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Stabilization of Sewage Sludge from North Moroccan Wastewater Treatment Plants Using Convective Indirect Solar Drying

El Houssayne Bougayr[1*], Younes Bahammou[2,3], Azeddine Fantasse[2], El Khadir Lakhal[2], Fatiha Berroug[2], Abdelkhalek Bouziane[4], Ali Idlimam[3]

[1] Engineering & Applied Technologies Laboratory (LITA), Higher School of Technology - Beni Mellal, Sultan Moulay Slimane University, Morocco

[2] Laboratory of Fluid Mechanics and Energetics (LMFE), Faculty of Sciences Semlalia, Cadi Ayyad University, Marrakesh 40000, Morocco

[3] Team of Solar Energy and Medicinal Plants EESPAM, Laboratory of Processes for Energy & Environment ProcEDE, Cadi Ayyad University Marrakesh, Morocco

[4] Laboratory LAMIGEP, Moroccan School of Engineering Sciences, Marrakesh, Morocco

* Corresponding author's e-mail: bougayr@gmail.com

ABSTRACT

The significant production of sewage sludge by wastewater treatment plants on a global scale and the lack of correspondence between housing development and the expansion of sanitation infrastructure indicate a genuine concern regarding environmental preservation. This study addresses the crucial issue of effective sewage sludge management and its environmental impact. In the context of searching for new drying methods that optimize energy use and effectively stabilize sewage sludge, this work investigated the drying behavior of sewage sludge from treatment plants in two northern Moroccan cities using a prototype of an indirect forced convection solar dryer. The drying experiments enabled the determination of drying kinetics as well as highlighted the influence of temperature and humidity on the drying rate. The characteristic drying curve (CDC) and its mathematical expression were determined using Van Meel's formalism. Thermal diffusivity of wastewater sludge during drying was also investigated. Using Fick's diffusion model, diffusion coefficients ranged between 0.59×10^{-9} m²/s and 1.43×10^{-9} m²/s, demonstrating an increase in effective diffusivity with rising temperature. The Arrhenius equation provided activation energy values of 16.80 kJ/mol for Oujda samples and 19.72 kJ/mol for Nador samples, indicating the effect of temperature on effective diffusivity. A new equation based on the Midilli-Kucuk model was proposed to predict the drying behavior under untested aerothermal conditions, considering drying temperature and the initial dryness. This study offers a comprehensive analysis of the drying kinetics and effective diffusivity of sewage sludge, providing valuable insights for designing large dryers for sludge management in WWTPs. This approach presents an optimal solution for drying and stabilizing sludge, contributing to environmental preservation efforts.

Keywords: sewage sludge, stabilization, drying kinetics, thermal diffusivity, activation energy, modeling.

INTRODUCTION

Growing populations and the expansion of human activities lead to increased water consumption and, consequently, greater discharges of wastewater. These discharges are a significant source of pollution, degrading water quality and overwhelming existing treatment facilities. This contamination affects aquatic ecosystems as well as poses risks to public health and the environment. Effective wastewater management and treatment are crucial to mitigating these impacts and ensuring sustainable water quality for the future. Wastewater treatment has become a necessity for our societies and a major sustainable development challenge for the next generations. Thus, sludge is produced as a direct result of treating wastewater. More than a hundred million tons per year of sludge are produced in WWTPs worldwide, and the treatment of this sludge costs about two thirds of the total cost of treatment plants (Jin et al., 2016; Malek, Skoczkowska, and Ulbrich, 2017). The regular increase in the volume of sludge generated by the treatment of wastewater is related to demographic development and urban expansion. Currently, as the preservation of the environment has become a major concern, the treatment of sewage sludge is considered indispensable to reduce its volume and transform it into a recoverable product. This reduction in the volume of sludge while preserving subsequent recovery or disposal options is the purpose of drying process, Therefore, the design of sludge treatment channels is strongly related to their final destination (agricultural spraying, composting, landfill, incineration, etc.). Moreover, this method is useful for dewatering sludge and serves as a key step in sludge handling, optimizing logistical efficiency and significantly lowering overall transport as well as storage expenses (Al Kanej and Hammar, 2016; Żogała, 2016).

The volume of publications that appear annually on the modeling of the drying of different materials, mainly sewage sludge, indicates that the fundamental drying process is not completely under control and that the knowledge of the thermophysical properties of the material during drying plays an important role in determining the mechanisms of thermal and water transfers within the material.

Several research papers have been published to investigate this research topic, Lecomte studied thin-layer drying by boiling of aluminum hydroxide sludge and developed a method for the design and sizing of the process (Lecomte et al., 2004). Ferrasse developed the tools for the characterization and understanding of the behavior of wastewater sludge in a conductive drying process with agitation (Ferrasseet al., 2002). The convective drying of an individual sewage sludge sample obtained by extrusion and the change in its texture was analyzed by Léonard (Léonard et al., 2004). The dependence of climatic conditions on the solar drying model was highlighted by Slim (Slim el al., 2009). The major challenge is the design of a drying process that would enhance the use of solar energy and provide the additional energy necessary to improve drying performance over an annual sludge management cycle. Convective solar dryers, known for their energy efficiency and effectiveness in drying agricultural products, offer a promising solution in this context. Despite the proven advantages of convective solar dryers in terms of energy efficiency and drying performance for agro-food products, this method has not yet been thoroughly studied for wastewater sludge drying.

The drying process of sludge and organic products is very complex. On the one hand, it involves the internal transfers as transport of heat and mass in an unsaturated porous medium, and on the other hand, the external transfers which come under the aerothermal of flow of the drying fluid in the vicinity of the surface of the product (Bahammou et al., 2019). The heat transfer contributes to favor the phase change, while the mass transfer takes place to evacuate moisture as the liquid and /or vapor phase from inside the product to the air flow responsible for its removal (Belghit et al., 2000).

Recently, several theoretical or experimental approaches dealing with the topic of convective drying have been developed to properly study the drying characteristics and determine the heat transfer coefficient throughout the drying process. The diffusion coefficient is a crucial parameter in drying kinetics simulation, as it influences the temperature difference between the air and the product (Ali et al., 2016).

The empirical or semi-empirical approach offers the benefit of accurately representing drying kinetics without the need for complex equations. While these methods do not provide insight into the internal behavior of the product, they offer a reliable approximation of the product behavior and are useful for designing suitable dryers (Bahammou et al., 2019; Mardiyani, 2024). A thorough knowledge of transfer parameters as well as diffusion of heat and mass during drying sludge is required for the simulation, design and optimization of drying process. That is why it is necessary to develop an adequate model that can anticipate drying behavior and describe the drying kinetics of the product (Hassini et al., 2007).

The primary hypothesis of this study is that a convective solar dryer can effectively dry wastewater sludge and that understanding the drying kinetics is crucial. Previous studies have demonstrated the energy efficiency of this dryer type for various products, indicating its potential for broader applications. The dimensioning of industrial-scale dryers begins with thorough research on the drying kinetics of the product to be dried. This involves the experimental determination of properties related to the drying process, such as thermal diffusivity and activation energy.

