CHEMICAL ENGINEERING TRANSACTIONS
VOL. 113, 2024
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-14-4; **ISSN** 2283-9216
DOI: 10.3303/CET24113071

Energy and Exergy Assessment of a Modular Offshore Seaweed Solar Dryer

Alexander Hamilton S. Atienza*, Luke Dave M. De Luna, Girard Robin R. San Juan, Raymund L. Solis

Mapua Institute of Technology at Laguna, Mapua Malayan Colleges Laguna, Pulo-Diezmo Road, Cabuyao, 4025 Laguna, Philippines
ahsatienza@mcl.edu.ph

This research had aimed to study and design a modular offshore solar dryer to answer the need for a more efficient dryer and for a more lenient one to assemble with aid of energy and exergy analyses. Most of the seaweed had reached the target moisture ratio of 40 % after varying drying periods, the longest of which had been observed after five days of testing, which had been 9.5 h per day. In the testing, the upper tray was the fastest in terms of drying speed. The testing had also showed that the lesser seaweed, the faster the drying time. In the first few runs, the amount of seaweed that had been placed in each tray had been higher compared to the last run. The average maximum temperature in the dryer had been observed to be 36.86 °C with the least relative humidity at 61.02 %. The average dryer performance had been discovered to be 47.68 % while the exergy efficiency ranges from 1.96 % to 93.58 %.

1. Introduction

Biofuels are yielded directly or indirectly from organic materials and animal waste. These are also used to derive bioenergy. Seaweeds, also known as marine macro-algae, are organisms that are plant-like and generally dwell in coastal areas attached to rocks or other hard surfaces. Algae are diverse organisms that can conduct photosynthesis. Photosynthesis is the process of harnessing energy from sunlight and carbon dioxide then convert it into chemical energy. Terrestrial plants grow in non-aquatic habitats, and they have the capability to collect sun's rays more effectively to fuel photosynthesis. Most common examples are trees. Algae may be farmed without the need for agricultural land, in contrast to land-based crops grown for biofuel and as a result of their ability to grow in brackish or saltwater, a wide variety of algae can produce food without competing with one another for freshwater and land (Milledge and Harvey, 2016).

The antibacterial, antiviral, and antifungal qualities of proteins, lipids, and polyphenols, as well as the high concentration of minerals, vitamins, and polysaccharides found in seaweeds, make them highly valued (Tasende, 2016) and relevant in food and pharmaceutical industries (Pralisa Putri et al., 2018). Significant antiviral activity against enveloped viruses, including herpes and HIV, is exhibited by carrageenan, fucoidans, and sulfated rhamnogalactans (Pati, 2016).

In the Philippines, of the 820 species of seaweeds recorded, some 350 species are known to have some economic value. However, less than 5 % of these are economically significant in the country since most have yet to be developed. Seaweed farming contributed 69% of all aquaculture production in the Philippines because of its significant market importance and robust market potential (BAS, 2010), which makes it a prominent and significant economic activity in the rural areas that alleviate poverty.

There are currently types of drying seaweeds which are direct sunlight drying and conventional convective drying. Although it guarantees process continuity and is more practical for flexible drying conditions, the traditional convective drying approach comes with a high cost in terms of energy and nutrition deterioration from heat input. The cheaper and simpler type is the direct sunlight method. On the other hand, the weather has an impact on how fast seaweeds dry out. Direct sunlight drying can likewise affect the quality of the seaweeds due to exposure to outside air (Djaeni and Sari, 2015). When a product is dried directly in the sun, its natural air

Paper Received: 8 May 2024; Revised: 20 July 2024; Accepted: 25 October 2024
Please cite this article as: Atienza A.H.S., De Luna L.D.M., San Juan G.R.R., Solis R.L., 2024, Energy and Exergy Assessment of a Modular Offshore Seaweed Solar Dryer, Chemical Engineering Transactions, 113, 421-426 DOI:10.3303/CET24113071

