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Conceptualization of Bioreactor Landfill Approach for Sustainable Waste Management in Karachi, Pakistan

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Abstract: Finding a sustainable approach for municipal solid waste (MSW) management is becoming paramount. However, as with many urban areas in developing countries, the approach applied to MSW management in Karachi is neither environmentally sustainable nor suitable for public health. Due to adoption of an inefficient waste management system, society is paying intangible costs such as damage to public health and environment quality. In order to minimize the environmental impacts and health issues associated with waste management practices, a sustainable waste management and disposal strategy is required. The aim of this paper is to present a concept for the development of new bioreactor landfills for sustainable waste management in Karachi. Furthermore, this paper contributes to estimation of methane (CH_4) emissions from waste disposal sites by employing the First Order Decay (FOD) Tier 2 model of the Intergovernmental Panel on Climate Change (IPCC) and determining of the biodegradation rate constant (*k*) value. The design and operational concept of bioreactor landfills is formulated for the study area, including estimation of land requirement, methane production, power generation, and liquid required for recirculation, along with a preliminary sketch of the proposed bioreactor landfill. This study will be helpful for stockholders, policy makers, and researchers in planning, development, and further research for establishment of bioreactor landfill facilities, particularly in the study area as well as more generally in regions with a similar climate and MSW composition.

Keywords: municipal solid waste; sanitary landfill; open dumps; waste to energy; climate change

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1. Introduction

In order to control environmental impacts and maintain better public health, municipal solid waste (MSW) must be managed in a sustainable way [1]. However, sustainable management of huge amounts of MSW is a challenge, especially in developing countries, due to lack of financial and technical resources, increasing population, economic development, and rapid urbanization [2]. According to the study [3], the financial costs to the public of negligence are five to ten times higher than the economic costs of efficient management of the waste. The costs to be paid by society if waste is not managed effectively is a 'cost of negligence' which includes public health costs, the cost of environmental deterioration because of uncollected wastes, uncontrolled dumping, open burning, and inefficient resource recovery, productivity loss, flood damage, loss of business and tourism, and long-term cleanup costs [3].

Worldwide, about 2.01 billion metric tonnes of MSW are generated yearly, and this amount is expected to increase more than two- or even three-fold in lower-income countries by 2050 due to significant economic development and rising populations [4,5]. One study [3] estimated that two billion members of the global population lack access to regular waste collection services, and about three billion people have no access to controlled waste landfilling facilities. Despite many years of rising public awareness, the problem of uncollected waste disposal continues to exist in developing countries [6]. The rate of waste collection strongly depends on the income of the citizens in a country. In high-income countries, the collection rate is close to 100%; however, in lower–middle income and low-income countries the waste collection rate is about 51% and 39%, respectively [5].

However, governments are presently proceeding towards sustainable methods of waste disposal after realizing the environmental risks and economical costs of open waste dumping [7]. In this regard, economic conditions, specific legislation, and the geographical location of a country has a significant influence on the adoption of certain waste disposal approaches [8,9]. Generally, effective MSW management practices involve source separation, door-to-door collection, transportation, storage, separation of organic and inorganic waste (plastics, glass and metals) at the storage point, material recycling, biological treatment (anaerobic digestion and composting) of biodegradable wastes, thermal treatment (incineration) with energy recovery, and final disposal of residual waste residues at landfills [10].

Over the years, approaches to MSW disposal on land have evolved from uncontrolled open dumping to engineered landfill systems [11]. Land disposal of MSW accounted for more than 1.5 billion tonnes of the total 2.01 billion tonnes of waste generated globally in 2016 [5]. The total number of waste disposal sites in operation globally is about 300,000–500,000 [12]. In the recent past, uncontrolled dumping was the main approach to waste disposal used worldwide [13]. However, open dumping remains in practice as the main solid waste disposal method for more than half of the global population [14,15].

According to studies [16,17], the MSW generation rate in Karachi is 15,600 tonnes/day, with 53–60% of this the organic fraction. Typically, organic waste is neglected after sorting of recyclables from waste mixture. It is neither collected by scavengers, nor do the municipal authorities utilise it through compositing, anaerobic digestion, or other treatment [17]. Neither municipal authorities nor private companies are willing to separate organic waste for biological treatment due to the lack of vision and policy to utilize it for energy generation and the absence of a market for compost products [18]. Hence, this mismanagement of waste results in the loss of both a valuable energy-containing resource and leads to environmental and public health issues.

One study [19] estimated that the amount of MSW annually disposed of at dumpsites (2.2 million tonnes) has the potential to emit about 3.9 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq.) emissions. In order to minimize the environmental impacts and health issues associated with open waste disposal in Karachi, a sustainable waste management and disposal facility is required. This study intends to present a concept for the development of bioreactor landfills and sustainable waste management in the city.

This paper contributes to estimation of methane (CH_4) emissions from waste disposal sites, determination of the degradation rate constant (k) value under the prevailing climatic conditions in Karachi and formulation of a design and operational concept for a bioreactor landfill. Additionally, estimations concerning land requirements, methane production, power generation, and liquid required for recirculation in order to maintain the required waste degradation rate in bioreactor landfill conditions are reported in this paper.

2. MSW Landfilling Approaches

2.1. Open Dumps

The open dump method is an elementary level of solid waste disposal, and is identified with the uncontrolled deposition of waste with only limited or without any control measures [20]. Overall, 33% of waste is openly disposed of at dumpsites globally, and in lower income countries (where dumpsites are the leading waste disposal facilities) more than 90% of waste is openly disposed of [5,21]. In Pakistan, 70% of waste generated ends up in dumpsites [17].

The operation of open dumps poses serious threats to the environment and human health [22]. The environmental and public health damage caused by open disposal of waste includes ground and surface water contamination through the generation of leachate, contamination of soil by solid waste or leachate, air pollution due to gaseous emissions, provision of breeding grounds to disease vectors such as mosquitos, flies, and rodents, odour problems, and uncontrolled methane emissions [23,24]. Furthermore, open burning of MSW, commonly practiced in developing countries, leads to the release of harmful contaminants including fine particulates ($PM_{2.5}$), and damages the air quality in urban areas [25].

2.2. Anaerobic Landfills

Anaerobic sanitary landfills are known as well-designed waste disposal facilities which do not require any processes to influence waste degradation [26,27]. However, control measures to minimize environmental and public health effects are incorporated at the site, including a bottom liner and surface top cover as well as leachate and gas treatment (heat/power generation or flaring) facilities [26,27].

The sanitary landfill approach is the most popular waste treatment method due to its high volume handling capacity, low investment, and minimal technical requirements [28]. It has been reported [29] that the biodegradation processes of the organic fraction of municipal solid waste are slower under anaerobic conditions than under aerobic conditions in a landfill. Investigation results from old landfills in Germany and other European countries showed noticeable emission potential from landfills operated under anaerobic conditions, and it is estimated that gaseous emissions can last at least for thirty years, and that leachate emissions can last for many decades or even centuries depending on site-specific conditions [30].

2.3. Semi-Aerobic Landfills

The semi-aerobic is the oldest approach regarding landfill aeration; this method was developed in the early 1970s in Japan and is known as the "Fukuoka method" [9,31]. The semi-aerobic landfill process is driven by a natural air ventilation mechanism which provides a speedy waste stabilization solution through the availability of oxygen in the waste mass without demanding high resources and technology [31]. The semi-aerobic landfill system can be a suitable method for meeting the sustainability requirements cost-effectively and with low technical input, especially in developing countries which are lacking in sustainable waste disposal due to funding issues and technical limitations [32].

A semi-aerobic landfill system consists of a horizontally-installed perforated pipe network with an adequate slope at the bottom of landfill for leachate collection, with perforated pipes erected vertically at intersections and at the end of each branch for air ventilation [9,31]. Furthermore, in a semi aerobic landfill system, air flows through the pipe network by means of a natural advection process due to temperature differences between the landfill body and the ambient environment [9,31]. The temperature difference is a result of exothermic biodegradation of the organic fraction of the waste mass; the release of this heat can raise the temperature in the waste body by 50–70 °C [31].

