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# **Advanced Monitoring and Control of Anaerobic Digestion in Bioreactor Landfills**

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Mohamed Abdallah and Kevin Kennedy

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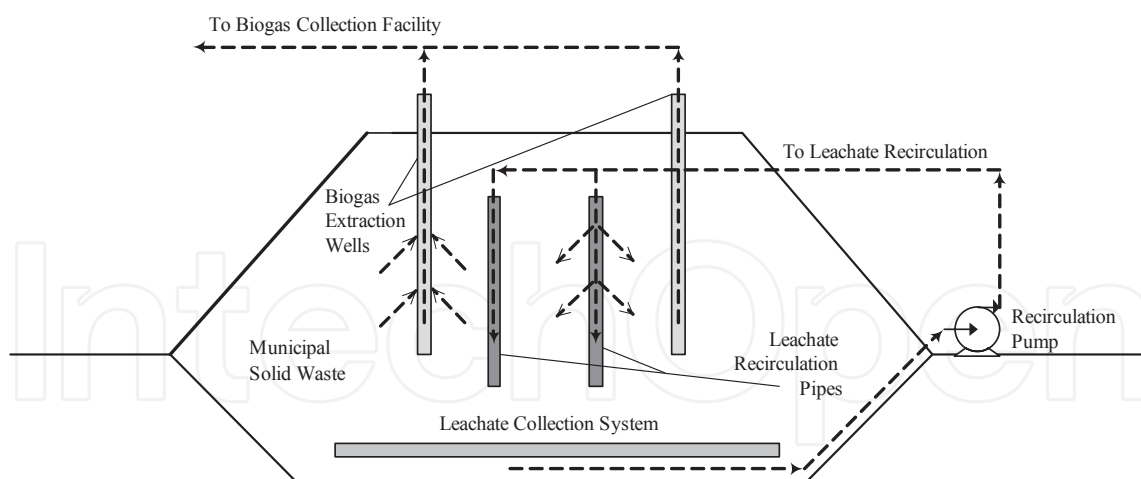
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## **1. Introduction**

Despite recent increases in recycling, composting, and incineration, the sanitary landfill remains the predominant and most economical municipal solid waste (MSW) management alternative. Modern MSW landfills strive to optimize the design, construction, and operation processes in order to mitigate many of the potentially negative impacts, and improve the profitability. The bioreactor landfill (BL) is considered one of the promising developments that have recently gained significant attention. This waste-to-energy technology requires specific management activities and operational procedures that enhance the microbial decomposition processes inside the landfill resulting in higher production of landfill gas [1]. The recirculation of leachate, which is conducted by recycling the water passing through and collected from the landfill, is considered the main operational characteristic in the BL to increase moisture, and consequently stimulate the biodegradation process (Figure 1). The potential benefits of the BL include increased waste settlement rates and airspace utilization, decreased costs for leachate treatment, more rapid gas production (which improves the economics of gas recovery), and more rapid waste stabilization (which may reduce the post-closure maintenance period). These potential benefits have led to many full-scale BL applications in the last decade, mostly in the United States, resulting in the generation of design and operation data. In 2004, the Solid Waste Association of North America conducted an inventory that identified over 70 BLs in North America [2]. Many of these experiences revealed scale-up issues and technical limitations that merit further research and development [3-5].

One of the most critical, yet little studied, issues in the operation of BLs is process control. In field applications, unsupervised operational procedures can disturb the dynamics of the landfill biological processes causing serious consequences on the overall evolution of the ecosystem, i.e., unstable and sometimes unsuccessful transition from one operational phase to