circulation system removes moisture because of changes in air density (Visavale, 2012). Drying agricultural crops with contemporary drying techniques is not economically viable. Open air or sun drying has been a practical option with the finite supply of fossil fuels and surge in fuel cost. Thus, sun drying systems have been created as an efficient and cost-effective method of drying agricultural products (Lokesh, 2015). Solar natural dryers are directly irradiated solar dryers, and solar energy is directly absorbed by the products. Direct solar radiation heats and dries the top layer, and conduction heats the layers below it (Lokesh, 2015).
The study was focused on a modular design of an offshore solar dryer that would help the beneficiary from Calatagan Batangas in a more accessible and efficient way of drying the seaweeds using solar technology with the support of the exergy and energy-based analyses and design. It is evident to also consider the type of seaweeds in selecting the appropriate drying methods since they may affect the food quality (Wirenfeldt et al., 2024), energy intensiveness and sustainable potential biomass source (Thomas et al., 2020). The species of seaweeds is essential in the drying process. For instance, the water content of samples of algae from the same species can vary due to differences in tissue morphology, structure, age, size, collection site, or seasonality (Silva et al., 2008) Thermal conductivities of different species may directly affect the drying process (Tolstorebrov et al., 2019). According to Kardgar (2020) in exergy analysis, gathering proper information regarding the exact locations of inefficiencies and its magnitude of effect were deemed vital. It was a helpful approach that could clarify the distinction between energy wasted to the environment and internal irreversibility in the system. The energy that could be obtained from the dryers, both in terms of quantity and quality, was determined by the analysis (Bolaji, 2011).

2. Materials and Method

Fresh seaweed was placed into a container with ice, water and salt then shipped from Calatagan to Calamba. The fresh seaweed was weighed then placed into the tray of the seaweed dryer. Depending on the weather, the seaweed dried for 7 to 9.5 h over the course of five days. Anemometer, humidity sensor, and temperature sensor were used to note the wind speed, relative humidity and temperature of air in the air intake of the solar drier, respectively. As seen in Figure 1, the top, middle, and bottom trays, each holding delegate samples, were employed to gauge the seaweed's moisture level.

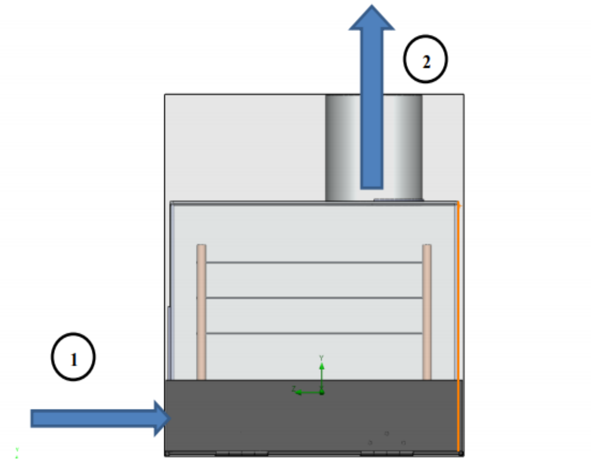

Figure 1: Solar dryer with top, middle, and bottom trays (1) air intake (2) air exhaust

2.1 Site Selection

Barangay Uno formerly known as Poblacion, is a barangay in the Municipality of Calatagan, in the province of Batangas. It is known that the area is home to two different kinds of seaweed. They are "Lato," also known as Caulerpa, and "Gulaman," also known as Euchuema. The drying process takes two (2) to three (3) days in the summer season and it is much longer when rainy season comes which takes a week to dry. Another problem arises primarily during rainy seasons because it takes a week to dry the seaweeds, their quality suffers, and they are exposed and more vulnerable to contaminations.

2.2 Material Selection

Stiffness, density, and strength of the materials will be taken into consideration when building the solar dryer. The materials used in the drying process of seaweed should be buoyant and as light as possible for floating purposes, but they should also be able to withstand offshore conditions. Observing the principle and theories of natural convection, the drying chamber/solar collector will maximize the solar capacity of the dryer for which the thermal expansion and the thermal conductivity of the materials will also be evaluated. The initial selection of the materials will be done by using the Ashby’s method. Ashby's material selection chart can be helpful in the initial review of materials since it allows for the evaluation and setting of various relationships referring on the properties of the materials to be utilized (Farag, 2015).

2.3 Computational Fluid Dynamics

Using Solidworks software, Computational fluid dynamics (CFD) simulation of the dryer has been conducted by the researchers to be observed the drying process inside the solar dryer design. Maximum temperature of 47.81 °C for the fluid (air) has been attained with a least relative humidity of 27.47 % peculiarities as shown in Figure 2.