This temperature difference leads to density differences in the gas inside the landfill, creating a buoyance force which allows the gas to flow up through the waste mass and vent out the vertical gas extraction pipes, developing negative pressure as a result that allows more air to be drawn inside the landfill body through the leachate collection pipes [31,33]. In an aerobic environment, organic matter degrades more effectively than in anaerobic conditions; thus, air circulation through the waste mass results in enhanced waste stabilization and improved emission quality and quantity [31].

A study on full-scale aeration in semi-aerobic landfills by [34] has shown that the relationship between airflow rate and ambient temperature is negatively proportional, as in winter a large flow rate was noticed, while no flow of air was observed in summer. In a semi-aerobic landfill system, anaerobic conditions prevail inside the waste mass due to insufficient air distribution, which promotes methane formation. However, the CO_2 and CH_4 emission ratio of a semi-aerobic landfill (4:1) is much lower than an anaerobic landfill system (1:1) [31].

2.4. Aerated Landfills

In situ aeration is a quite new technology for intensified removal of biodegradable organic material left in old landfills [35]. For aeration of landfills, two approaches are applied; one is forced aeration, while in the second air is supplied in natural conditions. Forced aeration is realized by injection of air into the landfilled waste mass through means of different types of blowers [36]. The major objective of the aerobic in situ aeration is to stabilize and change the emission behavior of organic matter deposited in the landfill [37].

Aerobic degradation processes in landfills enable the significantly faster decomposition of organics (e.g., hydrocarbons) compared with anaerobic processes, resulting in increased carbon discharge in the gas phase and decreased leachate concentration [38,39].

A study by [35] reported that when landfill gas production is decreased to such a level that energy generation is not economically feasible and even flaring of extracted gas is not practical, there will be up to 10–20% residual gas production potential remaining of the total production potential. Moreover, it may take decades to stabilize the remaining organic material in the anaerobic environment; by providing aerobic conditions, the residual organic matter can be degraded in a limited time (<10 years under a conducive environment) [35].

The in situ aeration approach goes beyond the concept of injecting air into the landfill, including a well design and spacing options for the suitable volume and pressure of air, air distribution, temperature, and moisture control as well as pollution discharge in the leachate and gas phases [9]. The major objective of aerobic in situ aeration is to oxidize and change the emission behavior of organic material deposited in landfill, and in the end to significantly reduce the emission potential in a more appropriate way [37].

Aerobic degradation processes in landfills enable the significantly faster decomposition of organics (e.g., hydrocarbon) compared with anaerobic processes; as result, carbon discharge in the gas phase increases and leachate concentration decreases [38,39]. In all, nitrogen elimination is the most significant advantage that can be obtained from aeration technology [40,41]. Several authors [9,42] mention that the aeration of waste material in the landfill body is an essential and unavoidable pretreatment step in the landfill mining process to prevent uncontrolled gaseous emissions from waste during excavation activity. Presently, various approaches and concepts are applied in the aeration of landfills, such as semi-aerobic landfills, high pressure aeration, low pressure aeration (including active aeration with and without off-gas extraction), passive aeration via air venting, and energy self-sufficient landfills [9].

2.5. Bioreactor Landfills

A bioreactor landfill is an engineered and modern shape of a conventional anaerobic/aerobic landfill where moisturization of the waste takes place by injecting water (fresh or wastewater) and recirculating the leachate to optimize waste degradation processes [43–45]. The recirculation of leachate facilitates cycling of microbes and nutrients into the waste mass and maintains an optimal moisture content in the landfilled waste [46]. The cycling of microbes and nutrients is intended to enhance microbial processes for transformation and stabilisation of easily and moderately degradable organic waste fractions, within the timeframe of 5–10 years for bioreactor process execution [47].

Various studies [48–51] have reported the positive effects of moisturization of the waste and leachate recycling during landfill operation, which includes speedy waste biodegradation and stabilization, increasing LFG (methane) production, rapid settlement, reduced leachate quantity, and leachate treatment cost savings. Furthermore, bioreactor landfills and their variations represent a sustainable alternative approach to conventional sanitary (dry tomb) landfills [52]. However, bioreactors can have drawbacks, e.g., odours and physical instability of the waste material due to increased moisture [53].

Moreover, establishment of infrastructure for leachate recirculation and/or aeration may cause increased capital and operational costs [53]. Studies have suggested that the high upfront costs involved in operation and construction of bioreactor landfills can be balanced by future economic benefits, including an increase in the active life of the landfill (waste disposal period), more efficient use of airspace [54], lower minimum leachate treatment/disposal costs, delay in the need to construct a new cell and cap, savings in the post-closure care period thanks to less need for monitoring and lower financial guarantee obligations, and higher efficiency in landfill gas collection, resulting in larger revenues generated from production [55].

According to [53], the bioreactor approach can be applied when the waste to be deposited possesses a high quantity of biodegradable organics. Bioreactor landfills can be designed as anaerobic, aerobic, semi-aerobic, and hybrid landfills [36,56]. The basic differences between these designs of bioreactor landfills are linked with their operations, layouts, and arrangements for leachate recirculation, landfill gas collection, and (optional) air injection system [45]. Bioreactor landfills are mostly operated under anaerobic conditions [57,58]. In a hybrid bioreactor landfill, a series of aerobic and anaerobic conditions are observed [53,59]. The aeration of the bioreactor landfill is realized through injection of air/oxygen to establish an environment for aerobic biodegradation of the landfilled waste in order to control methane emissions and accelerate waste stabilization [60].

However, hindrances in oxygen distribution in the waste mass due to high moisture content and leachate recirculation have been reported by various research studies [61–63]. Moreover, other studies [64,65] have stated that degradation of waste is significantly influenced by the rate of oxygen distribution. The pros and cons associated with the different waste disposal approaches discussed in the above sections are summarized in Table 1.

Table 1. Summary of pros and cons of different landfill approaches.

Landfilling Approach	Pros	Cons	Reference
Open disposal	No or low cost is involved in the short-term. Income source for waste scavengers.	Long-term environmental costs such as uncontrolled emissions of toxic gases due to open decomposition of waste, ground water contamination, and soil contamination due to toxic and concentrated leachate release. Public health problems.	[66]
Anaerobic landfills	LFG with high methane concentration can be used as an energy source. Relatively low cost is involved in the short term.	High COD, BOD_5 and VFA concentrations in leachate. High level of ammonia in leachate. Formation of hydrogen sulphide (H_2S) gas from the decomposition of gypsum wall board in waste. Long duration in waste stabilization. Long term LFG (methane) emissions.	[59,67]
Semi-aerobic landfills	Promotes waste and leachate stabilization Reduced biological stabilization time of landfilled waste. In situ leachate treatment. Low-cost system.	Careful management and operation needed for optimal performance	[33,59,68]
Aerobic landfills	Speedy waste stabilization. No or low methane production with reduced GHG emissions. Low or no residual methane emissions. In situ leachate treatment. Moisture removal by air stripping. Nitrogen removal. Better waste settlement.	High energy demand.	[35,59,68]

3. Methods and Data

3.1. Estimation of Methane Emissions from Waste Disposal Sites in Karachi

The estimations of methane emissions from waste disposal sites in Karachi provided here are based on the LFG production model by Tabasaran and Rettenberger, (1987) [69] as given in Equation (1). This model is considered a simple method for prognosis of methane from waste disposal sites, and depicts the anaerobic degradation of degradable organic carbon (*DOC*) as in the first-order decay (FOD) Tier 2 model of the IPCC [70,71]. This model is used by various studies to estimate landfill gas production rates, such as [37,70]:

$$G_t = 1.868 C_{org} (0.014T + 0.28)\left(1 - e^{-kt}\right) \quad (1)$$

where G_t is the LFG production during a specific time, t (m^3/tonne fresh waste); C_{org} is total organic carbon in waste (kg/tonne); T is the temperature (35 °C); k is the degradation rate constant, ($k = \ln 2/T_{0.5}$); and t is the landfill operation time (years).

The C_{org} was determined by considering the degradable organic content (*DOC*) according to the organic fraction of MSW in Karachi (as reported by [72–74]), and is provided in Table 2. The degradable organic content (*DOC*) of MSW used in this study was determined using Equation (2), as per the Intergovernmental Panel on Climate Change (IPCC), 2001 [75]:

$$DOC = (0.4 \times A) + (0.2 \times B) + (0.15 \times C) + (0.43 \times D) + (0.24 \times E) + (0.24 \times F) \quad (2)$$

where A, B, C, D, E, and F represent the fractions of paper, green waste, food waste, wood, textile, and nappies, respectively, present in MSW generated in Karachi, as shown in Table 3.