The determination of thermal diffusivity, or drying diffusion coefficients, is essential in the dimensioning and design of industrial dryers. Thermal diffusivity indicates the ability of the material to transmit heat, influencing the rate at which moisture can be removed from the product. A precise understanding of this property allows for optimizing the drying process, ensuring uniform moisture removal and avoiding over-drying or under-drying that can affect the quality of the final product. Additionally, knowledge of diffusion coefficients helps predict drying kinetics, which is crucial for efficiently and economically sizing drying equipment. Studies have shown that the variation of thermal diffusivity with temperature and water content is a determining factor for choosing appropriate drying conditions and designing the dryers tailored to the specific needs of the products being processed (Aghfir et al., 2008; Benhamou et al., 2008). Activation energy, on the other hand, represents the energy required to initiate the moisture diffusion process within the material. This value is crucial for understanding and modeling drying processes at different temperatures. A precise knowledge of activation energy allows for designing the dryers that operate optimally at specific temperatures, thus minimizing energy consumption and maximizing the efficiency of the drying process. Industrial dryers must be designed considering these parameters to ensure that the drying process is not only effective but also economically viable. Research has demonstrated that integrating these data into drying models improves dryer performance, thereby reducing operational costs and increasing the sustainability of industrial facilities (Doymaz 2004; Krokida et al., 2003; Midilli et al., 2002).

This paper constitutes a continuation of previous studies, which involved an experimental approach, the sorption isotherm and hygroscopicity of sludge and characterization of thermodynamic sorption properties (Bougayr et al., 2018). The objective of this study was to investigate the behavior of convective drying of wastewater sludge collected by the WWTP of Oujda city and Nador city by utilizing a convective solar dryer. To achieve a better understanding of drying kinetics and determine the characteristic drying curve and thus the suitable model to describe drying behavior, this allows anticipating the shape of a drying curve in aerothermal conditions other than those studied in this paper in order to establish an empirical model to predict drying kinetics based on the initial properties of the sludge and drying temperature. The second aim of this paper was the determination of diffusion coefficients and activation energy by using the Fick's diffusion expression and the Arrhenius approach.

These findings are essential for designing large-scale dryers suitable for wastewater treatment plants (WWTPs). By providing these insights, the authors aimed to enhance the design and efficiency of sludge drying systems, ultimately contributing to more effective and sustainable wastewater management practices.

MATERIAL AND METHODS

Origin of samples

The residual sludge used in this study was collected from two wastewater treatment plants (WWTPs) located in geographically distinct cities in Morocco, namely Oujda and Nador. These cities were selected due to their significant population sizes and the recent construction of high-quality wastewater treatment plants that meet international standards, following the implementation of Morocco's National Liquid Sanitation Plan (PNAL). These samples of sewage sludge were of primary type, obtained downstream from the primary treatment stage. This choice ensures that the sampled sludge reflects the conditions typical of modern, well-regulated wastewater treatment processes, which are essential for developing effective drying technologies tailored to local environmental and operational requirements.

Wastewater treatment plant of Oujda city

The sewage sludge samples studied were primary type and were generated from the Oujda WWTP of Oujda city. (Eastern Morocco) located on the left bank of river Oued Bounaim. The station is designed for 530,000 inhabitants and treats 40,000 m^3/d of wastewater. This station, the treatment process of which is of the aerated lagoon type, has been in service since May 2010.

Wastewater treatment plant of Nador city

The WWTP was launched in 2010, it treats the effluents from Nador, Zghanghan and Selouane and with a capacity of 115000 PE. It is of the activated sludge type with nitrogen and phosphorus treatment as well as UV disinfection and treats a wastewater volume of 20600 (m^3/d).

Description of the indirect solar dryer

The experimental device utilized for investigating the drying of municipal waste is an indirect solar dryer with forced convection (Figure 1). This prototype solar dryer is installed at the Laboratory of Solar Energy and Medicinal Plants (EESPAM) at Cadi Ayyad University (Kouhila et al., 2020). The dryer has been instrumental in the development of numerous publications focusing on improving the drying quality of various agro-food products (Lahnine et al., 2016; Ouaabou et al., 2020). Previous studies conducted in the authors' laboratory have demonstrated its energy efficiency (Bahammou et al., 2022; Tagnamas et al., 2021). The apparatus allows for the complete or partial recycling of heated air as it passes through versatile shelves inside the drying chamber. Additionally, it facilitates the generation of a controlled flow of hot air, effectively managing its aerothermal parameters (Ali et al., 2016; Bougayr et al., 2023) The dryer is consists of the following components:

- A solar collector facing south with an inclination of 31° allowing the heating of the fresh air that comes from the outside.
- An aspirating aeraulic conduit pipe connecting the outlet of the solar collector to the drying cupboard, a valve for adjusting airflow value is fixed in this conduit pipe.
- Drying cupboard (Lxlxh: 0.9 × 0.5 × 1.4 m) containing a trolley consisting of ten floors in trays.
- A centrifugal fan of 0.1kW electric power.
- A thermoregulator that can monitor temperatures ranging from 0 °C to 100 °C with an accuracy of 0.1 °C.
- Auxiliary electrical source consisting of resistors 4 kW with a PT100 platinum probe for adjusting temperature value.

The fresh air drawn from the outside is heated inside the collector and is then sucked by the centrifugal fan through the air aeraulic conduit pipe to the inlet of the drying cupboard. At this level, a thermocouple measures the temperature of drying air and turns on the auxiliary electrical source in case this temperature is below the temperature regulated by the controller unit. The drying air through the shelves inside the drying cupboard to an opening in its ceiling offers the choice of complete or partial recycling of the heated air.

Experimental protocol

The sewage sludge was prepared on the support of samples with a cylindrical shape 0.5 cm high and 10 cm in diameter, the granules were distributed uniformly and regularly on the support to guarantee uniformity of diffusion throughout the drying process.

The dryer must operate empty thirty minutes before proceeding to the experiment to guarantee the uniformity of the temperature inside the experimental device. When the samples of sludge are prepared, the support of samples were introduced directly to the inside the dryer, and then the mass losses of the sample were measured every 5 min. the experiment is interrupted when mass losses that do not exceed 0.1g are detected three times. The measurement of mass loss allows determining the evolution of the moisture content according to drying time defined by the following equation:

$$X(t) = \frac{M_h(t) - M_s}{M_s} \quad (\%\ d.b) \qquad (1)$$

where: X water content (% d.b), $M_h(t)$ product wet mass (kg), Ms dry mass (kg).

