Energy and Power Engineering, 2023, 15, 37-51
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Influence of Leachate Recirculation on Landfill Degradation and Biogas Production

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How to cite this paper: N'wuitcha, K., Aoukou, K.D.D., Nougbléga, Y., Banna, M. and Chesneau, X. (2023) Influence of Leachate Recirculation on Landfill Degradation and Biogas Production. *Energy and Power Engineering*, **15**, 37-51.
https://doi.org/10.4236/epe.2023.151002

Received: November 14, 2022
Accepted: January 16, 2023
Published: January 19, 2023

Abstract

Population growth combined with the rising standard of living of people around the world is the reason for the ever-increasing production of waste which management is costing states a lot of money for its disposal. Among available waste treatment techniques, landfill is one of the most promoted waste management techniques with the emergence of the bioreactor concept. However, the control of biodegradation parameters in order to accelerate waste stabilization is an important issue. For environmental and economic reasons, the technique of leachate recirculation by injection into the waste is increasingly used to improve the degradation of landfilled waste. The injection of leachate is possible using vertical boreholes, horizontal pipes, infiltration ponds or a combination of these. Indeed, moisture is the main factor in waste degradation and biogas production. The migration of leachate to the bottom of the landfill creates low moisture in the upper areas of the landfill reducing the growth of microbial populations. This results in low or no biogas production. The main objective of the present work is to develop a numerical model of leachate recirculation by injection into the waste to rewet the waste and restart biological activity. The analysis of the results shows that the diffusion of the wet front increases with time and depth. The lateral widening of the wet front is slow in relation to the progression of the wet front towards the bottom of the waste cell. This indicates the predominance of gravity effects over diffusion phenomena. The results reveal that the distributed re-injection is the best mode of leachate recirculation because the moisture distribution on the whole waste mass is totally satisfactory and the biogas generation is more important. Leachate recirculation campaigns should be done periodically to rewet the waste, boost microbial activity and hope for a quicker stabilization of the landfill.

Keywords

Moisture, Leachate Recirculation, Biogas, Distributed Reinjection, Landfill

1. Introduction

The humidity of the waste is a determining factor in the kinetics of waste degradation and gas production. It allows biological stabilization of the stored waste and the production of biogas. Landfills need water and the availability of this water affects the growth of microorganisms.

The availability of water also depends on the water content but also on the concentration of solutes dissolved in the water. The amount of available water can be reduced by interactions with soluble molecules (osmotic effect) and by adsorption on solid surfaces (matrix effect). The phenomenological understanding of the relationship between the water content of a solid substrate and biological activity has led some authors to introduce the concepts of water activity and matrix and osmotic water potential to qualify this moisture.

In the anaerobic phase, optimization of methane production in landfills is controlled by moisture distribution in the waste [1] [2] [3]. Many authors have shown that below a certain moisture content, microbial populations cannot grow properly and any gas production becomes almost non-existent. Palmisano *et al.* [4] found the value ranging 10% - 20% relative to total wet mass. Buivid *et al.* [5] and Noble *et al.* [6] stated the value of 25% - 30%.

The minimum moisture content corresponds to an amount of water that is vital to the microorganism's active in the degradation process. It can also be considered as a thin film of water surrounding the solid particles of the porous matrix, necessary for the mobility and diffusion of bacteria [7]. Above this minimum moisture content, biogas production increases with the water content of the waste. Too high a moisture content, *i.e.* close to saturation, would be inhibitory for the degradation reactions [8] [9]. The dilution of the bacteria in the aqueous medium would make their actions on the solid substrate less effective and the gas production can decrease consequently.

Few models exist in the literature to describe the increase in degradation and biogas production with increasing water content. The type I model used in our model considers that the biogas production term is obtained directly from the degradation of solid waste according to a first order degradation kinetics of the biodegradable fractions of the waste. Three main classes of waste characterized by their degradation speed are highlighted in [7] [10] [11] [12] [13] [14].

Rapidly, biodegradable wastes are composed mostly of putrescible materials, green waste, fruits and vegetables, animal materials, etc. They represent on average 15% of the composition of wastes. The moderately biodegradable wastes are estimated at 55% of the waste composition, including everything from sludge to grease. The slowly biodegradable wastes are composed mainly of paper, cardboard and wood and represent nearly 30% of the waste composition.

