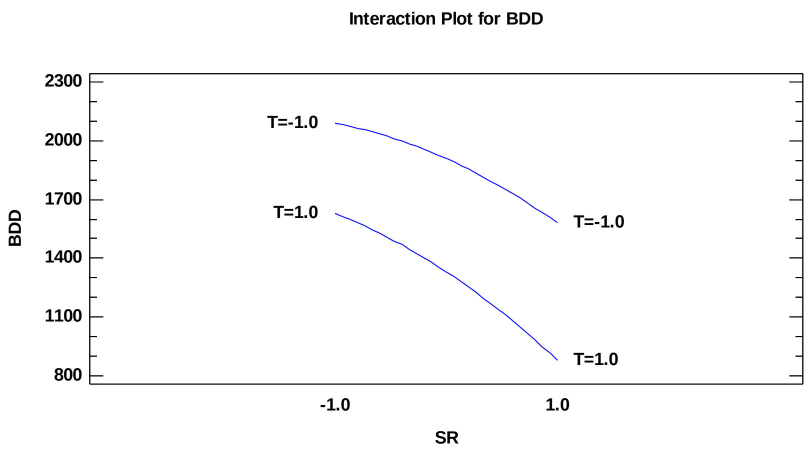
Figure III.5 (a), (b) and (c) represents the different effects and interaction on the drying time. We note that the effect of sludge ratio (A), Temperature (B) and the interaction (AB), (AA) present negative effects.



(a)



(b)



(c)

Figure III. 5: Pareto chart (a), effects (b) and interaction (c) on drying time.

The response surface and the contour of ***Figure III.6*** show that the temperature and sludge ratio have negative effect on BDD.

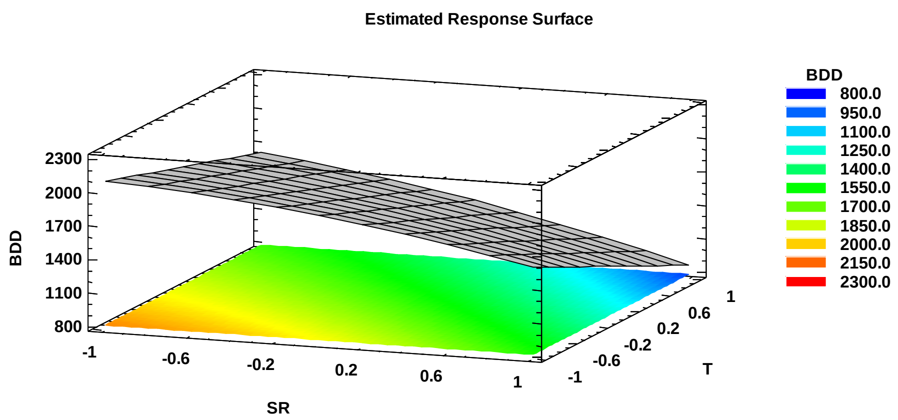


Figure III. 6: Response surface and contour on BDD.

III.2.2 Optimal conditions:

In order to determine the optimal temperature and sludge ratio conditions, an optimization study based on the analysis of all the responses (Multiple Response Optimization) using the experimental design method. The optimization objective is to minimize biodrying duration and maximize volatile solids.

The optimization results presented in the ***Table III.8***, ***Table III.9*** and ***Table III.10*** show that the optimal conditions of temperature and sludge ratio are of the order of 45°C and 33% respectively and the different responses Duration, volatile solid 900 and 4.72 respectively**.**

Table III. 8:Optimal condition real system.

Factor	*Low*	*High*	*Optimum*
SR	*0.0*	*33.0*	*33.0*
T	*35.0*	*45.0*	*44.7143*

Table III. 9: Optimal condition coded system.

Factor	*Low*	*High*	*Optimum*
SR	-1.0	1.0	1.0
T	-1.0	1.0	0.942857

Table III. 10: Different optimization responses.