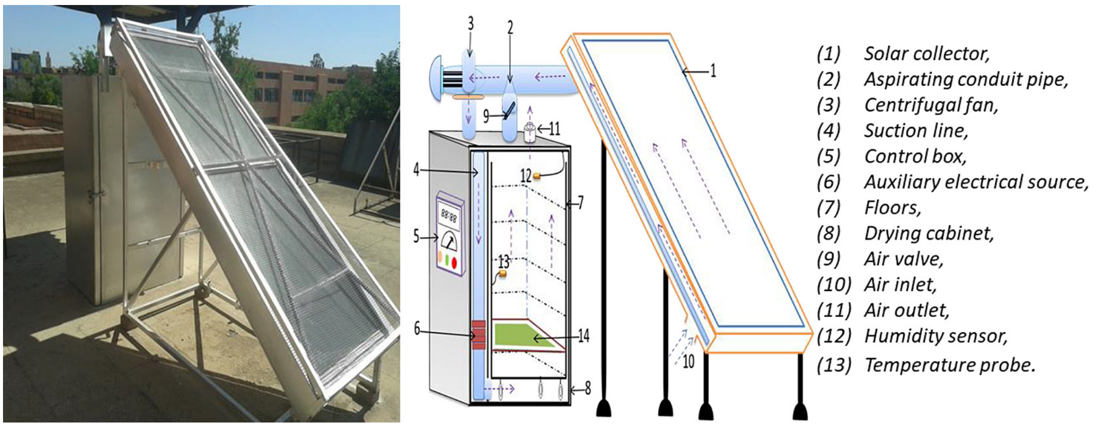

Figure 1. Experimental device (solar dryer located in the EESPAM laboratory at Cadi Ayyad University)

The experimental conditions for the tests were established based on the assigned values for each aerothermal parameter. The procedure was the same for every test conducted; the airflow rate was fixed at 0.083 m^3/s and the experiments were conducted for three temperatures (50, 60, 70 °C). This choice of temperature covers the solar drying temperature range for regions rich in solar energy resources and with a temperate climate.

Characteristic drying curve

The global analysis method of the drying process, developed by Van Meel in 1958, relies on normalizing experimental data to obtain a characteristic drying curve (CDC). This curve summarizes the ratio of the drying rate at a given moment to that of the first phase, according to reduced water content. The equation for the CDC, $f = (X*)$, is primarily applicable to non-massive and thin-layer samples, allowing for the neglect of diffusion gradients. The adoption of CDC by several researchers has simplified the expression of the drying rate of products under various aerothermal conditions. CDC is recognized for its simplicity of use, allowing the prediction and description of the drying kinetics of a product from the initial and equilibrium moisture content values extracted from desorption isotherms. This tool reduces experimental data into an easily usable form, thus facilitating its application both by experimenters and by the scientific community at large (Ali et al., 2016; Bougayr et al., 2018; Tagnamas et al., 2022).

$$X^* = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \tag{2}$$

$$f = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(-\frac{dX}{dt}\right)_0} \tag{3}$$

Modeling of drying curves

Drying is a complex process influenced by various physical and environmental parameters. To understand and optimize it, mathematical models have been developed, predicting the water content of materials over time. These models are divided into two categories: phenomenological models and empirical or semi-empirical models. Phenomenological models explain the mechanisms of water transport, such as diffusion and capillarity, requiring experimental data to adjust parameters, and allowing detailed analysis of internal processes. Empirical and semi-empirical models, less dependent on the understanding of internal processes, use adjustable constants to align with the observed data, making them useful for practical applications that require rapid predictions.

Table 1. Models applied in fitting the drying curves of sewage sludge

Model	Analytical equation	
Newton	$X^*=e^{(-kt)}$	(4)
Page	$X^*=e^{(-kt^n)}$	(5)
Henderson & Pabis	$X^*=ae^{(-kt)}$	(6)
Two-term	$X^*=ae^{(-k_0t)}+be^{(-k_1t)}$	(7)
Two-term exponential	$X^*=ae^{(-kt)}+(1-a)e^{(-kat)}$	(8)
Wang & Singh	$X^*=1+at+bt^2$	(9)
Approach to diffusion	$X^*=ae^{(-kt)}+(1-a)e^{(-kbt)}$	(10)
Midilli-Kucuk	$X^*=ae^{(-kt^n)}+bt$	(11)

To describe the drying behavior wastewater sludge, eight drying models were employed (Table 1). These models, widely recognized in the literature for their effectiveness in describing drying kinetics, were fitted using the Marquardt-Levenberg algorithm via appropriate software. The fitting process involved non-linear optimization to align the models with experimental data (Mardiyani 2024; Moussaoui et al., 2021).

To evaluate the effectiveness of each model, statistical criteria such as the correlation coefficient (r), the reduced mean square deviation (χ^2), and the mean biased error (MBE) were used. These criteria help determine which model best fits the experimental data, thus enabling a more accurate prediction of the drying kinetics.

$$MBE=\frac{1}{N}\sum_{i=1}^{N}\left(X^*_{pre,i}-X^*_{exp,i}\right) \tag{12}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X^*_{pre,i}-X^*_{exp,i}\right)^2}{N-n} \tag{13}$$

$$r = \sqrt{\frac{\sum_{i=1}^{N}\left(X^*_{pre,i}-\bar{X}^*_{exp}\right)^2}{\sum_{i=1}^{N}\left(X^*_{exp,i}-\bar{X}^*_{exp}\right)^2}} \tag{14}$$

where: $X^*_{exp,i}$ – the ith experimental moisture ratio; $X^*_{pre,i}$ – the ith moisture ratio predicted by the model; $\bar{X}^*_{exp}$ – the average moisture ratio; N and n represent the number of experimental points and the number of variables in each model, respectively.

The selection of the appropriate model is based on the application of non-linear optimization methods and the use of specialized software, such as "Curve Expert", which facilitates the fitting of models to experimental curves and the quantification of drying parameters.

EXPERIMENTAL RESULTS

Drying kinetics

Solar drying tests were conducted in June in Marrakech city. During the drying process, the ambient air temperature was from 22 to 38 ± 1 °C. The experimental parameters during experiments are presented in Table 2. It was noted that the drying time increased with decrease of temperature and the same for the final water content.

The evolution of moisture content according to drying time can be carried out by applying the equation N °1; this evolution is shown in Figures 2 and 3 under varying conditions of the drying air. The results indicate that the sample water content decreases according to drying time for the three tests. The sludge dries quickly for a temperature of 90 °C in comparison with temperatures 70 °C and 50 °C. Indeed, the quality of the water changes with advancement of the drying process: drying passes by evaporation of free water towards evaporation of bound water.

The evolution of the drying rate according to water content is shown in Figures 4 and 5. The rate curve indicated that phase 0, which corresponds to the warming-up stage, was absent in all sludge samples. This phenomenon is commonly observed in the drying of various types of urban residues and agrifood products. Furthermore, temperature homogenization within the drying cabinet was achieved by operating the entire apparatus empty for at least half an hour before introducing the samples into the drying chamber.

The drying curves show the presence of the second phase (drying phase at a decreasing rate), the energy acquired is used for the evaporation water from the product as well as for increasing its temperature and marked by the decrease in the drying rate (Figures 6 and 7) (Bennamoun and

Table 2. Values of aerothermal parameters during drying experiments

Samples	Experiment	Dv ± 0.002 (m^3/s)	Θ ± 0.3 (°C)	X_0 ± .001 (% d.b)	X_f ± .001 (% d.b)	T (min)
WWTP Oujda	1	0.083	50	0.943	0.006	240
	2	0.083	70	1.125	0.092	210
	3	0.083	90	1.010	0.025	145
WWTP Nador	1	0.083	50	3.557	0.513	275
	2	0.083	70	3.672	0.448	260
	3	0.083	90	3.873	0.092	140