As the main limiting factor for biodegradation under anaerobic storage conditions is moisture, the most common means of accelerating biodegradation is recirculation of leachate through the waste mass. Kumar *et al.* [15] studied the effect of leachate recirculation in waste in a bioreactor in Florida (New River Regional Landfill), USA [15]. The initial temperature measured at different depths is 53˚C, 51˚C, and 42˚C at the bottom, middle, and surface of the cell, respectively. The temperature initially decreases with leachate recirculation, as the leachate is generally cooler.

Leachate recirculation improves the conditions for waste degradation, such as pH and temperature [16] [17] [18]. Gurijala *et al.* [19] proposed a water content between 50% - 60% as the best value for the methanogenic phase. Recirculation of leachate can result in an increase in the Chemical Oxygen Demand (COD) of the leachate [18]. This increase in COD can be attributed to the acceleration of waste hydrolysis in the presence of water and also to the dilution of Volatile Fatty Acids (VFAs) which can inhibit hydrolysis [20]. McCreanor [20] summarizes the effect of leachate recirculation in five parts according to the work of different authors [21] [22] namely nutrient distribution, pH buffer, dilution of inhibitors (VFAs), recirculation and distribution of methanogenic populations, modification of leachate composition.

Even though several models have been developed in the past decades, not much attention has been paid to the effects of leachate recirculation on the biodegradation of waste and its consequence on the amount of biogas production. The objective of this work is to study the effect of leachate recirculation on the waste biodegradation in order to enhance biogas production. For this reason, a mathematical model describing the hydro-thermo-biological phenomena of the waste has been developed from the conservation of mass and energy equations for each component (solid, liquid, biogas and steam) considering the waste as a reactive porous medium. The resulting system of equations is discretized using the finite volume method and solved using the Thomas algorithm. In the present work, the influence of point and distributed re-injection on biogas production and waste degradation were studied.

2. Problem Formulation

2.1. Problem Configuration

The schematic of the problem is represented in **Figure 1**. It is a rectangular physical domain with depth H and width L representing half landfill waste cell. The right vertical wall of the landfill cell is in contact with an older waste cell. This wall and the bottom wall are completely sealed by the geomembrane.

The landfill cell is assumed to an undeformable porous medium. The porous solid matrix remains immobile despite of the degradation, settlement and humidification. The energy transfer by radiation is neglected. The porous medium is considered homogeneous; It is considered that there is thermal equilibrium

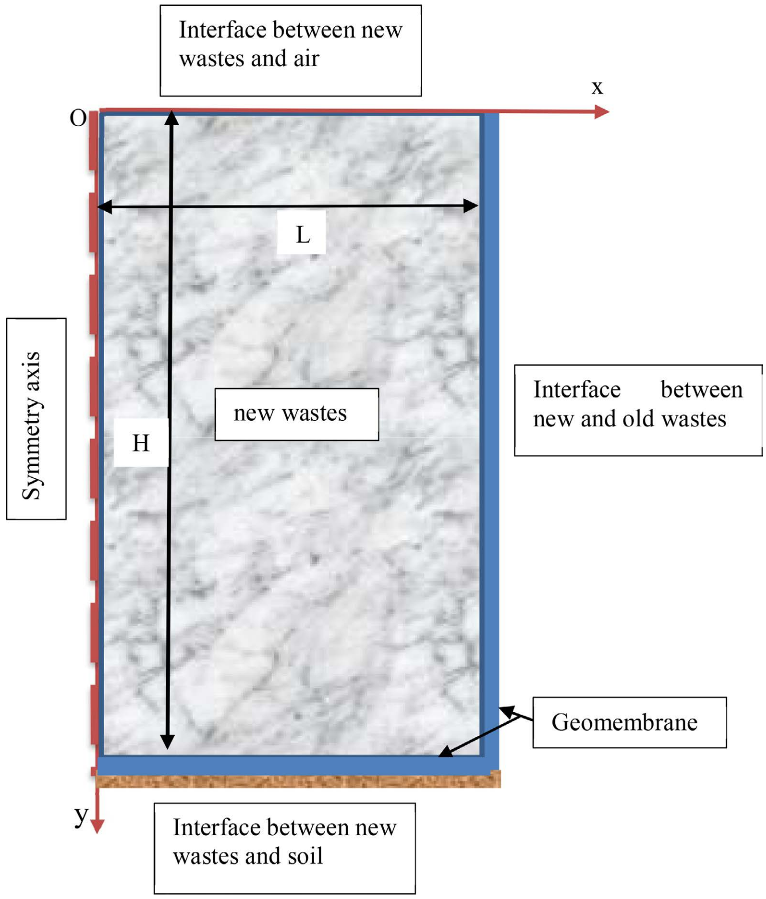

Figure 1. Schematic diagram of the landfilling of waste cells.

between solid, liquid and gaseous phases. The gas mixture is considered to be a perfect gas mixture. The viscous dissipation and the effects of thermal inertia are neglected. The gaseous and liquid phases are considered immiscible and Darcy's law is applicable for both fluid phases. The biogas is considered as an equimolar mixture of methane (CH_4) and carbon dioxide (CO_2).