Table 2. Composition of MSW generation in Karachi.

Waste Component	FW	GW	Paper	Glass	Metal	Plastic	Fines	Nappies	Textile	TP	Wood
Fraction in sample [% w/w]	26.10	17.04	7.97	5.6	1.1	8	3.7	9.8	5.57	10	3.11

Table 3. Determination of *DOC* in the synthetic waste sample using IPCC default values.

Waste Components	%	*DOC* Default Value	*DOC* %
Paper (A)	7.97	0.4	3.2
Green waste (B)	17.04	0.2	3.4
Food (C)	26.10	0.15	3.9
Wood (D)	3.11	0.43	1.3
Nappies (E)	9.8	0.24	2.4
Textile (F)	5.57	0.24	1.3
Total			15.5

For selection of the degradation rate constant (k) value of waste disposed at dumpsites in Karachi, three different k values were analysed. In the first, an average of half-lives of easily (four years), moderately (nine years), and hardly (twenty years) degradable wastes were considered. The k value determined in this approach was 0.095/year.

In the second, the default k value 0.05 suggested by IPCC 2000 [76] was applied, and the third k value for conventional landfills reported in the literature [43,77], 0.04, was used to model the landfill gas emissions. The data utilized for the estimation of landfill gas emissions from waste disposal sites in Karachi are provided in Table 4.

Table 4. Data used for estimation of methane emissions from waste disposal sites in Karachi.

Data	Unit	Value	Reference
MSW generation	[tonnes/day]	15,600	[17]
MSW landfilled	[%]	70	[17]
MSW landfilled-FM	[tonnes/day]	10,920	
MSW landfilled-FM	[million-tonnes/year]	4	
Density of methane	[kg/m^3]	0.66	[78]
Methane fraction in LFG	[%] average	50	
Global warming potential of methane (over 100 years horizon)	[CO_2-eq]	25	[79,80]
Total *DOC* in the waste	kg/tonne FM	155	
Default k value for waste disposal sites		0.05	[76]

3.2. Estimation of Land Requirement for Bioreactor Landfill

The landfill requirements for bioreactor development were estimated using Equation (3), as reported by previous studies [81,82]:

$$Total\ required\ disposal\ area = \left[\left(\frac{Waste\ quantity\ (t)}{waste\ density\ (\frac{t}{m3})}\right)/landfill\ height\ (m)\right] \quad (3)$$

3.3. Estimation of Power Generation from Bioreactor Landfill

The electric power generation from recovered methane during anaerobic operation of a bioreactor landfill was estimated using Equation (4), as reported by [78,83]:

$$P_e = \Psi \times f_{methane} \times \rho \times \omega \times \frac{1\ \text{kWh}}{3.6\ Mj} \times \eta_e. \quad (4)$$

where $P_{el.}$ is the electrical power generated (kWh), Ψ is landfill gas collection rate (m^3/h), $f_{metahne}$ is the methane fraction in landfill gas (%), ρ is the density of methane (0.66 kg/m^3), ω is the calorific value of methane (55.53 MJ/kg), and $\eta_{el.}$ is the electrical efficiency of the gas engine (%).

3.4. Determination of k Value for Waste Degradation in Karachi

The *k* value is the biodecomposition half-life value in a year (year^{-1}) for landfilled waste, and is influenced by waste depth, density, pH, and other environmental conditions [77,84]. Several authors have [84–86] reported precipitation as the most significant parameter in the estimation of *k* value, because a higher moisture content results in faster biodegradation of waste. Thus, for the estimation of *k* value considering the local precipitation regime, the following Equation (5) provided by [87] and reported by [84] can be used:

$$k = (3.2 \times 10^{-5} \times annual\ precipitation\ in\ mm) + 0.01 \quad (5)$$

3.5. Estimation of Liquid Required for Bioreactor Landfill

The degradation rate constant (*k*) value (0.3/year) considered for the proposed bioreactor landfill was taken from the literature [43,77] and is shown in Table 5. In the case of a bioreactor landfill where additional liquids are introduced into the landfill, the amount of additional liquid should be determined and added to the amount of precipitation, as suggested by Alberta Environment [87]. In this case, the equation for *k* value would be

$$k = 3.2 \times 10^{-5} \times (AP + AL) + 0.01 \quad (6)$$

where *AP* is the annual precipitation rate in mm and *AL* is the amount of additional liquid required.

Table 5. Data used for estimation of designing a bioreactor landfill for Karachi.

Parameter	Value	Unit	Reference
Waste tipping	3700	[tonnes/day]	
Waste compaction	0.8	[tonnes/m$^{3]}$	
Landfill height	30	[meters]	
Total *DOC* in the waste	155	kg/tonne FM	
DOC loss in pre-treatment	10	[%]	
DOC in the waste disposed in bioreactor landfill	139.9	kg/tonne FM	
Landfill gas collection efficiency	50	[%]	[88]
k value for bioreactor landfill	0.3		[43,77]
Density of methane	0.66	[kg/m^3]	
Methane fraction in landfill gas	64	[%]	Average CH_4 concentration in LFG in simulating bioreactor landfill conditions in Karachi [19]
1 kWh	3.6	[MJ]	
Electric efficiency (η)	30	[%]	[78]
Calorific value of methane	55.53	[MJ/tonne]	
LHV of methane	36.48	[kJ/m^3]	

4. Proposal for Development of Bioreactor Landfills in Karachi

The conventional sanitary waste landfill method (dry tomb) is not a long-term sustainable solution and has negative impacts on the environment and urban sustainability [52,89]. According to one study [11], two major obstacles are associated with conventional (dry tomb) sanitary landfills; the first is slow gas production, and the second is that the use of low-permeability daily/intermediate cover layers hinders the free flow of gas during extraction. Hence, conventional sanitary landfills are not compatible for the landfill gas recovery and utilization approach and only serve as places for perpetual storage of waste, occupying valuable land resources [46].

In the development of new landfill sites in Karachi, a hybrid form of the bioreactor landfill approach can be applied for rapid gas production and waste stabilization. This approach can be more environmentally sustainable when bioreactor landfill facilities are planned with aftercare measures (in situ aeration) taken into account and followed by a decrease in landfill gas production rate. Furthermore, in [56] the hybrid bioreactor concept is demonstrated to be an efficient technique for enhancing methane production and achieving landfill completion in a 25–35% shorter time compared to traditional (dry tomb) anaerobic landfill systems. Furthermore, the results of a study [19] conducted by simulating bioreactor landfill conditions in the situation of Karachi (MSW composition and climatic conditions) reported that a bioreactor landfill with post-aeration (a hybrid bioreactor) showed accelerated methane production higher than that of a conventional sanitary landfill.

In this context, the present paper proposes a more advanced and environmentally sustainable solid waste landfill approach, a hybrid bioreactor landfill for future landfills development in the city. Under this approach, the waste placed in the landfill would be subjected to aerobic oxidization by means of in situ aeration after completion of an anaerobic phase when the landfill gas production will be significantly reduced. The post-aeration phase is intended to accelerate the degradation of the remaining hardly-degradable organic material and shorten the aftercare period of the landfill, as reported by various authors [35,36].

The bioreactor landfill approach without the aftercare option is only better than existing waste disposal sites in Karachi regarding its environmental performance and landfill gas generation. Under this approach there will be significant risks to the environment, such as long-term residual gas emissions even after power generation from landfill gas can no longer be economically feasible. As the MSW generated in Karachi contains a high organic fraction and as most of the recyclable material in the solid waste is collected by waste pickers (or can be systematically collected through the establishment of material recovery facilities), leftover organic material can be valorised by methane production through application of the bioreactor landfill approach. Later, when the gas production reaches minimal levels, the landfill could be aerated.