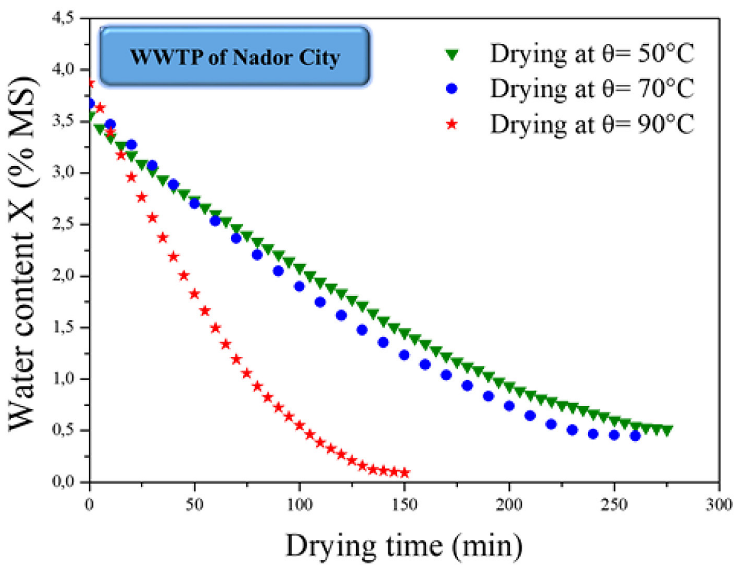

Figure 2. Evolution of moisture content during drying of sludge samples of WWTP Nador

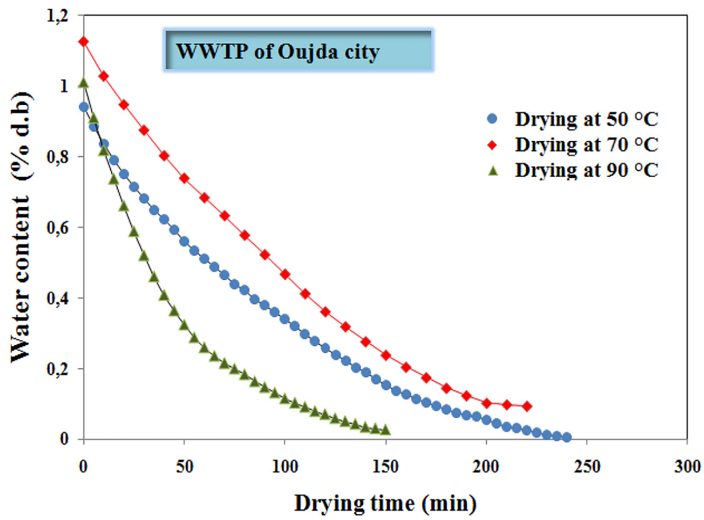

Figure 3. Evolution of moisture content during drying of sludge samples of WWTP Oujda

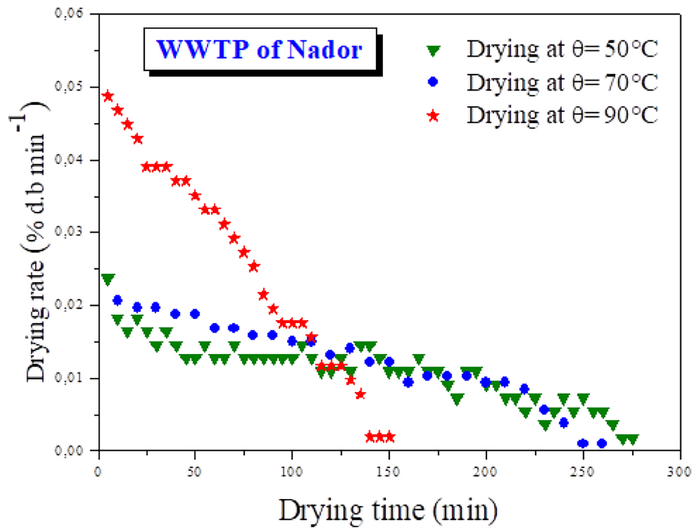

Figure 4. Evolution of the drying rate of sludge samples (WWTP Nador) according to drying time

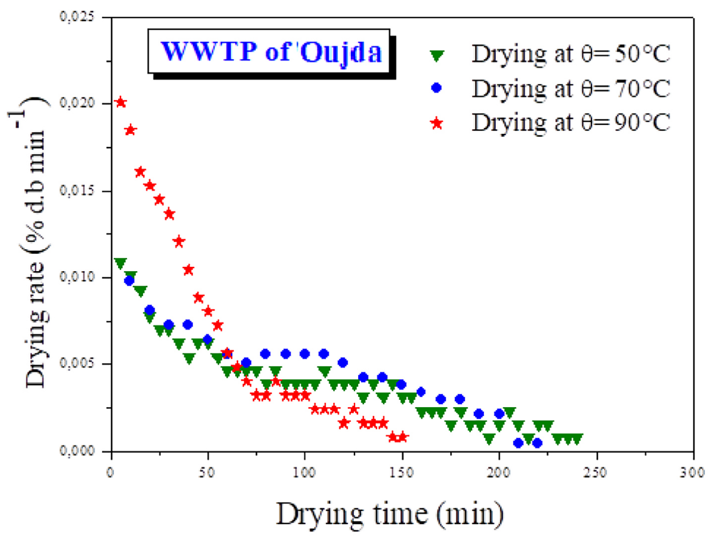

Figure 5. Evolution of the drying rate of sludge samples (WWTP Oujda) according to drying time

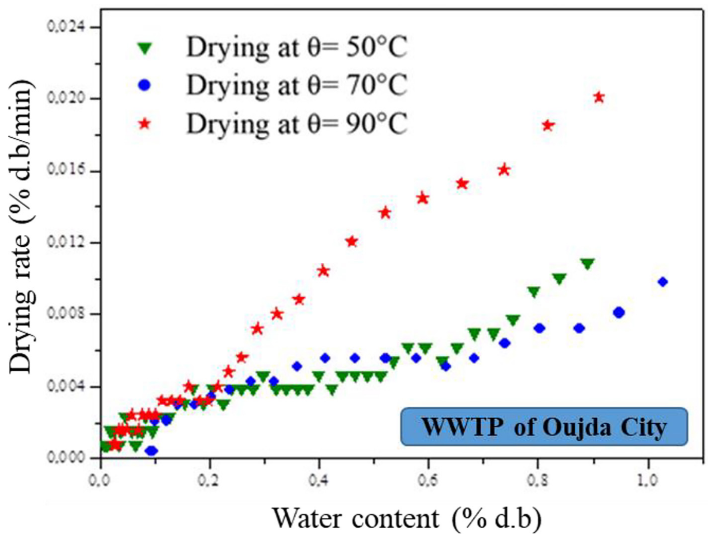

Figure 6. Evolution of the drying rate of sludge samples (WWTP Oujda) versus the moisture content

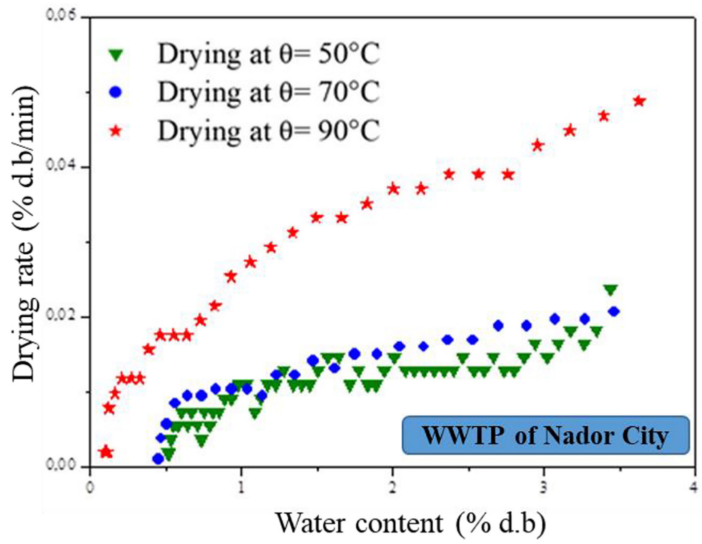

Figure 7. Evolution of the drying rate of sludge samples (WWTP Nador) versus the moisture content