2.2. Governing Equations

The governing system of equations representing the conservation of mass of different phases and energy [23] [24] under the above assumptions are given as:

- Mass conservation of phase *j*

$$\frac{\partial\left(m_j\right)}{\partial t}+\nabla\left(\rho_j \boldsymbol{U}_j+\boldsymbol{J}_j\right)=\dot{q}_{m,j} \tag{1}$$

where $\boldsymbol{J}_j$ is diffusion mass flux density and $\dot{q}_{m,j}$, source term of mass production of phase *j* (**Table 1**).

The Darcy law can be expressed as followed:

$$\boldsymbol{U}_j=-\frac{k_i k_{rj}}{\mu_j}\left[\nabla P_j-\rho_j \boldsymbol{g}\right] \tag{2}$$

where: k_i is intrinsec permeability, k_{rj} is relative permeability of phase *j*, μ_j

Table 1. Definition of diffusion mass flux densities and source terms of mass production.

Liquid phase	Gas phase	Vapor phase	Biogas phase
$\boldsymbol{J}_l = \boldsymbol{0}$	$\boldsymbol{J}_g = \boldsymbol{0}$	$\boldsymbol{J}_V$	$\boldsymbol{J}_b$
$\dot{q}_{m,l} = -\dot{m} - \alpha_l$	$\dot{q}_{m,g} = \dot{m} + \alpha_b$	$\dot{q}_{m,V} = \dot{m}$	$\dot{q}_{m,b} = \alpha_b$

Table 2. Source and sink terms.

Source term of biogas production	Source term of heat production	Sink term of moisture
$\alpha_b = \sum_{i=1}^{3} f(\omega) A_i C_b \lambda_i(T) \exp(-\lambda_i(T)t)$ With; $\lambda_i(T) = \beta_i \exp\left(-\frac{E_{ai}}{RT}\right)$	$\alpha_q = \frac{H}{2M_b}\alpha_b$	$\alpha_l = \frac{M_{H_2O}}{3.4M_b}\alpha_b$

is dynamic viscosity of phase *j*, P_j and ρ_j denote pressure and density of the phase *j*, $\boldsymbol{g}$ is gravity acceleration.

- Energy equation

$$\frac{\partial\left(\sum_j \rho_j h_j\right)}{\partial t} + \nabla\left(\sum_i \rho_j h_j \boldsymbol{U}_j\right) = \nabla\left(\lambda^* \nabla T\right) + \alpha_q \tag{3}$$

where h_j ($j = s$ for solid, l for liquid, g for gas) is the enthalpy of phase j per mass unit, λ^* the thermal effective conductivity, T the temperature and α_q heat source term.

Table 2 presents source and sink terms where C_b denote the potential biogas production, A_i is the fraction of each component ($i = 1$: rapidly biodegradable, $i = 2$: moderately biodegradable and $i = 3$: slowly biodegradable) and α_b is the rate of biogas production. β_i is a hydrolysis rate of substrate i and E_{ai} is the activation energy of each component. $f(\omega)$ represents an empirical function of water content and t is the time. H is the energy released for each mole of methane, which is produced during waste degradation and M_b is the biogas molar mass. M_{H_2O} is the molar mass of water vapor.

2.3. Boundary and Initial Conditions

2.3.1. Boundary Conditions

The boundary conditions are defined as follow:

- at the top horizontal boundary: a zero-flux condition for water content (ω) expect at the injection points, the pressure (P) condition is equal to the atmospheric pressure and for the temperature (T), convective exchange is considered.
- at the bottom horizontal boundary: a zero-flux condition except the temperature condition which is equal to the ground temperature
- at the vertical boundary and on symmetric axis: a zero-flux condition for water content, temperature and pressure
- at the symmetric axis: a zero-flux condition for water content, temperature

and pressure

2.3.2. Initial Conditions

The initial conditions are those of a one-month old cell after the filling period (state of the cell after 30 days of simulation without reinjection). The initial water content, pressure and temperature in the landfill are estimated respectively 54%, atmospheric pressure and average ambient temperature equal to 298.15 K.