Response	*Optimum*
VS	4.72707
BDD	900.0

III.1.2. Step 2:

Bio drying at the dryer tunnel took about a week and the results presented in Figure below:

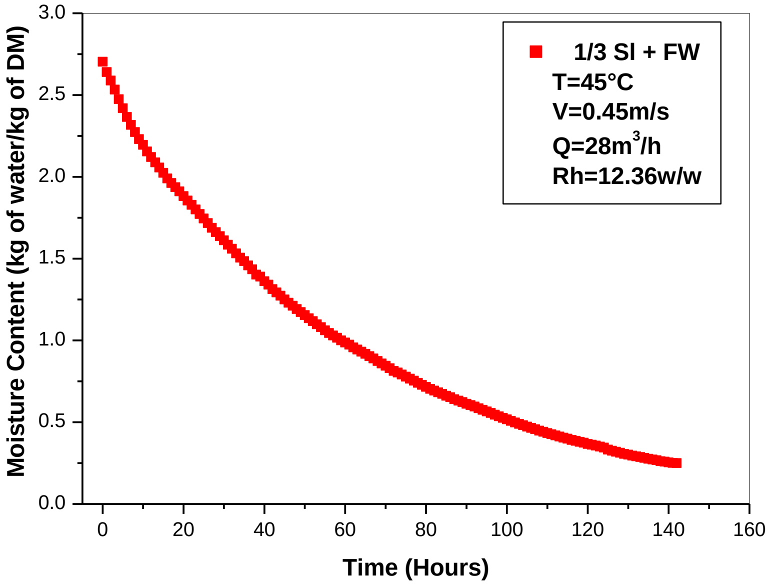


Figure III. 7: Evolution of moisture content as a function of time.

The figure shows the evolution of MC of biomass as a function of time, in the first days we notice a decrease in the graph due to diffusion and easy transfer of matter due to the evaporation of surface water (with large quantity). A slow decrease is noticed in the last days due to a diffusion of stored water (intermolecular level).

Also note about the duration of biodrying (7 days) a combination of thermal drying and biological reaction, the latter generates biological energy due to bacterial activity which improves thermal drying and therefore reduces the duration of biodrying.

III.1.2.1. Volatile Solids determination:

Table III. 11:Initial VS determination.

Sludge Ratio	Residue at 105C° (full) (g)	The void (g)	(-)
1/3 Sl +FW	52.1	48	4.1
Sludge Ratio	Residue at 550C° (full)	The void	(-)
1/3 Sl + FW	50.2	48	2.2

$$\text{VS (Initial)} = \frac{4.1 - 2.2}{4.1} \times 100 = 46.34\%$$

Table III. 12: Final VS determination.

Sludge Ratio	Residue at 105C° (full) (g)	The void (g)	(-)
1/3 Sl + FW	43.8	4.9	38.9
Sludge Ratio	Residue at 550C° (full)	The void	(-)
1/3 Sl + FW	81	66.6	14.4

$$\text{VS (Final)} = \frac{38.9 - 14.4}{38.9} \times 100 = 62.98\%$$

After finishing the experiment, we get the SRF as shown in the figure below:

Figure III. 8: Final product.

General Conclusion

This work presents an experimental study of biodrying a mixture of food waste and sludge and reported in two stages; the first one come to optimize two factors (bio drying operation temperature & sludge ratio) using an mixed factorial experimental design, the goal of the second stage is to use the dryer tunnel to apply the optimum biodrying parameters from the first experimental setup to improve the quality of the final biodryed product using a forced air stream.

The optimization study shows that the optimal operating conditions of our dryer operating temperature, sludge ratio are: (T=45C° & 1/3 sludge) and the different responses ΔVS and BDD are: 4.72%, 900 min respectively, the parameters of temperature and sludge ratio applied in the dryer tunnel.

The modeling results show that the temperature and sludge ratio have negative effects on all the response.

The finale results of dryer tunnel shows that final VS=62.98% and this means that the micro-organisms played their role in bio heat generation in the presence of air stream and reducing moisture content to get the final product (SRF) can be stored for a future use for produce energy (heat, electricity…).

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