Belhamri, 2008). From a certain water content of the sludge called critical water content, the activity of water on the sludge surface begins to decrease and consequently, the drying rate which is no longer limited by aerothermal conditions, but rather by the characteristics of the dried product, such as the internal migration of water, the structure of sludge(Aghfir et al., 2008; Kouhila et al., 2002). The shapes of the obtained curves were consistent with findings from other research on products with similar structures (Ali et al., 2016; Bougayr et al., 2023; Fantasse et al., 2024; Léonard et al., 2004).

It was also noted that the absence of the first phase corresponds to a linear decrease in the moisture content of the product, in this case, the heated air is used to evaporate water from the product (generally represented by a constant rate of drying) for the samples from WWTP of Oujda. A slight presence of the first phase (I) was also noted for the sludge from the treatment plant of the city of Nador, in particular for the temperature 70 °C. This result has been observed in the previous studies conducted in authors' laboratory for the sludge from the WWTP of Marrakech and Meknes city (Ali et al., 2016; Bougayr et al., 2023).

This phase is described as a surface evaporation step under the effect of the difference between the pressure of water vapor in a thin layer in the vicinity of the product and that of water in the drying air. The presence of the first phase for the sludge from Nador can be explained by the initial water content of the two samples greater than 3.5 kg/kg d.b, while it is less than 1.2 kg/kg d.b for Oujda city.

The determination of the drying characteristic curve is indispensable and holds great importance for practical use. The adopted method consists in establishing a correlation of the normalized drying rate of wastewater sludge with a polynomial of order 4 in X* by non-linear Marquard-Levenberg optimization. Figures 8 and 9 represent the shape of the characteristic drying curve of wastewater sludge of two WWTPs. The determination of coefficients of the equation of the normalized drying rate was done by smoothing of all the experimental data of the characteristic drying curve of the sewage sludge. The criteria for choosing the best smoothing is based on standard error Sr and correlation coefficient R.

Sewage sludge generated form WWTP of Oujda city

$$f = 6.691710^{-2} + 1.764X^{*} - 3.5961X^{*2} + 4.5041X^{*3} - 1.7068X^{*4} \quad (15)$$

where: $r = 0.9593$, $Sr = 7.63422\ 10^{-2}$

Sewage sludge generated form WWTP of Nador city

$$f = 0.1266 + 2.5673X^{*} - 4.9722X^{*2} + 3.9875X^{*3} - 0.7077X^{*4} \quad (16)$$

where: r = 0.9202 Sr = $9.829977\ 10^{-2}$

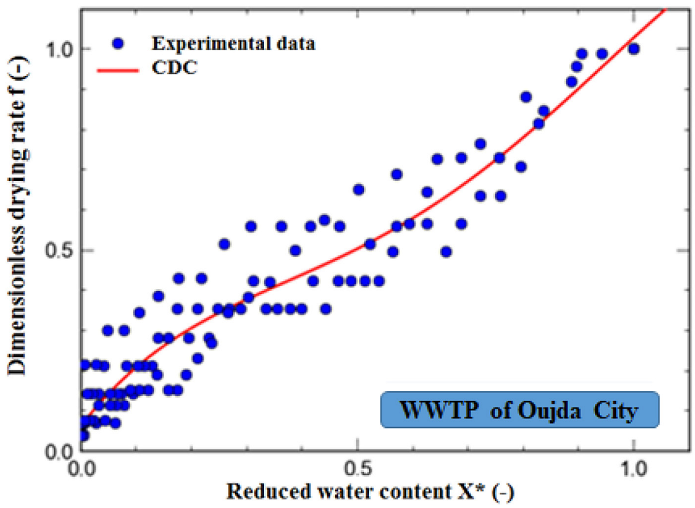

Figure 8. Characteristic drying curve of wastewater sludge generated from the WWTP of Oujda city

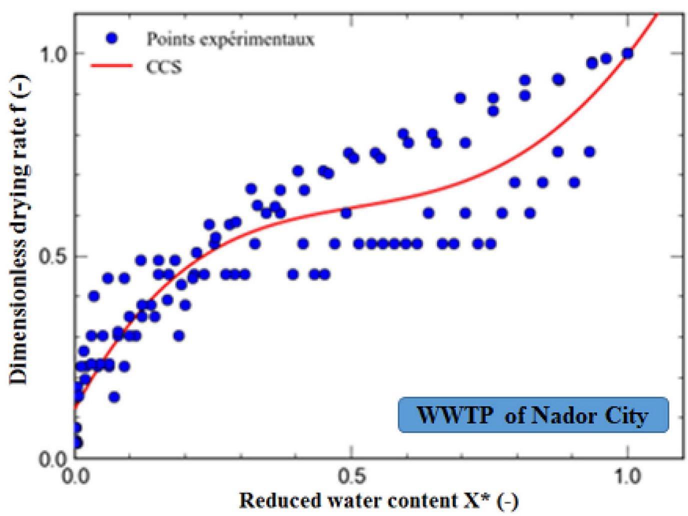

Figure 9. Characteristic drying curve of wastewater sludge generated from the WWTP of Nador city

Thermal diffusivity

In the phase of decreasing drying rate, water transport from within the sample to its surface occurs through various mechanisms. By incorporating these mechanisms into a diffusion coefficient, the utilization of the second Fick's law enables to characterize mass transfer throughout the drying process.

$$\frac{\partial X^*}{\partial t} = D_{eff} \nabla^2 X^* \quad (17)$$

The diffusion coefficient (Deff, in m^2/s) and X^* (reduced moisture content) are commonly used for interpretation of mass transfers comprehensively. The analytical solution of Fick's second law [21], as established by Crank in 1975, applies to slab geometry assuming uniform initial moisture distribution. This solution simplifies water movement by considering diffusion, negligible shrinkage, constant diffusion coefficients, and constant temperature. It could be represented as the following:

$$X^* = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \times \exp\left(\frac{-(2n+1)^2 . \pi^2 D_{eff} . t}{4 . L^2} \right) \quad (18)$$

where: L is the ½ of samples thickness, while n being a positive integer constant.

In practical applications, typically just the first term of Equation 18 is utilized (Aghfir et al., 2008; Benhamou et al., 2008). For appropriately long drying durations, the solution of this equation simplifies to the first term. The natural logarithm of the reduced moisture content in this simplified formula yields the following expression:

$$Ln(X^*) = Ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4 L^2}\right) \quad (19)$$

The diffusion coefficient is determined by plotting the natural logarithm of experimental values of reduced moisture content against drying time represented in Figures 10 and 11. The graphic representation of Equation 19 yields a straight line with a slope:

$$p = \left(\frac{\pi^2 D_{eff}}{4 L^2}\right) \quad (20)$$

The slope of Equation 19 represents a measurement of effective diffusivity. The diffusion coefficient values measured are shown in Table 3, D_{eff} ranges around 0.5 $10^{-9} m^2 \cdot s^{-1}$ and 1.4 $10^{-9} m^2 \cdot s^{-1}$. The results show that the diffusion coefficients increase along with the temperature of the air increases, the effect of temperature is presented in Figure 12.