Karachi has two major official solid waste landfill sites, known as Jam Chakro (N = 25°01.675′, E = 67°01.61′) and Gond Pass (N = 25°00.634′, E = 66°55.263′), located north-west and west of the city, respectively [19,90]. Presently, there is no landfill for the disposal of solid waste generated in the eastern parts of the city. The absence of an official designated waste disposal site on the eastern side of the city leads to mismanagement of waste, and provides reasons to the public for open disposal of the waste on street sides, vacant plots, drainage channels, and in the Malir river.

Furthermore, transportation of solid waste from the eastern side to officially designated landfill sites located on the northern side of the city has high costs in terms of both fuel consumption and time. The Sindh Solid Waste Management Board (SSWMB) is planning to establish a new sanitary landfill to serve the waste disposal needs of the eastern parts of the city, for which 3000 acres (1214 hectares) of land have been allocated at the Dhabeji site (N = 24°48.804′, E = 67°30.567′) [91]. The locations of Jam Chakro and Gond Pass landfill sites and the future landfill site at Dhabeji are shown in Figure 1.

Figure 1. Locations of Jam Chakro, Gond Pass, and Dhabeji landfill sites in Karachi (Google maps).

According to SSWMB, both the Jam Chakro and Gond Pass waste disposal sites are operated as controlled landfills, and sanitary landfills are under planning for future waste disposal [92].The proposed concept for transformation of waste disposal strategies from open dumps to sustainable waste disposal in Karachi is illustrated in Figure 2.

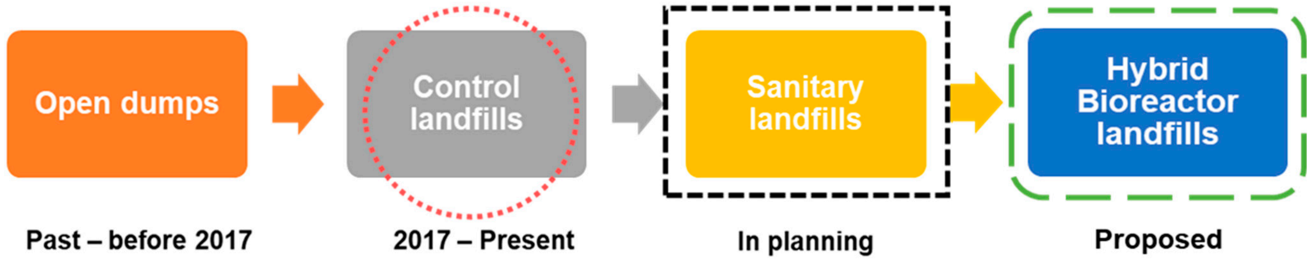

Figure 2. Evolution of solid waste landfilling approach in Karachi.

The following sections provide details regarding the proposed approach.

4.1. Estimation of Methane Emissions from Waste Disposal Sites in Karachi

The methane emission potential is estimated using Equation (1), with three different values of the degradation rate constant (k) considered: 0.095/year, 0.05/year, and 0.04/year. The results with all three values of the degradation rate constant (k) were similar, ranging from 438.6 to 446.9 m^3/tonne fresh waste (FW) for the estimation of landfill gas over 100 years. For the modelling of methane emissions from waste disposal sites in Karachi, the middle value of the degradation constant (k) 0.05 suggested by the IPCC (2000) [76] was used. The comparison of landfill gas emissions with three different values of the degradation rate constant (k) for LFG emissions over 100 years is shown in Figure 3.

A significant amount of solid waste generated in Karachi is openly burned, either at community bins in the city or at the landfill sites [93,94]. Therefore, as a result of burning, the biodegradable fraction (*DOC*) in the waste can be significantly reduced.

Therefore, the estimations of methane production for waste disposed at landfill sites in Karachi are made at four different *DOC* ranges here: first, considering theoretical (100%) *DOC* in solid waste with no loss of *DOC*; second, at 75% *DOC* (25% *DOC* loss); third at 50% *DOC*; and fourth at 25% *DOC* (75% *DOC* loss). The estimated cumulative methane production from waste disposal sites over 100 years at different *DOC* fractions in the solid waste disposed of is shown in Figure 4.

Considering the latest waste disposal quantity and data in Table 4, the theoretical global warming potential (GWP) over time of 100 years for the solid waste annually disposed (about 4 million tonnes/year) at dumpsites in Karachi is estimated as 7.3 $MtCO_2$-eq., with a specific GWP of 1.83 tCO_2-eq/t fresh mass (FM). Furthermore, at the *DOC* levels of 75%, 50% and 25%, the GWP of the waste quantity disposed annually at dumpsites is estimated as 5.5 $MtCO_2$-eq (1.4 tCO_2-eq/t FM), 3.7 $MtCO_2$-eq (0.9 tCO_2-eq/t FM), and 1.8 $MtCO_2$-eq (0.5 tCO_2-eq/t FM), respectively, over a time of 100 years.

According to the results obtained from this study and modelling of the methane emission potential of landfilled solid waste, it is evident that the existing dumpsites in Karachi are causing significant GHG emissions. These waste disposal sites can be transformed into sanitary landfill facilities and sources of renewable energy generation by extracting methane-rich landfill gas. Later, captured methane can be utilized for power generation, transportation, and industrial purposes. After reaching a point where power generation from produced landfill gas is no longer economically feasible, the waste placed in landfills can be rapidly stabilized by employing in situ aeration as a landfill aftercare approach. Given this idea, a sustainable approach is proposed for the development of new landfills in Karachi.

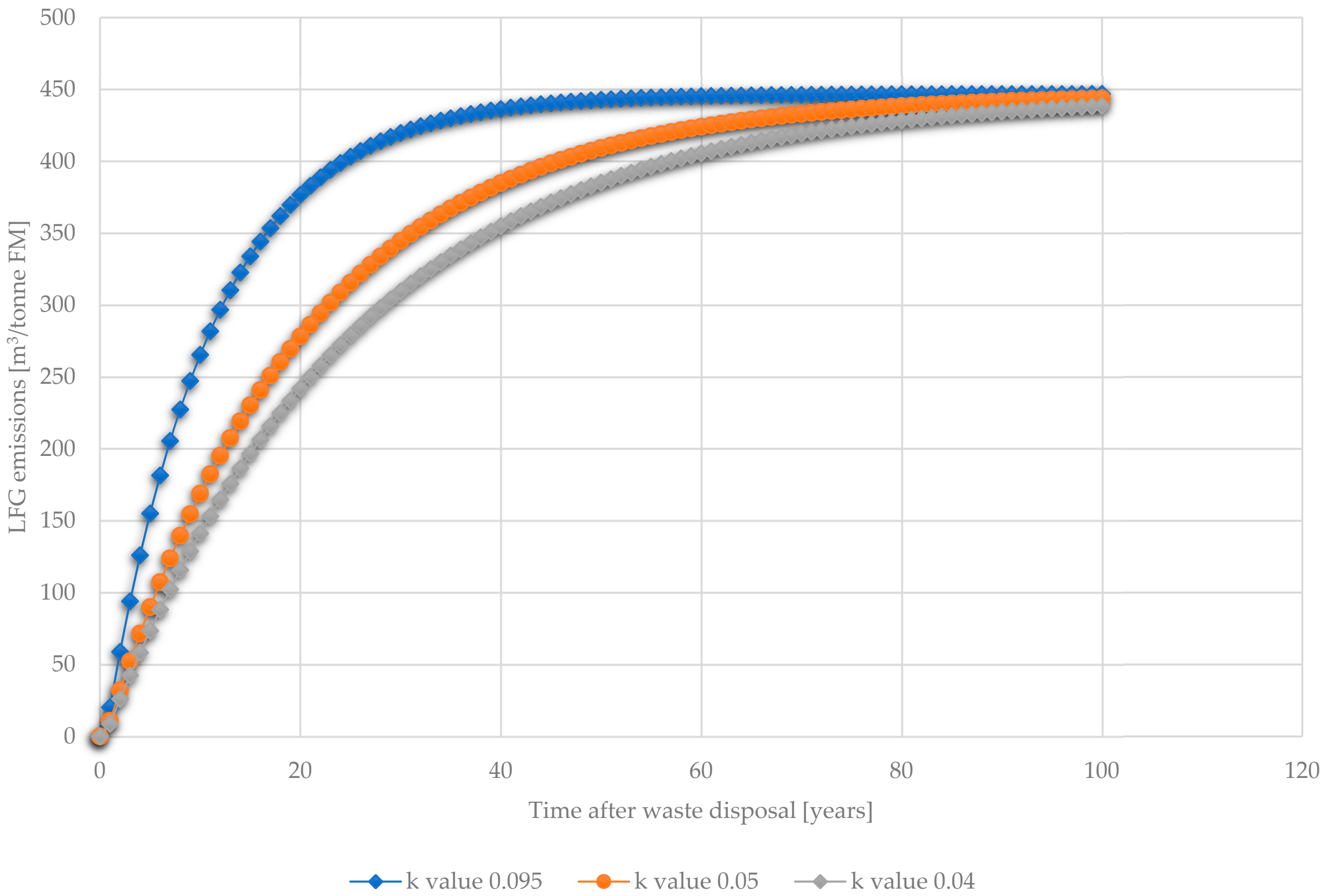

Figure 3. Comparison of different degradation constant (*k*) values for LFG emissions.