3. Numerical Approach and Validation

The numerical discretization method used in this study is the finite volume method. The studied domain is defined by a mesh of discretely spaced points on which the control volumes are centered. The nonlinear differential equations are integrated on each control volume. The temporal discretization is based on a Cranck-Nicholson method. The Thomas algorithm was used to solve the resulting algebraic equations system. The simulation is performed numerically using a computer code implemented in Fortran language. The iterative procedure is used with a sub-relaxation coefficient for each dependent variables (water content, temperature and pressure). This procedure is stopped when the following test is verified:

$$\left| \frac{\phi^{n+1} - \phi^{n}}{\phi^{n+1}} \right| \le \epsilon$$

where ϕ is the dependent variable, n is the number of iterations and ϵ the precision.

To study the validation of this simulation, the current results of water content distribution in the wastes are compared with those obtained by Aran [7]. The results show that this numerical method has a good accuracy (**Figure 2**). The slight difference observed between the distribution of the temperature fields of the two models can be explained by the fact that the nature of waste used in [7] is not known as well as the initial temperature of waste.

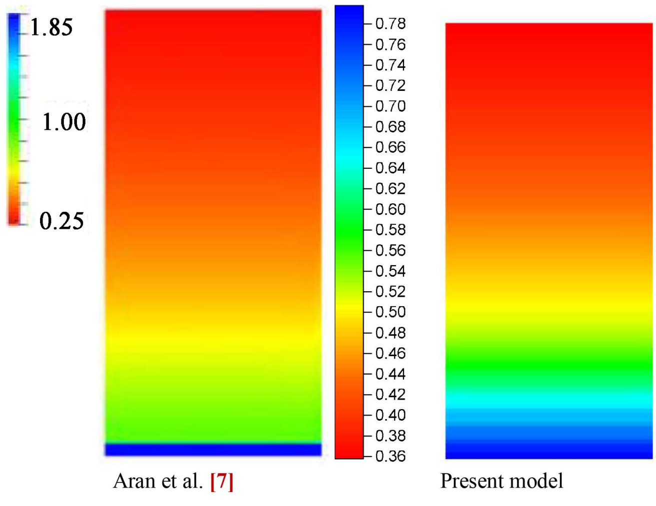

Figure 2. Comparison of the distribution of water fields in landfill waste cell for $t = 50$ s.

4. Results and Discussion

This part reports the results of the numerical simulation from the leachate recirculation. These results are then discussed.

4.1. Influence of Point Leachate Re-Injection on Waste Biodegradation and Biogas Production

The point re-injection of leachate is done by sending a flow of liquid to the injection point for a few days followed by a phase during which the injector is closed. The reinjection is done during one day. **Figure 3** presents the evolution of the water content within the waste in the case of a point re-injection. The analysis of the **Figure 3** reveals a saturated bubble progressing towards the bottom of the waste cell under the influence of gravity and capillary pressure. It is can be observed that the diffusion of water towards the bottom of the landfill is quick. After 35 days, the wet front has crossed the whole 40 meters of the cell and is about to feed the already saturated zone. The transfer of leachate to the bottom of the cell is essentially controlled by gravity.

Figure 3 shows that the lateral diffusion of the wet front increases with depth and time. This lateral widening of the wet front is slow compared to the progression of the wet front towards the bottom of the waste cell. This shows the predominance of gravity effects over diffusion phenomena. The rapidity with which the wet front moves can be explained by the high values of the hydraulic conductivities used.

It is important to note that the water accumulates at the bottom of the cell and creates a water saturated zone characterized by high values of water content (**Figure 3(d)**). This is due to the fact that no drainage system has been integrated in our model.

Furthermore, the analysis of the **Figure 3** also shows that when the wet front reaches the saturated zone, the recharge of this zone is characterized by an increase in the height of the water table. The spread of the wet front also becomes more and more important.

Leachate recirculation increased the moisture content of the waste. **Figure 4** and **Figure 5** show the temporal evolution of moisture content and biogas production rate for the position ($x = 10$ m; $z = 8$ m) for $t = 93$ days. This evolution is divided into two main parts. The time intervals, $t = 0$ day to $t = 30$ days and from $t = 30$ days to $t = 93$ days respectively represent the phase without reinjection and the phase with leachate reinjection. The analysis of **Figure 4** reveals an increase in moisture content due to leachate recirculation starting on the 30th day of simulation. This increase in moisture content led to a resumption of biological activity and consequently to a high production of biogas (**Figure 5**). This highlights the importance of leachate recirculation on the biogas production rate.