According to Arrhenius (Lopez et al., 2000), the effective diffusivity correlates with activation energy and temperature as expressed below:

$$D_{eff} = D_0 \cdot exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (21)$$

From the diffusivity values obtained at various temperatures, the natural logarithm of Deff (Ln(Deff)) was plotted against the reciprocal of temperature (1/T) to assess the activation energy:

$$Ln(D_{eff}) = Ln(D_0) - \frac{E_a}{R(T+273.15)} \quad (22)$$

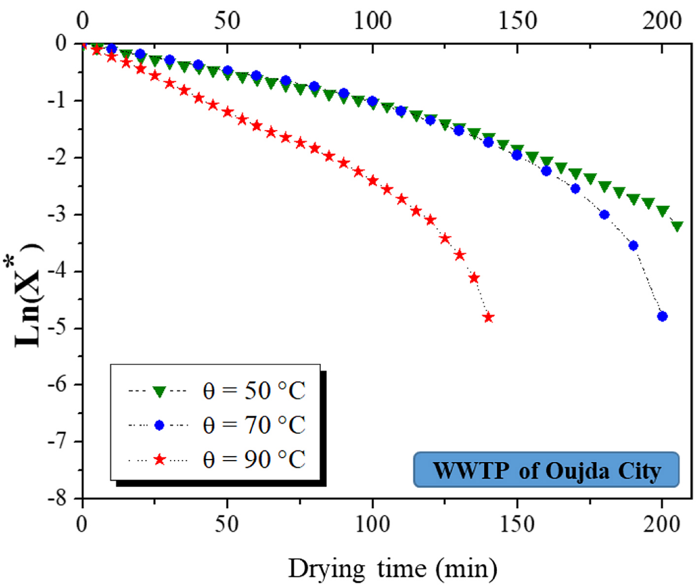

Figure 10. The logarithmic evolution of the moisture content of wastewater sludge (from WWTP Oujda) over time under various drying air conditions

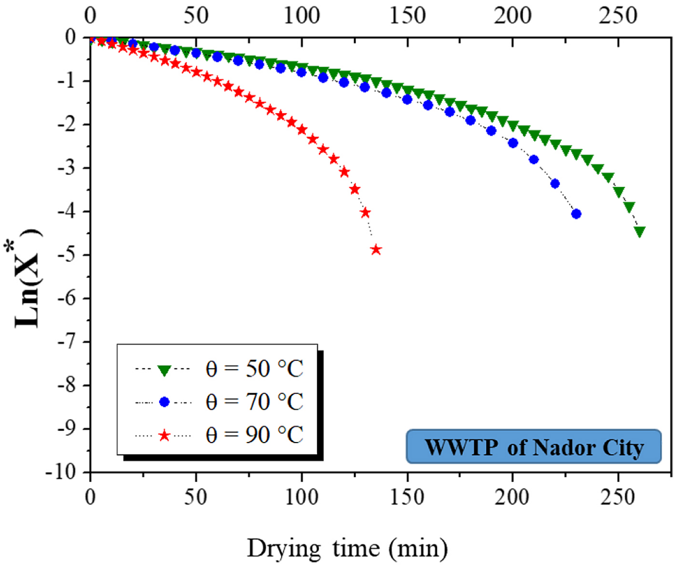

Figure 11. The logarithmic evolution of the moisture content of wastewater sludge (from WWTP Nador) over time under various drying air conditions

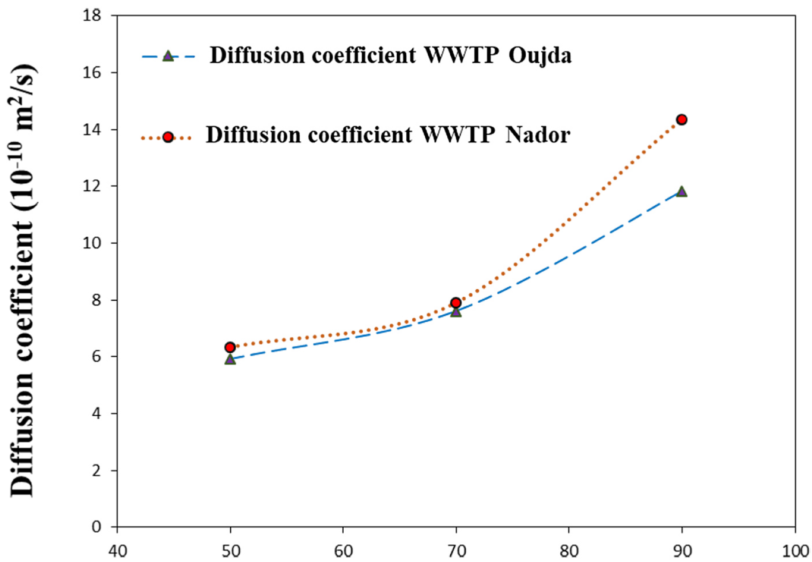

Figure 12. Influence of temperature on the diffusion coefficient

Table 3. Evaluation of the effective diffusivity of wastewater sludge generated by the wastewater treatment plants of the cities of Oujda and Nador

Samples	Experiment	Dv ± 0.002 (m^3/s)	Θ ± 0.3 (°C)	D_{eff} ($m^2 \cdot s^{-1}$)	(r) correlation coefficient
WWTP Oujda	1	0.083	50	0.5910 10^{-9}	0.991
	2	0.083	70	0.7599 10^{-9}	0.979
	3	0.083	90	1.1821 10^{-9}	0.988
WWTP Nador	1	0.083	50	0.6332 10^{-9}	0.990
	2	0.083	70	0.7899 10^{-9}	0.985
	3	0.083	90	1.4353 10^{-9}	0.979

The slope of the Arrhenius equation-defined straight line was used to calculate the activation energy of the wastewater sludge and it gave the following values:

- wastewater sludge collected form WWTP of Oujda city: E_a = 16.80 kJ/mol;
- wastewater sludge collected form WWTP of Nador city: E_a = 19.76 kJ/mol.

Modeling of drying curves

To predict the drying behavior under different aerothermal conditions than those under which the trials were conducted, the experimental data were adjusted using a nonlinear optimization method, specifically the Marquardt-Levenberg algorithm, applied through specialized software such as CurveExpert and Origin6.1. In the conducted study, eight mathematical models were evaluated to accurately describe the drying kinetics of wastewater sludge. To choose the most suitable model, the following criteria were used:

- correlation coefficient (R) to assess the accuracy of the fit,
- mean bias error (MBE) to measure the average deviation of the model predictions from the experimental data,
- chi-square (χ^2) to test the dispersion of residuals.