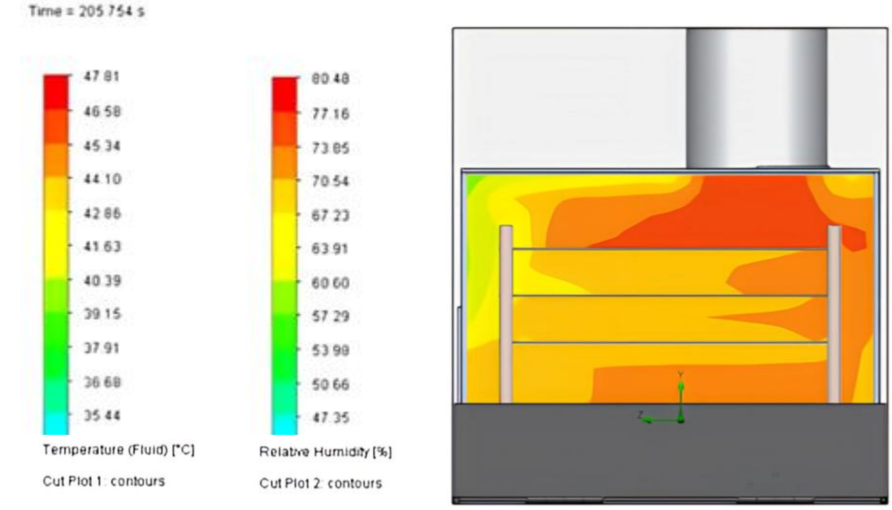

Figure 2: CFD Simulation

2.4 Final Design

To make the dryer more stable in water, it was selected in the material selection to use Polyvinyl Chloride (PVC) for base of drying chamber, exhaust, and rack holder while polyethylene sheet for the body of the drying chamber. To lessen more the cost and maximize the use of available resources especially the recyclable ones, a standard fishing net filled with recycled Polyethylene Terephthalate (PET) bottles of different sizes will serve as a floating device that will be clamped to the base of the drying chamber using a heavy-duty stainless snap hook attached in the fishing net as seen in Figure 3.

Figure 3: Modular Offshore Dryer

2.5 Experimentation

Data on temperature and relative humidity of air, seaweeds' moisture content reduction and solar irradiation were gathered during five trials, one of which included a full load test. After the drying, the dried seaweeds in each tray were weighed and the gathered data will be collected for the computation of moisture content. Dried seaweeds should have a desired moisture content at most 40 %. To maintain the product's optimal quality throughout its shelf life, it is crucial to keep its moisture content at most 40 %, preserving its integrity from production to consumption (Mustafa et. Al, 2018). The percentage of moisture P, is defined in Eq(1):

$$P = \frac{W_o - W_f}{W_f} \tag{1}$$

In the realm of energy analysis, a crucial aspect to consider in evaluating drying performance is its efficiency. The efficiency of drying processes carries substantial significance when gauging the efficacy of dryers. To ascertain the energy efficiency η of the seaweed solar dryer, Eq(2), outlined by Culaba et al. (2021), can be employed, disregarding power input. This equation hinges on factors such as the quantity of moisture removed M, the heat of vaporization L, the solar collector area A, and solar irradiation I, in which W_o is the seaweed's previous weight prior drying and W_f is the seaweed's last weight post drying.

$$\eta = \frac{M(L)}{A(I)} \tag{2}$$

Contrarily, according to Haragovics and Mizsey (2012), the idea of exergy describes the greatest quantity of productive work that may be produced when a system enters thermodynamic equilibrium in the presence of a heat source. The dryer exergy efficiency η_{EX} is expressed as the exergy outflow to inflow ratio as expressed by Fudholi et al. (2011), in which where $T_{dryer,inlet}$, $T_{dryer,outlet}$ and $T_{ambient}$ are the inlet and outlet dryer temperatures, and ambient temperature, respectively. $Ex_{dryer,inlet}$ is the exergy inflow of the dryer while $Ex_{dryer,outlet}$ is the exergy outflow of the dryer and $Ex_{dryer,losses}$ are the exergy losses of the dryer, referring to Eq(3) to Eq(6).

$$Ex_{dryer,inlet} = \dot{m}C_p\left[T_{dryer,inlet} - T_{ambient} - T_{ambient}\ ln\frac{T_{dryer,inlet}}{T_{ambient}}\right] \tag{3}$$

$$Ex_{dryer,outlet} = \dot{m}C_p\left[T_{dryer,outlet} - T_{ambient} - T_{ambient}\ ln\frac{T_{dryer,outlet}}{T_{ambient}}\right] \tag{4}$$

$$Ex_{dryer,losses} = Ex_{dryer,inlet} - Ex_{dryer,outlet} \tag{5}$$

$$\eta_{EX} = \frac{Ex_{dryer,out}}{Ex_{dryer,inlet}} = 1 - \frac{Ex_{dryer,losses}}{Ex_{dryer,inlet}} \tag{6}$$

3. Results and Discussion

Variations in the average temperature and relative humidity were noted daily for various sections in the dryer. It was calculated that the air mass flow was 0.21 kg/s. It was monitored that the chamber's maximum mean drying temperature was 36.86 °C, with the least relative humidity of 61.02%. Day 3 had the highest solar irradiation reading, measuring 525.65 W/m^2. On the test day, the researchers calculated the energy and exergy efficiencies, as depicted in Figure 4 below.