The disadvantage of this point recirculation is that only the waste directly under the injection point is affected by the reinjection. Only this waste stabilizes by exhausting its methanogenic capacity, while the others remain potentially active.

Moisture increases during leachate recirculation in the layers directly below

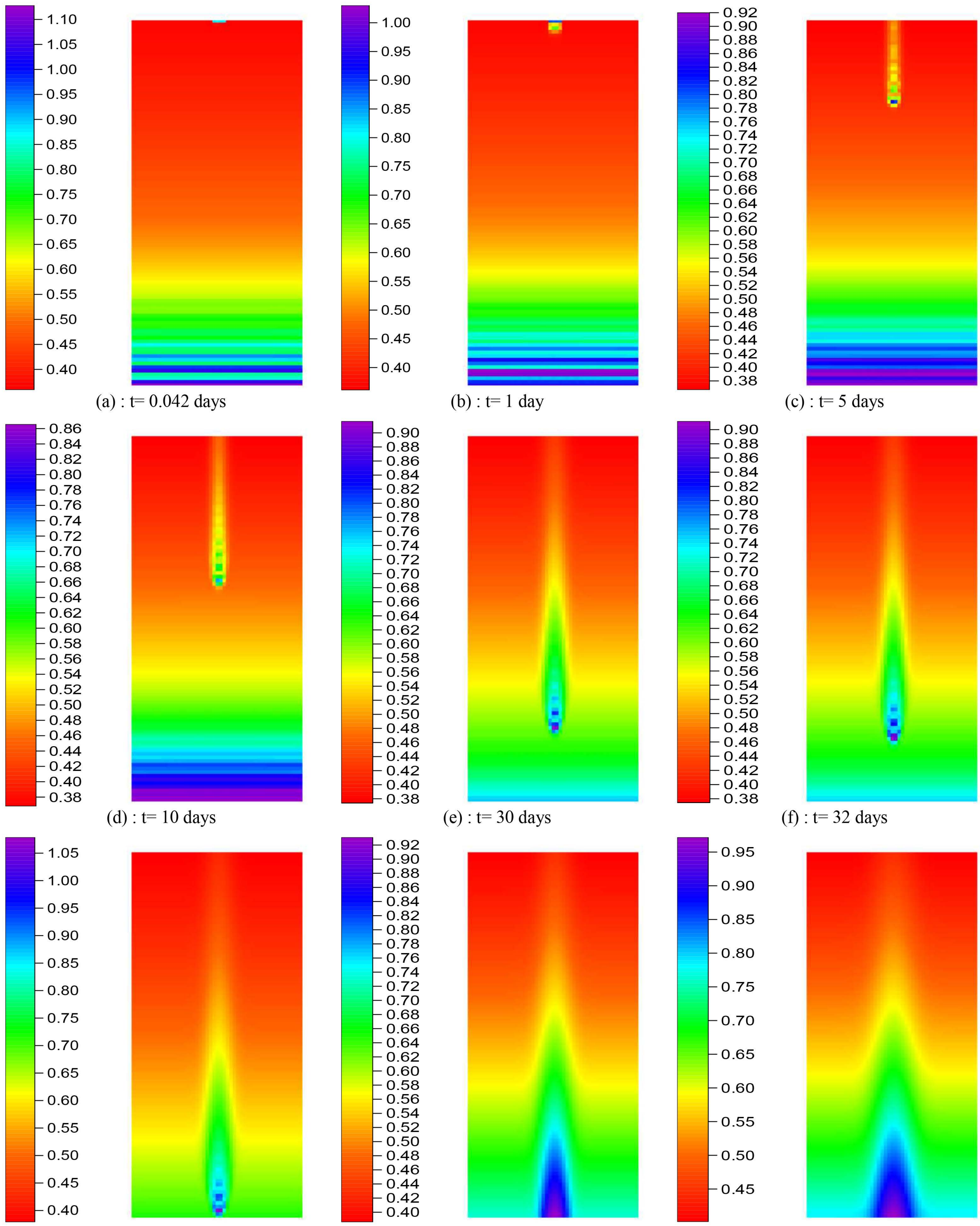

Figure 3. Evolution of the water content in the case of a punctual re-injection after one day (1 day of re-injection).