4.2. Bioreactor Landfill Operations

The operation of solid waste tipping in a new bioreactor landfill is proposed in ten phases, and the duration of each phase is assumed to be one year. After ten years of waste deposition, the whole landfill could be closed and capped by providing a final cover. Furthermore, in order to minimize leachate generation and initial operational costs the waste footprint is divided into cells, as recommended by [95].

Hence, the placement of the solid waste at the landfill site is planned by tipping in small daily cells of one larger cell of landfill and providing a daily cover, as recommended by the authors of [96]. The proposed operational layout of the new bioreactor landfill for Karachi is presented in Figure 5.

Solid waste arriving at the landfill would be weighed first at the entrance of the site, and material would be collected at the material recovery and treatment facility where the recyclable waste fraction would be separated from the organic and non-recyclable fractions of the waste. Furthermore, it is proposed that before tipping into the daily cell, waste material should be pre-treated by means of shredding and in situ aeration to reduce readily degradable organics and enhance landfill gas production, as recommended by the authors of [36,97]. A study by Ali et al. [98] recommended at least 27% reduction of volatile solids (VS) during aerobic pre-treatment in order to realize an early start to methanogenesis and increase LFG generation in the anaerobic phase.

Later, the anaerobic phase of landfill operation would be initiated to establish favourable conditions for methane production, with a landfill gas (LFG) capture and utilisation approach for power generation. At the point in time when the rate of LFG production would significantly decrease and the methane recovered would not be economically/technically feasible to utilise for power generation, the aftercare phase (in situ post-aeration) would be started for accelerated biodegradation of the remaining (mostly hardly-degradable) organics in the waste, as proposed by various studies [39,64,99]. The concept of transforming waste disposal strategies from open dumps to sustainable waste disposal is illustrated in Figure 6.

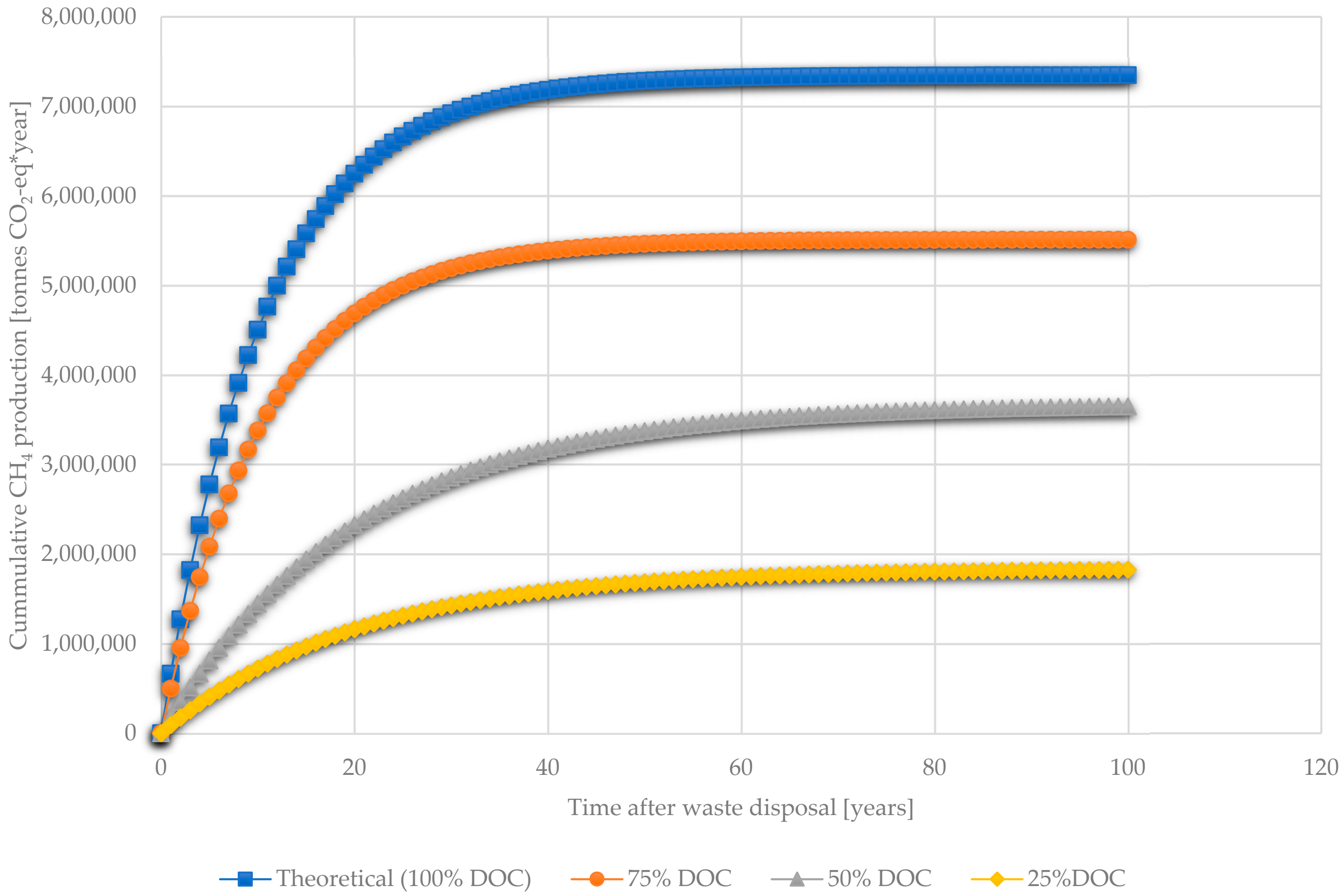

Figure 4. Estimated cumulative methane emissions from waste disposal sites in Karachi.

4.3. Estimation of Land Requirement for Bioreactor Landfill

It is assumed that the solid waste will be collected in closed community bins without initial segregation of recyclables by waste pickers and directly transported to the landfill site. Taking the total quantity of solid waste coming to the landfill site as 5000 tonnes/day, 25% (about 1300 tonnes/day) of recyclable material will be collected by establishing a material recovery facility at the landfill site, and only the organic fraction of MSW will be deposited in the daily cell of the landfill. Furthermore, it is assumed that each daily cell will receive about 3700 tonnes of solid waste on daily basis. Hence, each phase will be completed and covered after one year of waste tipping with a total capacity of 1.3 million tonnes. Overall, it is assumed that 13.5 million tonnes of waste would be accepted at the landfill facility.

The waste height for a sanitary landfill ranges between 15 and 30 meters (m) [82]. A similar study assumed a waste height of 22 m for the determination of the required landfill area [82]. However, if the waste height decreases, the area required for waste disposal increases [82]. In this proposal, the mean height of waste in the bioreactor landfill is assumed as 30 m, excluding intermediate and final covers. According to one study [52], the compaction density of the waste achieved by moderate compaction may range from 0.5–0.85 tonnes/m^3. This study assumed the specific density of waste to be placed in the landfill as 0.8 tonnes/m^3, the commonly-used value for compacted waste in sanitary landfills [32,82]. The land required for landfill construction was determined using Equation (3).