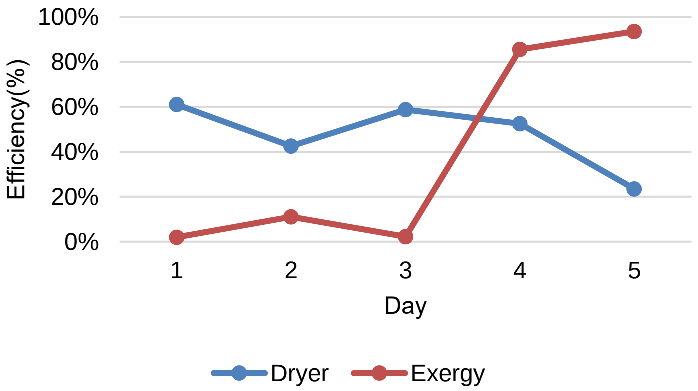

Figure 4: Comparison of Dryer and Exergy Efficiency

The results of the study were compared to other studies focusing on exergy and energy analysis on seaweeds with innovations such as modified pipes (Culaba et al., 2021) and auxiliary heaters (Fudholi et al., 2014). The average dryer efficiency was determined to be 47.68 %, surpassing the figures reported by Culaba et al. (2021) at 32.79 % and Fudholi et al. (2014) at 13 %. The exergy efficiency ranged from 1.96 to 93.58 %, like Fudholi

(2014), which ranged from 1 to 93 %, and higher compared to Culaba et al. (2021), which ranged from 16.62 % to 42.70 %. The average exergy efficiency is approximately 38.85 %, higher than Culaba et al. (2021) at 28.72 % and Fudholi et al. (2014) at 30 %. In these comparisons, the modularity of the offshore dryer helped in enhancing the efficiencies. To achieve the best drying results for these investigations, the efficiency figures show that the dryer needs to be improved. It is relevant to incorporate possible innovations and modifications to the components of the dryer.

4. Conclusions

The study employed a modular offshore seaweed solar dryer which involved the use of polyvinyl chloride, plastic mesh, and stainless steel. The drying parameters of the dryer were monitored and it was found out that most seaweeds reached the desired moisture ratio of 40 % after varying drying periods, with the longest observed period being five days at 9.5 h per day. The upper tray exhibited the fastest drying speed, and it was noted that a smaller quantity of seaweed led to a faster drying time. Additionally, the amount of seaweed placed in each tray decreased over subsequent runs. Energy and exergy evaluations of the dryer were carried out. These evaluations are thought to be crucial to dryer design since they identify weak points of drying systems. It suggested that better outcomes could be achieved by modularizing the dryer. Dryer innovations and improvements are still important to reduce energy loss and increase efficiency for the best drying results.

Nomenclature

A– area of solar collector, m^2
CFD – computational fluid dynamics
C_P– constant pressure specific heat, J/kg·°C
I – solar irradiation, W/m^2
L – heat of vaporization, J/kg
$Ex_{dryer,inlet}$ – Rate of Exergy inflow of the dryer, W
$Ex_{dryer,outlet}$ – Rate of Exergy outflow from the dryer, W
$Ex_{dryer,losses}$ – Rate of Exergy losses in the dryer, W
$\dot{m}$– air mass flow, kg/s
M – removed mass, g
P – percent of moisture content, %
$T_{ambient}$ – ambient temperature, °C
$T_{dryer,inlet}$ – inlet dryer temperature, °C
$T_{dryer,outlet}$ – out dryer temperature, °C
W_0 – seaweed's previous weight prior drying, g
W_f – seaweed's last weight post drying, g
η – dryer efficiency, %
η_{EX}– exergy efficiency, %

References

BAS, 2010, Facts and Figures on the Philippine Economy, Bureau of Agricultural Statistics < countrystat.bas.gov.ph /index.asp?cont=factsandfigures> accessed 04.04.2024.