The analysis of these criteria proves that the Midilli-Kucuk model presents the r value closest to 1 and the lowest χ^2 and MBE values (Tables 4 and 5). This is reflected by a remarkable match with the drying data of wastewater sludge collected from WWTP of Oujda city and Nador city with the values predicted by the Midilli-Kucuk model. This model has been validated for simulating the behavior of sewage sludge in studies previously conducted on WWTP sewage sludge from Marrakech and Meknes. The Midilli-Kucuk model has been extensively used to describe the drying of various products with similar structures in numerous studies. (Ali et al., 2016; Azeddine et al., 2023; Bougayr et al., 2023)

To enable the prediction of drying behavior under experimental conditions different from those under which the experiments were conducted, the effect of drying air temperature and sludge moisture content on the coefficients of the Midilli-Kucuk equation was considered. To establish a more reliable correlation, the results of sludge drying from WWTP of Marrakech (Ali et al. 2016) and that of the city of Meknes (Bougayr et al. 2023) were taken into account. In this section, the authors aimed to propose a generalization of the Midilli-Kucuk equation through multiple regression of the model

Table 4. Statistical parameters and coefficients of models describing the drying law of sludge from WWTP of Oujda

Model	θ°C	Coefficients				R	χ2	MBE
		C_1	C_2	C_3	C_4			
Newton	50 °C	0.01144	-	-	-	0.9909	0.0017	0.0370
	70 °C	0.01131	-	-	-			
	90 °C	0.02367	-	-	-			
Page	50 °C	0.0051906	1.1701	-	-	0.9965	0.0007	0.0239
	70 °C	0.002372	1.3374	-	-			
	90 °C	0.01833	1.06473	-	-			
Henderson and Pabis	50 °C	1.0336	0.01182	-	-	0.9921	0.0015	0.0351
	70 °C	1.0655	0.01204	-	-			
	90 °C	1.0208	0.02416	-	-			
Logarithmic	50 °C	1.1705	0.007844	-0.1917	-	0.8114	0.0296	0.1050
	70 °C	0.6581	8.3476	0.3419	-			
	90 °C	1.0363	0.02209	-0.03051	-			
Two term	50 °C	0.5024	0.01182	0.5312	0.01182	0.9921	0.0017	0.0364
	70 °C	0.5327	0.01204	0.5327	0.01204			
	90 °C	0.5817	0.02416	0.4391	0.02416			
Two term exponential	50 °C	1.6718	0.01489	-	-	0.9961	0.0007	0.0249
	70 °C	1.834	0.01613	-	-			
	90 °C	1.4926	0.02791	-	-			
Wang and Singh	50 °C	$-8.36102\ 10^{-3}$	$1.7916\ 10^{-5}$	-	-	0.9950	0.0009	0.0253
	70 °C	$-8.0699\ 10^{-3}$	$1.5749\ 10^{-5}$	-	-			
	90 °C	$-1.6501\ 10^{-2}$	$6.8982\ 10^{-5}$	-	-			
Approximation de la diffusion	50 °C	1.0965	$8.8292\ 10^{-3}$	-0.1873	-	0.9993	0.0001	0.0110
	70 °C	16.5528	$3.9254\ 10^{-3}$	0.9227	-			
	90 °C	5.0127	0.01707	0.9251	-			
Midilli Kucuk	50 °C	0.9833	0.009221	0.9968	$-5.3839\ 10^{-4}$	0.9994	0.0001	0.0106
	70 °C	0.9821	0.004785	1.1244	$-7.0263\ 10^{-4}$			
	90 °C	1.0062	0.02241	1.0043	$-1.8293\ 10^{-4}$			

Table 5. Statistical parameters and coefficients of models describing the drying law of sludge from WWTP of Nador

Model	θ°C	Coefficients				R	χ2	MBE
		C_1	C_2	C_3	C_4			
Newton	50 °C	0.0081	-	-	-	0.9805	0.0037	0.0610
	70 °C	0.009239	-	-	-			
	90 °C	0.018044	-	-	-			
Page	50 °C	0.001127	1.4018	-	-	0.9958	0.0008	0.0283
	70 °C	0.001399	1.3922	-	-			
	90 °C	0.004128	1.3531	-	-			
Henderson and Pabis	50 °C	1.0846	0.008808	-	-	0.9849	0.0030	0.0545
	70 °C	1.08619	0.01002	-	-			
	90 °C	1.0832	0. 0.01948	-	-			
Logarithmic	50 °C	1.6287	0.003637	-0.6306	-	0.9992	0.0002	0.0128
	70 °C	-3.7585	0.001582	4.7556	-			
	90 °C	1.2587	0.01225	-0.2351	-			
Two term	50 °C	-3.758	$1.582\ 10^{-3}$	4.7556	$2.483\ 10^{-3}$	0.9974	0.0006	0.0226
	70 °C	31.725	0.0177	-30.7589	0.0182			
	90 °C	-49.174	0.0345	50.141	0.0339			
Two term exponential	50 °C	1.8814	0.01196	-	-	0.9942	0.0011	0.0334
	70 °C	1.8901	0.01361	-	-			
	90 °C	1.8683	0.02609	-	-			
Wang and Singh	50 °C	-0.005695	$0.720\ 10^{-5}$	-	-	0.9996	0.00009	0.0095
	70 °C	-0.006542	0.000010	-	-			
	90 °C	-0.013006	0.000042	-	-			
Approximation de la diffusion	50 °C	13.5302	0.002228	0.8682	-	0.9992	0.0002	0.0125
	70 °C	22.2627	0.002869	0.9339	-			
	90 °C	11.6666	0.007217	0.9091	-			
Midilli and Kucuk	50 °C	0.9697	$2.063\ 10^{-3}$	1.2053	$-6.662\ 10^{-4}$	0.9998	0.00004	0.0065
	70 °C	0.9891	0.003018	1.177	$-5.67\ 10^{-4}$			
	90 °C	0.9801	$5.374\ 10^{-3}$	1.2539	$-4.92\ 10^{-4}$			

parameters. Table 6 compiles all the values of dryness, temperatures, and the coefficients of the Midilli-Kucuk equation. Figure 13 illustrates the regression of the Midilli-Kucuk model coefficients against sludge moisture content and drying air temperature.

Hence, it can be inferred that this empirical correlation describes effectively drying kinetics of wastewater sludge during the process of convective partial solar drying, and has proven to be a reliable empirical tool, enabling the accurate description and prediction of the drying behavior.

The application of this model can significantly benefit the design of industrial convective dryers for the stabilization of sewage sludge. By accurately predicting the drying kinetics, the model allows engineers to optimize dryer design parameters, such as temperature, air-flow rate, and drying time, ensuring efficient moisture removal and consistent sludge quality. This optimization not only improves the efficiency of the drying process but also reduces energy consumption and operational costs.

$$X^*=a\exp\left(-kt^n\right)+bt \tag{23}$$

where:

$$a = -2.23829 + 5.76323\ 10^{-2}\theta + 5.32987\ Ds - 2.75466\ 10^{-4}\theta^2 - 3.08403\ Ds^2 - 3.56522\ 10^{-2}\theta.Ds$$
$$k = 6.62225\ 10^{-2} - 2.37477\ 10^{-3}\theta + 7.72697\ 10^{-2}Ds + 1.92149\ 10^{-5}\theta^2 - 5.04278\ 10^{-2}Ds^2 - 3.90270\ 10^{-4}\theta.Ds$$
$$n = 5.47565\ 10^{-1} + 3.59336\ 10^{-2}\theta - 3.45223\ Ds - 2.70774\ 10^{-4}\theta^2 + 2.99906\ Ds^2 + 1.00664\ 10^{-2}\theta.Ds$$
$$b = 2.5684810^{-4} + 1.31293\ 10^{-5}\theta - 7.02353\ 10^{-3}Ds - 2.18333\ 10^{-7}\theta^2 + 5.22373\ 10^{-3}Ds^2 + 4.70050\ 10^{-5}\theta.Ds$$

Moreover, the model's ability to generalize and predict drying behavior under various conditions can help in scaling up laboratory findings to industrial applications. It provides a robust framework for designing dryers that are adaptable to different climatic conditions and sludge characteristics, enhancing the overall stability and safety of the sludge treatment process. Consequently, this modeling approach supports the development of more efficient and cost-effective drying solutions, contributing to better resource management and environmental sustainability in wastewater treatment operations.