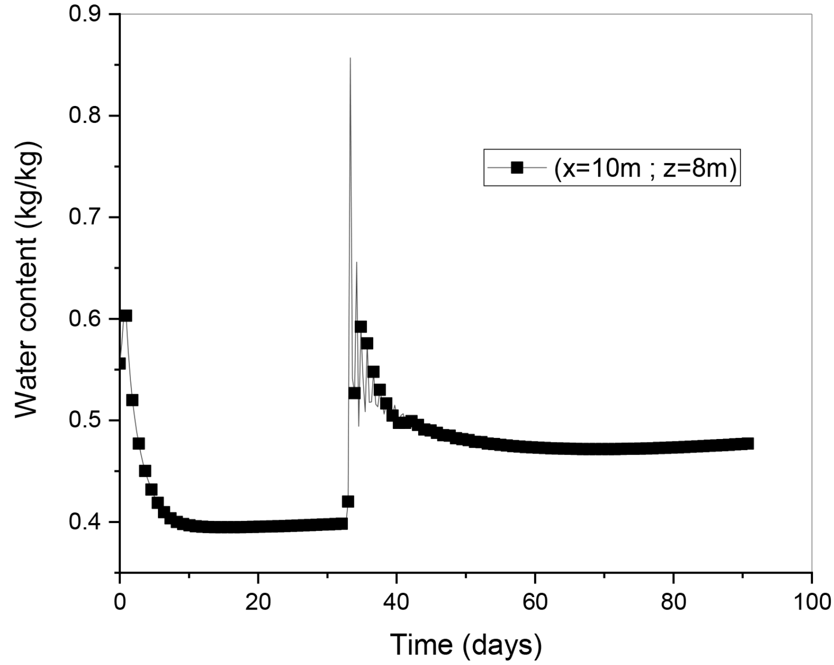

Figure 4. Evolution of water content for (x = 10 m; z = 8 m) for t = 93 days (start of reinjection after 30 days of simulation without reinjection or 63 days of reinjection).

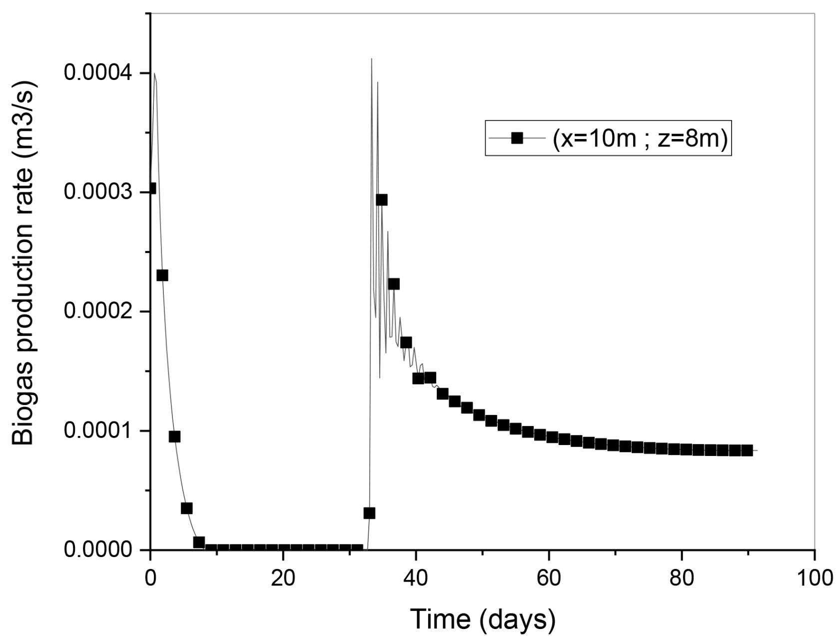

Figure 5. Evolution of the biogas production rate for (x = 10 m; z = 8 m) for t = 93 days (start of reinjection after 30 days of simulation without reinjection or 63 days of reinjection).

the injection point. Leachate injection seems to affect waste hydrolysis most of all and the first injection period has a very large effect [25].

To summarize, the distribution of moisture in the waste mass is not totally satisfactory in the case of point injection because the total stabilization of the site is not achieved and still presents risks for the environment.