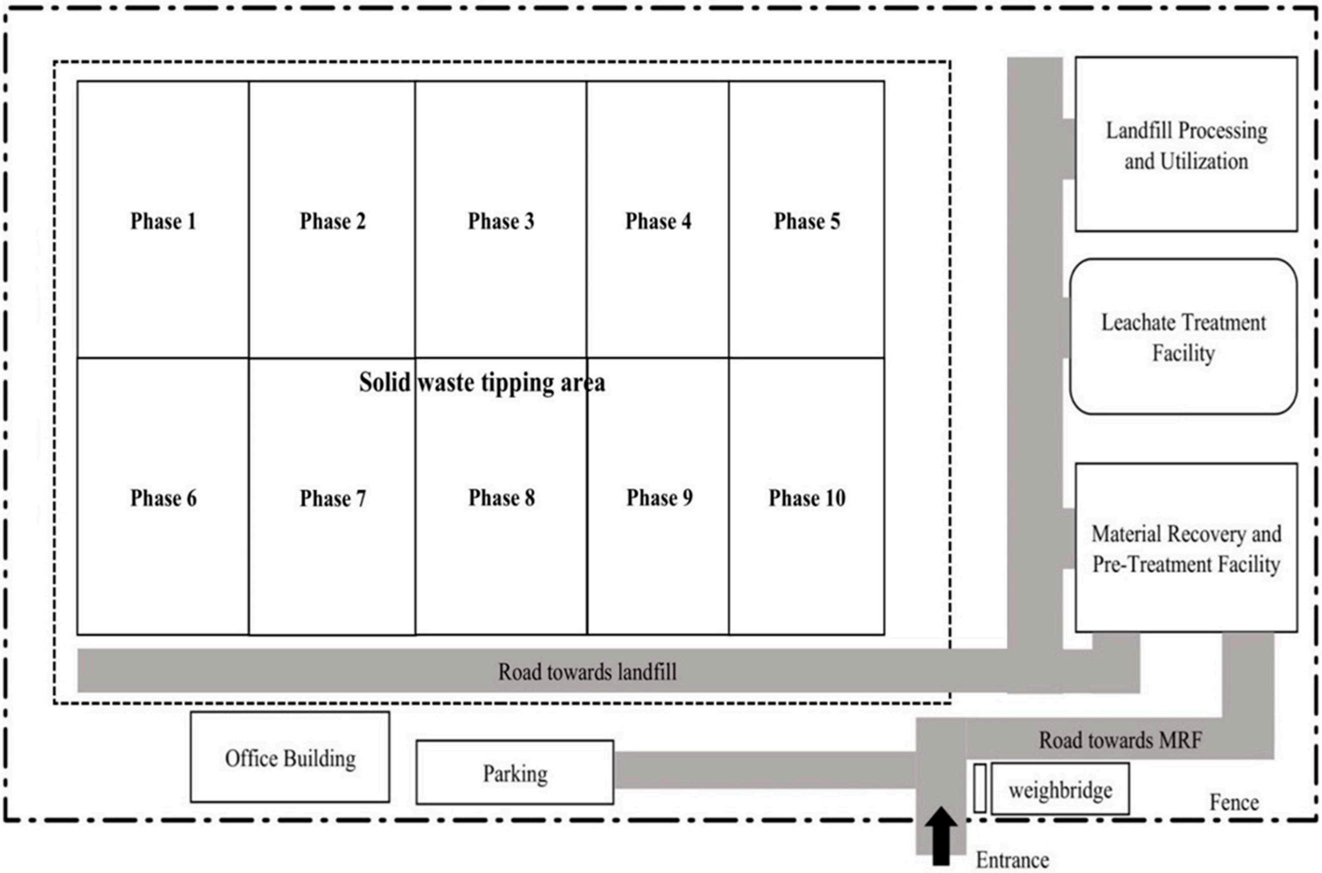

Figure 5. Proposed operational layout of new bioreactor landfill for Karachi.

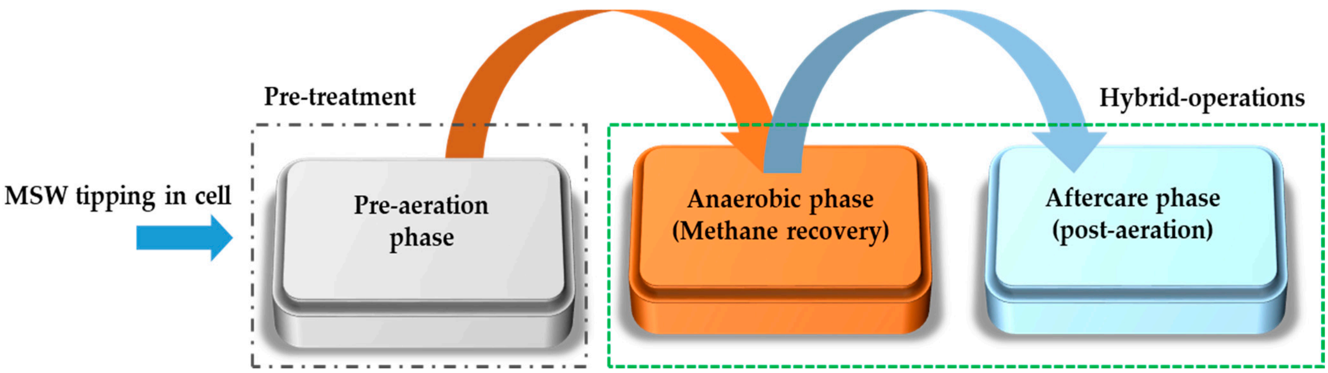

Figure 6. Proposed sequence of bioreactor landfill operations.

By assuming the total waste deposition capacity of a phase as 1.35 million tonnes of waste, it can be determined that an area of 5.6 ha (56,271 m^2) will be required for construction of each landfill phase, excluding the area required by daily and final covers and other landfill facilities. This area should be increased by 10–15% for the placement of daily and final covers [82]. An additional 40–50% area will be required for other facilities such as a receiving area, treatment facilities, and administration buildings [32,82]. The land area required by cover material (daily and final covers) was determined to be 0.84 ha (8440 m^2) by assuming 15% of the waste landfilling area. Hence, the total area required for waste placement is 6.5 ha for each phase of the landfill. Overall, 65 ha of land area will be required for tipping the waste during the landfill's operational life.

Similarly, the area required by the establishment of other facilities (leachate treatment, LFG process and utilization, road construction, office buildings, etc.) at the landfill site was determined to be 19.4 ha by assuming 30% of the total area required for waste placement and cover material. The total land area required to establish a new bioreactor landfill in Karachi, including waste tipping, cover material, and development of other facilities, is estimated to be 84 ha.

4.4. Estimation of Methane Production and Power Generation from Bioreactor Landfill

As discussed above in Section 3.2, landfill operation is divided into ten phases; therefore, methane production and power generation are estimated from the total amount of waste assumed to be disposed during the landfill during its life (ten years). The estimation of methane production from the biodegradation of the organic fraction of the waste in the landfill was calculated based on the LFG production model using Equation (1). The data considered for modelling methane production in the bioreactor, such as the k value, LFG collection rate, methane fraction in LFG, etc., are provided in Table 5. Landfill gas (methane) production from landfilled waste is modelled by considering a 10% loss in initial *DOC* content of 155 kg/tonne FM solid waste material during the pre-treatment phase.

The efficiency of the landfill gas collection system ranges from 13%−80%, with an average of 50% [88]. In this study, landfill gas collection efficiency is considered to be 50%, as shown in Table 5. Based on the modelled methane production and collection rate, the anaerobic phase is supposed to be prolonged until 23 years pass due to a significant reduction in LFG (methane) recovery rate, reaching about 52 m^3/h, as shown in Figure 6. The estimated methane recovery from bioreactor landfill starts from 2572 m^3/h in the first year of anaerobic operation and reaches a maximum rate of 9429 m^3/h in ten years of waste disposal. After closure of landfill, the methane recovery rate gradually decreases to 52 m^3/h thirteen years after closure (23 years of landfill anaerobic operation). The prognosis of the methane recovery rate during the anaerobic phase is illustrated in Figure 7.

The electric power generation potential of a bioreactor landfill could range from 7.8 MW to a maximum of 28.7 MW during the disposal period, and would be reduced to 0.16 MW until the 23rd year of landfill anaerobic operation. The estimated power generation from a bioreactor during the anaerobic operation period is provided in Figure 8.