Table 6. Summary of the coefficients values of the Midilli-Kucuk equation for sludge from four wastewater treatment plants

City	Temperature	Dryness	$X^*=a\exp\left(-kt^n\right)+bt$			
			a	k	n	b
Marrakech	50	0.2	0.99 10^{-1}	8.00 10^{-3}	1.1798	-1.69 10^{-4}
	70	0.2012	9.96 10^{-1}	4.23 10^{-3}	1.3442	-1.88 10^{-4}
	90	0.202	9.89 10^{-1}	2.15 10^{-2}	1.1783	-9.61 10^{-4}
Oujda	50	0.5146	9.83 10^{-1}	9.22 10^{-3}	0.997	-5.38 10^{-4}
	70	0.4704	9.82 10^{-1}	4.79 10^{-3}	1.12	-7.03 10^{-4}
	90	0.4974	1.01 10^{-1}	2.24 10^{-2}	1.00	-1.83 10^{-4}
Meknes	50	0.5806	1.01	1.55 10^{-2}	0.89	-6.30 10^{-4}
	70	0.5806	9.85 10^{-1}	5.26 10^{-3}	1.20	-2.24 10^{-4}
	90	0.579	9.88 10^{-1}	1.22 10^{-2}	1.14	-3.51 10^{-4}
Nador	50	0.2194	9.70 10^{-1}	2.06 10^{-3}	1.21	-6.66 10^{-4}
	70	0.214	9.89 10^{-1}	3.02 10^{-3}	1.18	-5.67 10^{-4}
	90	0.2052	9.80 10^{-1}	5.37 10^{-3}	1.25	-4.92 10^{-4}

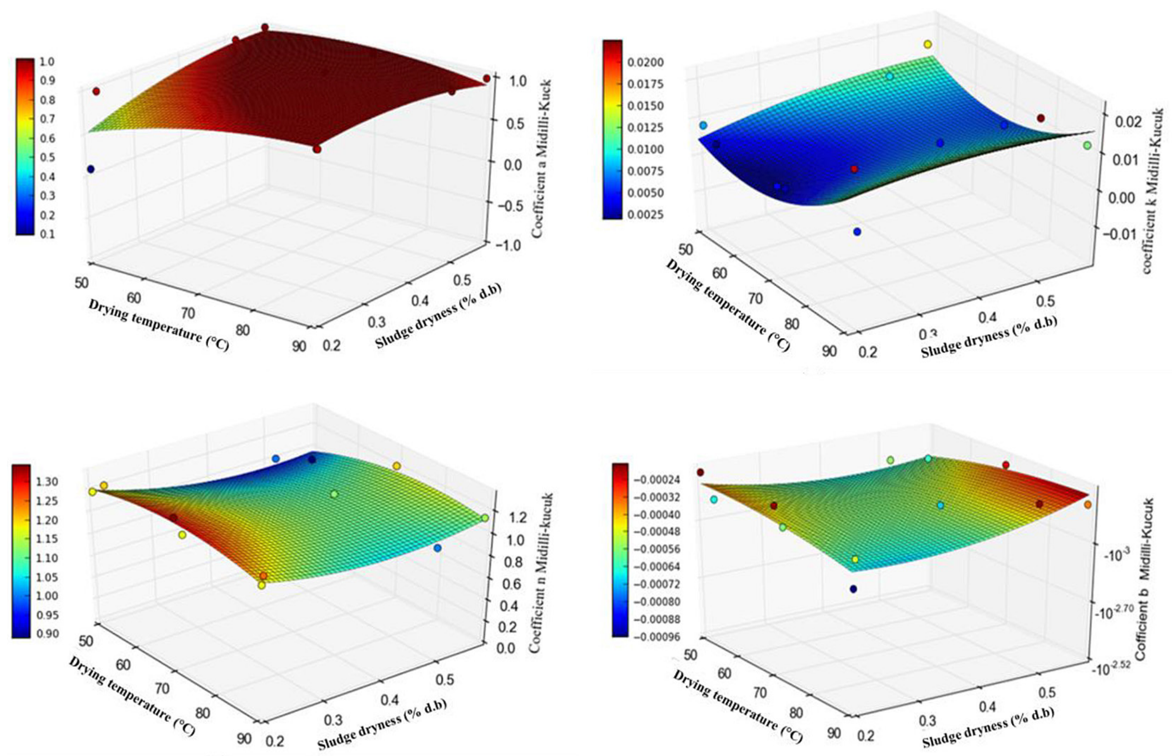

Figure 13. Regression of model coefficients according to dryness and temperature

CONCLUSIONS

In this paper, the drying kinetics of residual sludge from the wastewater treatment plant of Oujda City and Nador City in a convective solar dryer were studied. The analysis of the experimental results revealed the occurrence of the phase with decreasing rate illustrates the drying phase with a decreasing rate, a slightly presence of phase I of uniform speed for the sludge from WWTP of Nador Cityhas been observed. The obtained curves have demonstrated the influence of temperature on the drying rate, clearly showing a significant acceleration of the drying process with higher air temperatures.

The application of the non-linear Marquard-Levenberg optimization has allowed obtaining the characteristic drying curve thus deducing the empirical drying equation.

The analysis of the drying curves allowed studying the thermal diffusivity of sludge samples, the diffusion coefficient values are calculated for the three temperatures, the effective diffusivity measured for the three temperatures increases along with temperature. The activation energy was calculated by employing the experimental results of drying and the Arrhenius expression, and was 16.8 kJ/mol for sewage sludge generated from WWTP of Oujda city and 19.76 kJ/mol.

Fitting the drying curves with eight recognized empirical and semi-empirical models from the literature enabled the identification of the appropriate model for describing the drying kinetics under various aerothermal conditions. The Midilli-Kucuk model, selected based on the analysis of selection criteria values, proved to be the most appropriate, providing a reliable basis for predicting drying behavior at untested temperatures. A correlation based on the Midilli-Kucuk model was proposed to describe the drying of sewage sludge, taking into consideration the effects of temperature and moisture content on the drying behavior. This modeling aids in designing industrial convective dryers for sewage sludge by accurately predicting drying kinetics, optimizing design parameters, as well as reducing energy use and costs. It scales laboratory results to industrial applications, enhancing dryer adaptability to various conditions, improving sludge stabilization, and promoting efficient, sustainable wastewater treatment.

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