4.2. Influence of Distributed Leachate Re-Injection on Waste Biodegradation and Biogas Production

For the distributed reinjection, four (4) injection points are considered and modeled practically three (3) meters away from each other on the upper part. The distributed reinjection is done during one day. Figure 6 illustrates the temporal

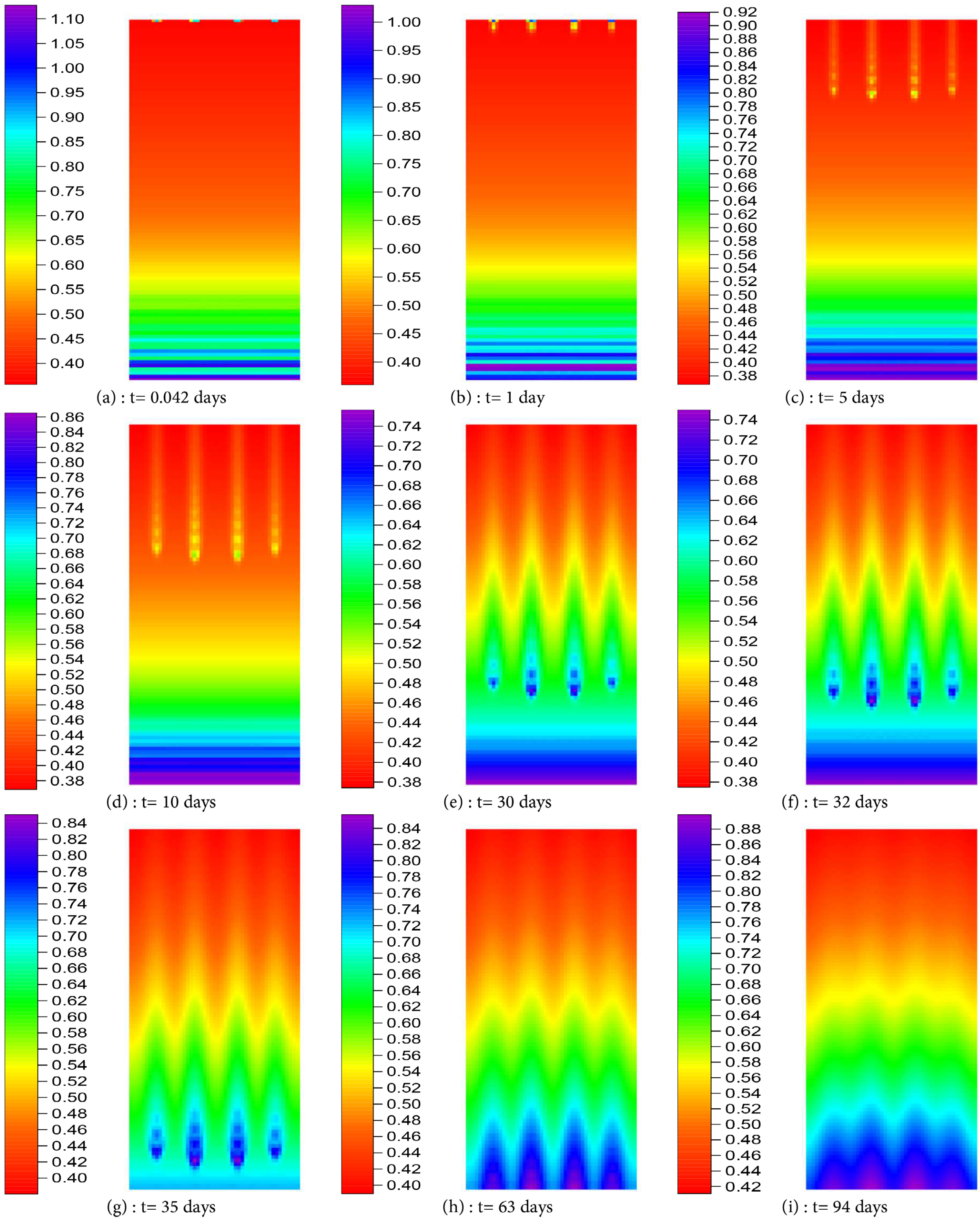

Figure 6. Evolution of the water content in the case of a distributed reinjection after one day (1 day of re-injection).

distribution of the water fields from the distributed re-injection. The analysis of **Figure 6** shows that the diffusion of water towards the bottom of the waste disposal facility is about to feed an already initially saturated zone.

The lateral diffusion of the wet front increases with depth and with time. The lateral spread of the wet front is slow compared to the progression of the wet front towards the bottom of the waste cell. This shows the predominance of gravity effects over diffusion phenomena. In general, the propagation of the wet front takes place normally, in the same way as during point re-injection.

Chenu *et al.* [26] studied the impact of distributed leachate recirculation on the cell behaviour. The recirculation revealed a saturated bubble progresses downward under the influence of gravity and capillary pressure and water accumulation at the bottom of the cells [26].