Moreover, through estimating the specific global warming potential of fresh MSW disposed at landfill sites in Karachi, the reduction in global warming potential by waste deposition at each phase of bioreactor landfill operation is estimated as being in the range of 2.5 $MtCO_2$-eq to 0.6 $MtCO_2$-eq (with different *DOC* levels, 100% to 25%, in solid waste) through methane collection and sustainable utilisation via power generation or flaring. Overall, approximately 25 $MtCO_2$-eq to 6 $MtCO_2$-eq of methane emissions can be controlled by total waste deposition during the ten year period of bioreactor landfill operation.

4.5. Determination of k Value for Waste Degradation in Karachi

Various researchers have found that the k value increases with higher moisture content and higher temperature [84,100,101]. The degradation rate constant (k) value for the biodegradation of the organic fraction of MSW under the climatic conditions (annual rainfall) of Karachi is determined by understanding the waste decomposition dynamics using Equation (5) and considering the total annual rainfall, 176 mm, as reported by [19,102].

It can be determined that with the moisture received through rainfall, the k value for waste degradation at landfill sites in Karachi is 0.016/year. This lower k value is due to low annual rainfall rates in Karachi. However, a study by authors Amini et al. [77] reported a k value of 0.1/year for wet cells and 0.08/year for a traditional landfill due to fact that the study was carried out on a landfill located in Florida, which has relatively high annual rainfall rates, therefore resulting in a higher k value.

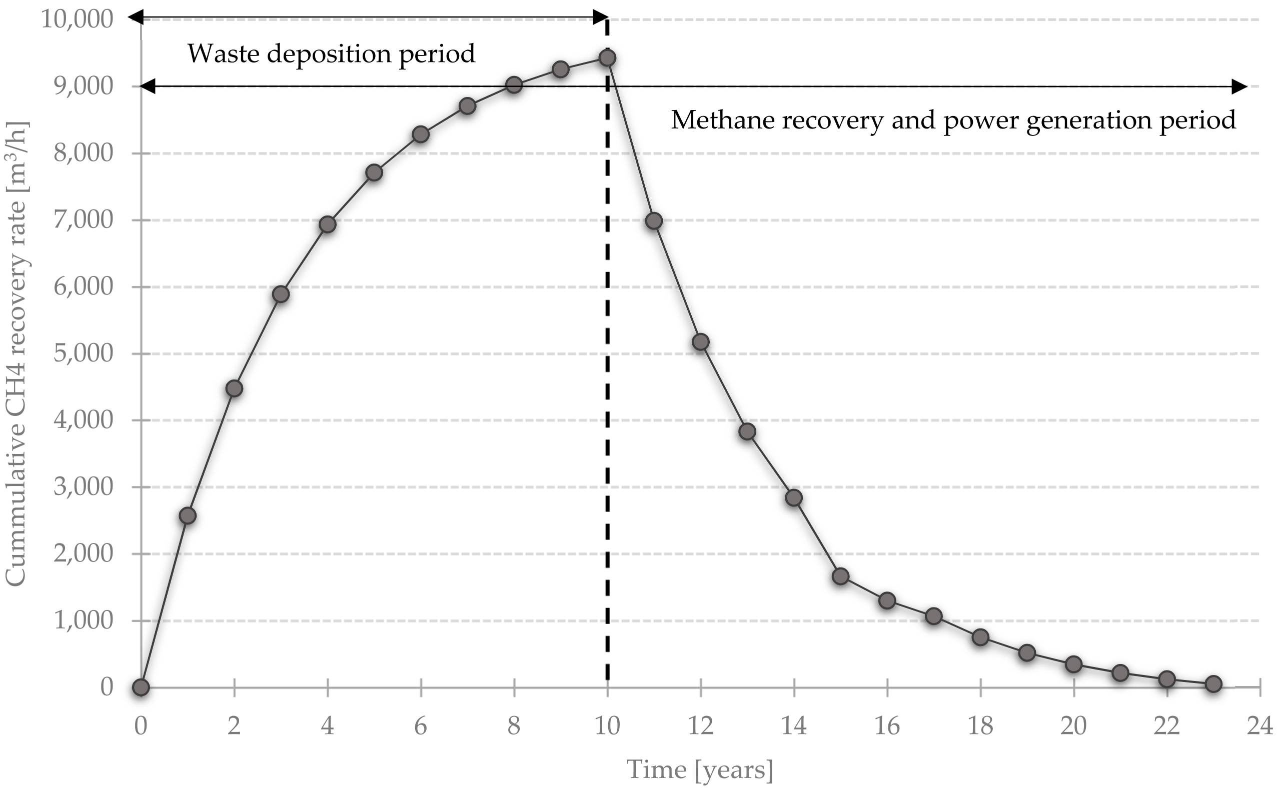

Figure 7. Prognosis of centralised methane recovery rate from bioreactor landfill.

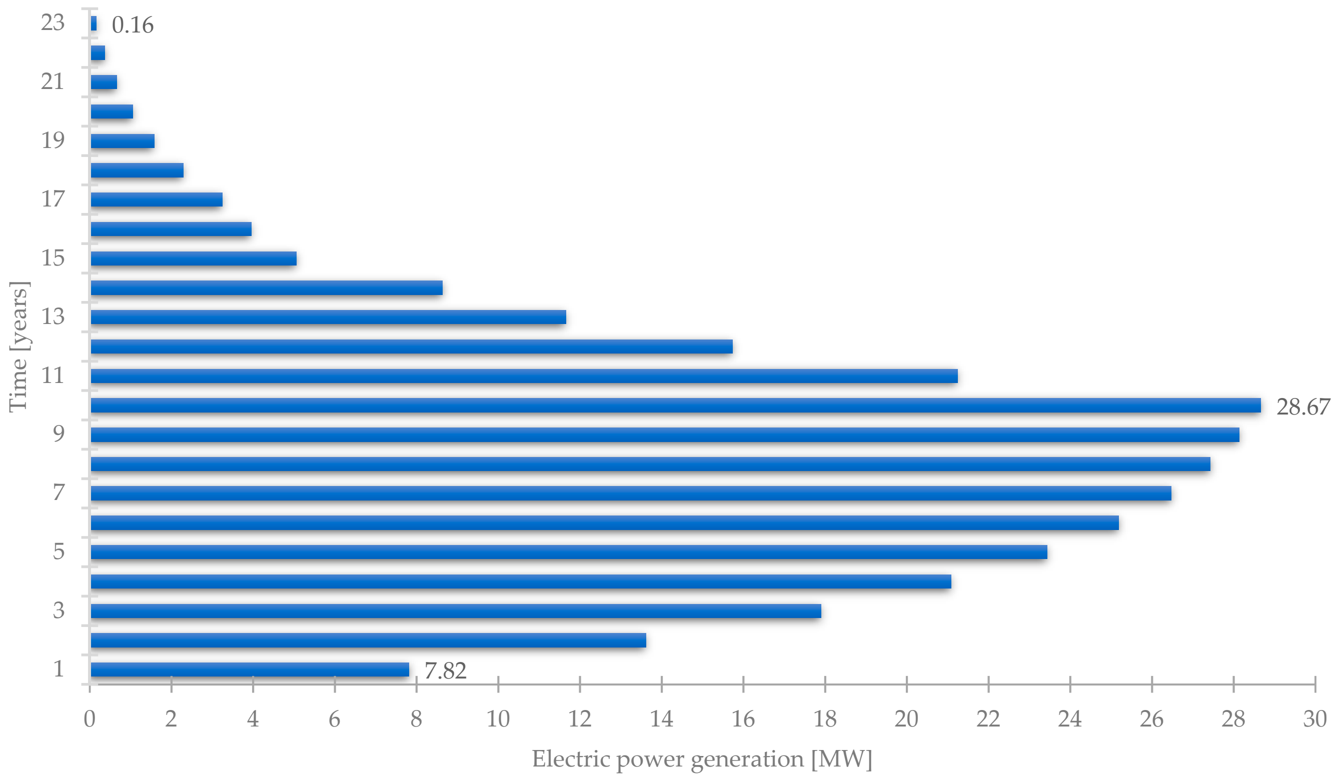

Figure 8. Estimated electric power generation during anaerobic operation of bioreactor landfill.