Bolaji B.O., 2011, Exergetic Analysis of Solar Energy drying Systems, Natural Resources, 2(2), 92–97.

Culaba A., Atienza A.H., Ubando A., Mayol A.P., Cuello J., 2021, Seaweed drying characterization via serial statistical criteria analysis, IOP Conference Series: Materials Science and Engineering, 1109(1), 12051.

Dhumne L. R., Bipte V.H., Jibhkate Y.M., 2015, Solar Dryers for Drying Agricultural Products, International Journal of Engineering Research-Online, 3(S2), 80–84.

Djaeni M., Sari D.A., 2015, Low Temperature Seaweed Drying Using Dehumidified Air. Procedia Environmental Sciences, 23, 2–10.

Farag M.M., 2015, Quantitative Methods of Materials Selection, Mechanical Engineers' Handbook, 1–22.

Fudholi O. M., 2011, Design and testing of solar dryer for drying kinetics of seaweed in Malaysia. Recent Research in Geography, Geology, Energy, Environment and Biomedicine., 119-124.

Fudholi A., Sopian K., Othman M. Y., Ruslan M. H., 2014, Energy and exergy analyses of solar drying system of red seaweed. Energy and Buildings, 68, 121–129.

Haragovics M., Mizsey P., 2012, Exergy Analysis of Multicomponent Distillation Systems for Efficiency Ranking, Chemical Engineering Transactions, 29, 343–348.

Kardgar M. B., 2020, Energy-exergy performance assessment with optimization guidance for the components of the 396-MW combined-cycle. Energy Science and Engineering, 8(10), 1–14.

Milledge J.J., Harvey P.J., 2016, Potential process “hurdles” in the use of macroalgae as feedstock for biofuel production in the British Isles, Journal of Chemical Technology & Biotechnology, 91(8), 2221–2234.

Mustafa K. ‘Ain, Md-Iqbal N.Z., Azahar N., Arizal M.M., Mohd-Khairi N.S.H., Komilus C.F., 2018, Drying Profile and the Mineral Content in Quality Determination of Kappaphycus Alverezii (Rhodophyceae) from Semporna, Sabah, Malaysia, Journal of Agrobiotechnology, 9(1S), 79-91.

Pati M.P., 2016, Uses of Seaweed and its Application to Human Welfare: a Review, International Journal of Pharmacy and Pharmaceutical Sciences, 8(10), 12.

Pelinggon R.T., 2009, Seaweeds Production, Module 7: Seaweeds Production, 48.

Putri N.P., Sanjaya A.S., Sari N.K., Sari R.P., Bindar Y., 2018, Carrageenan Extracted from Eucheuma cottonii Through Variant of Drying Time, MATEC Web of Conferences, 156, 02014.

Silva V.M. da Silva L.A., Andrade J.B., de Veloso, M.C. da C., Santos G.V., 2008, Determination of moisture content and water activity in algae and fish by thermoanalytical techniques, Química Nova, 31(4), 901–905.

Strom K., 2011, Product quality in solar dried carrots, tomatoes and onions, Norwegian University of Life Sciences.

Tasende M.M.H., 2016, Carrageenan Properties and Applications: A Review, In book: Carrageenans: Sources and Extraction Methods, Molecular Structure, Bioactive Properties and Health Effects, Nova Science Publishers, New York, USA, 2-34.

Thomas J.B.E., Sodré Ribeiro M., Potting J., Cervin G., Nylund G.M., Olsson J., Albers E., Undeland I., Pavia H., Gröndahl F., 2020, A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina latissimi, ICES Journal of Marine Science, 78(1), 451–467.

Tolstorebrov I., Eikevik T.M., Saether, M., 2019, Influence of thermal properties of brown seaweeds (Saccharina Latissima) on atmospheric freeze-drying process in fluidized bed. Proceedings of the 25th IIR International Congress of Refrigeration: Montréal, Canada.

Visavale G.L., 2012, Principles, Classification and Selection of Solar Dryers, CCTech internal research: CFD for Renewable industry, Singapore, 1-50.

Wirenfeldt C.B., Hermund, D.B., Feyissa A.H., Hyldig G., Holdt S.L., 2024, Nutritional value, bioactive composition, physico-chemical and sensory properties of Ulva sp. and Fucus vesiculosus depending on post-harvest processing: a drying comparison study, Journal of Applied Phycology, doi:10.1007/s10811-024-03210-4.