The distribution of moisture over the entire waste cell is satisfactory. The moisture is better distributed, even if in the upper part, some areas are still not affected by the leachate recirculation.

The analysis of the **Figure 6** reveals that zones near the surface have insufficient water content to maintain the degradation reactions of the waste after a few days of relaxation. In this case, it would be interesting to start another recirculation campaign to reactivate the biogas generation processes. Moisture flow induced by leachate recirculation through decaying solid waste increases the rate of methane production by 25% - 50% compared to the rate of production under conditions of minimal moisture movement and the same overall moisture content [27]. Water percolation is found to be an important factor in accelerating landfill degradation [28].

5. Conclusion

A two-dimensional numerical model based on the conservation of mass and energy equations was developed by the finite volume method using the Thomas algorithm to study the influence of leachate recirculation on the waste. The simulation results showed that the wet front migrates to the bottom of the waste cell and the leachate recirculation boosts the microbial activity and enhances the biogas production rate. Distributed re-injection was found to be the best means of leachate recirculation for improved degradation of the whole waste mass and optimum biogas production. The progression of the wet front towards the bottom of the waste cell is fast in comparison with the lateral widening of the wet front. It appears that the gravitational phenomena predominate over the diffusion phenomena. The outlook for this work is to study the optimal injection duration for the most efficient biogas production. The influence of the recirculation time and the injected leachate flow rates for waste degradation and gas generation are also to be considered in future works. Finally, approaches to thermoeconomic evaluation of the results will be considered by introducing a recent measurement of sustainability by Lucia and Grisolia [29] based on the exergy analysis and on the irreversible thermodynamic approach. They would allow evaluating both the bioreactor technological level and the environmental impact of the production processes and the socio-economic conditions of the countries.

Acknowledgements

The authors thank the Director and staff members of National Metrological Service of National Aviation Security Agency (ASECNA) of Togo for providing climate data required for this work. They are also grateful to the anonymous reviewers for their thorough reviews, helpful comments and suggestions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

L	Depth	[m]
H	Width	[m]
m_j	Mass of phase j	[kg]
U_j	Darcy's velocity of phase j	[m·s^{-1}]
ρ_j	Density of phase j	[kg·m^{-3}]
$\dot{m}$	Evaporation rate (mass rate of water transfer from phase l to phase v)	[kg·m^{-3}·s^{-1}]
α_l	moisture sink source term	[kg·m^{-3}·s^{-1}]
α_b	biogas production source term	[kg· m^{-3}·s^{-1}]
α_q	heat source term	[kg·m^{-1}·s^{-3}]
t	Time	[day]
$\boldsymbol{J}_j$	Diffusion mass flux density of phase j	[kg·m^{-2}·s^{-1}]
k_i	Intrinsec permeability (absolute permeability)	[m^2]
k_{rj}	Relative permeability of phase j	
P_j	Pressure of the phase j	[Pa]
$\boldsymbol{g}$	Gravity acceleration	[m·s^{-2}]
μ_j	Dynamic viscosity of phase j	[Pa·s]
h_j	Enthalpy of phase j	[J·kg^{-1}]
T	Temperature	[K]
P	Pressure	[Pa]
C_b	Potential biogas production	[kg·m^{-3}]
A_i	Fraction of each component i (i = 1: rapidly biodegradable, i = 2: moderately biodegradable and i = 3: slowly biodegradable)	[%]
E_{ai}	activation energy of each component i (i = 1: rapidly biodegradable, i = 2: moderately biodegradable and i = 3: slowly biodegradable)	[J]
R	Ideal gas constant	[J·mol^{-1}·K^{-1}]
H	Energy released for each mole of methane	[kJ·mol^{-1}]
M_b	Molar mass of biogas	[kg·mol^{-1}]
M_{H_2O}	Molar mass of water vapor	[kg·mol^{-1}]
E_{ai}/R	Activation energy	[K]

Greek Symbols

λ^*	Thermal effective conductivity	[W·m^{-1}·K^{-1}]
Ω	Water content (/dry mass of waste)	[kg·kg^{-1}]
λ_i	Reaction rate constant of refuse i	[s^{-1}]
β_i	Hydrolysis rate of substrate i (by Arrhenius law)	[s^{-1}]

Subscripts and Superscripts

L	Liquid
G	Gas
V	Vapor
B	Biogas
S	Solid
$*$	Porous medium