4.6. Estimation of Liquid Requirement for Bioreactor Landfill

The sources of liquid addition in a landfill may include storm water, groundwater, infiltrating rainfall, or leachate [47]. In the case of a lower annual precipitation rate, as in Karachi, additional liquid would be required to introduce moisture and leachate generation in the bioreactor landfill. Later, leachate can be collected and reintroduced into the landfill after pre-treatment (nitrification).

As the k value for the bioreactor landfill (0.3/year) and precipitation rate in Karachi (176 mm) are known, the additional liquid required to maintain the considered k value in the landfill can be estimated using Equation (6). Similarly, the additional liquid required for a bioreactor landfill has previously been estimated in [103]. By taking their recommendations and integrating Equation (6), it is estimated that 9063 mm of liquid will be required annually in order to maintain a k value of 0.3/year in the bioreactor landfill considering the local precipitation regime in Karachi.

Hence, in order to maintain the considered degradation rate, it is determined that 434.2 L/tonne waste liquid will be required for the daily amount of waste disposed in a cell of the bioreactor landfill at a rate of 67 m^3/h. Furthermore, it is determined that given the annual rainfall rate of the city, only 31 m^3/day water can be expected to be available as run-off from the area allocated to every phase of landfill. However, in the monsoon season (June-September), the run-off collection rate could increase to 77 m^3/day due to the higher precipitation rate in that period. Overall, due to the low annual rainfall rate in the city, almost all (98%) of the required liquid will have to be supplied.

4.7. Design Componetnts of Bioreactor Landfill

To operate a bioreactor landfill effectively, careful construction and operation of infrastructure is required beyond what is necessary in a conventional landfill [55]. The major infrastructure for an engineered landfill facility, includes bottom liner, daily covers, top cover, landfill leachate and gas collection system, embankments, berms, and monitoring systems, and the service life of this infrastructure is assumed to be up to 100 years [12]. Moreover, the design components of a bioreactor landfill include a leachate recirculation system, air injection system, intermediate covers, and final cap [47,104,105]. The leachate recirculation includes the collection of leachate from the bottom of the landfill cell for pumping back into the landfill waste mass [52]. The leachate recirculation system may consist of horizontal distribution pipes/trenches at different depths inside the landfill cell [52].

The landfill gas collection infrastructure consists of gas extraction wells, including a transmission pipe network and condensate knockout system [104]. The key component of the landfill gas collection system is a horizontal pipe network installed during the placement of the waste [104]. However, according to [106] the horizontal gas extraction pipe network is vulnerable to damage by overburdened pressure from the waste, and is easily clogged by leachate components. The vertical extraction wells are most commonly used; while these are easy to install and operate, they are mostly installed after the closure of a landfill cell [52].

Alternatively, during the aerobic operation phase an existing LFG extraction system can be utilized for air injection landfill waste mass [89]. The most commonly used bottom liner system in bioreactor landfills is the composite liner system, which includes a compacted clay liner (CCL) and a flexible membrane liner (FML) [52]. The preliminary design concept of the bioreactor landfill development in Karachi is presented in Figure 9.

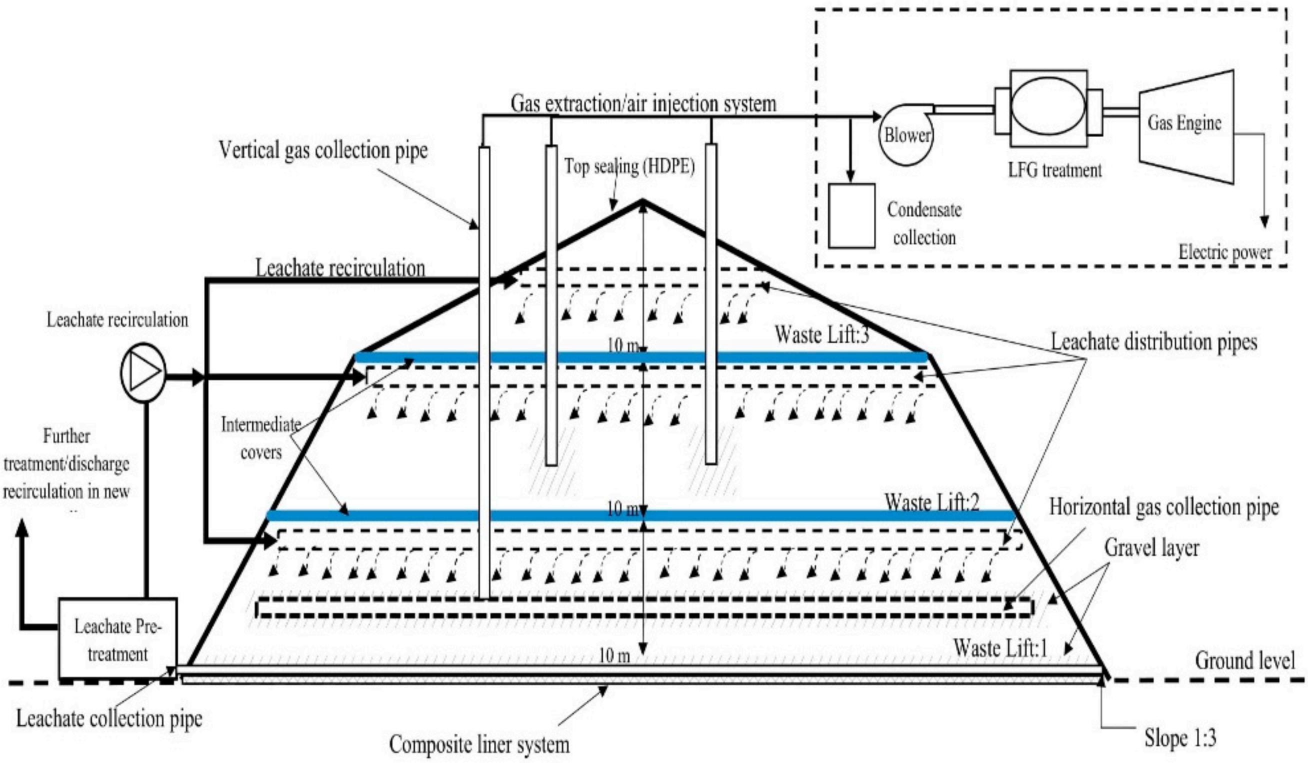

Figure 9. The preliminary design concept of the bioreactor landfill proposed for Karachi (adopted from [107]).

5. Conclusions and Recommendations

Population growth and increasing commercial activities are cumulatively increasing the amount of waste generated in Karachi. Additionally, the waste disposal sites in the city are reaching their saturation point, causing a continual degradation of environment and public health. Therefore, there is an immediate necessity for development of new sanitary landfills for sustainable disposal of a huge amount of waste while minimizing the negative implications associated with its uncontrolled disposal.

Both the former (City District Government of Karachi, CDGK) and present (SSWMB) authorities responsible for solid waste management have been planning the development of a new sanitary landfill to serve the solid waste disposal needs of the eastern side of the city beginning in 2007; however, the planning is at the very initial stage. This delay in the execution of the planned landfill project can be associated with various political, administrative, technical, and financial reasons.

Considering the recent progress in sanitary landfill development for Karachi from SSWMB, this study proposes the approach of a hybrid bioreactor with post-aeration for aftercare for the development of new sustainable landfills in the city based on the concept of energy recovery from municipal solid waste. All estimations made here (such as the quantity and organic fraction of MSW arriving at the landfill, land requirements, timing of each operation phase, methane production and power generation, etc.) as well as the proposed design for the development of the bioreactor landfill in the study area are based on carefully considered assumptions and an extensive literature survey related to the concept. In conclusion, a comprehensive feasibility study shall be conducted by developing a pilot-scale bioreactor on the proposed landfill sites in Karachi to confirm the assumptions taken in this study.

Furthermore, in order to improve the solid waste management situation and optimize the GHG mitigation potential of landfills, this study recommends the adoption of an integrated solid waste management approach in Karachi, with full financial, legal administrative and institutional support. The valorisation of the organic fraction of MSW generated in Karachi should be enhanced through separate collection and utilization for energy generation.

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