**Figure 1.** Schematic of an anaerobic bioreactor landfill

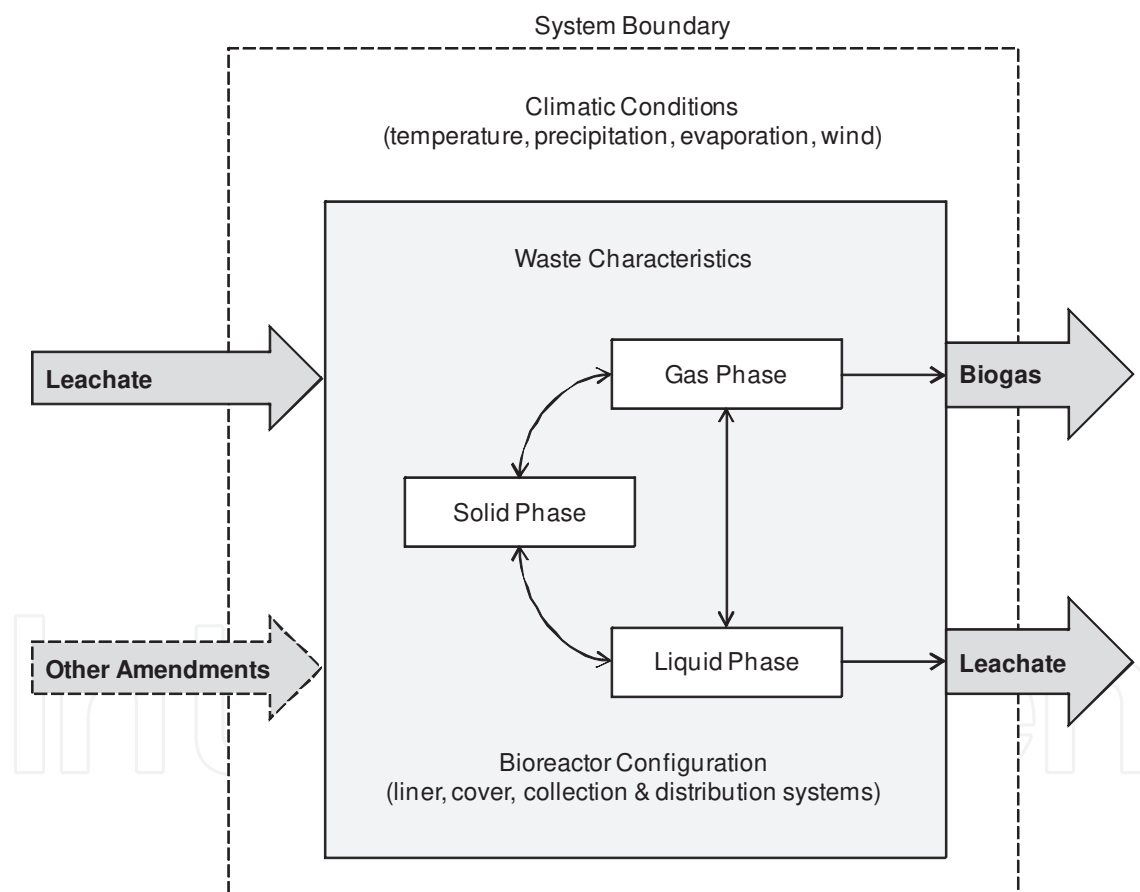
another. Dealing with the BL as a dynamic and evolving biological system could solve many of the BL control issues especially those pertinent to daily operation such as leachate recirculation. For example, one of the main operational issues, which are addressed in the present work, is the large variation in the characteristics of the collected leachate, which sometimes makes the leachate (as produced) unsuitable for recirculation. At the same time, the physical, chemical, and biochemical growth requirements of the bacterial consortia inside the BL change significantly during the different operational phases. *It is therefore necessary to manipulate the collected leachate before recirculation in order to suit the prevailing reactions and conditions inside the BL.* Several techniques have been tested in laboratory studies to enhance the performance of BLs either directly or indirectly through the manipulation of the recirculated leachate: pH adjustment, nutrients addition, and biosolids addition [1, 6-8]. However, these techniques are rarely, if ever, used in field applications due to lack of well-defined methodologies and the huge cost if applied excessively in an uncontrolled fashion. Applying advanced process control techniques offers an alternative solution for this problem. *Developing a control system that optimizes the leachate recirculation and manipulation processes based on real-time conditions of the controlled BL can provide a flexible engineered solution that is applicable to any typical landfill site..*

The proposed Sensor-based Monitoring and Remote-control Technology (SMART) features an expert controller that manipulates the controllable variables of the bioreactor process based on online monitoring of key system parameters. The objective of this control framework is to provide the optimal operational conditions for the biodegradation of MSW, and also, to enhance the performance of the BL in terms of biogas production. A comprehensive analysis of the process control of BLs is presented, followed by the conceptual framework of SMART including its structure, components, and instrumentation. In conclusion, a pilot-scale implementation of the control system is discussed.

### 1.1. Bioreactor landfill ecosystem

Controlling the BL requires a good understanding of the system and its dataflow including inputs, outputs, and interconnecting processes. The basic principles and mechanisms of the BL

are well documented in the literature [9-11]. A simplified dataflow diagram for an anaerobic BL is shown in Figure 2. The BL can be considered as an anaerobic fixed-bed reactor in which the biodegradable organic fraction of the solid waste is the substrate. The factors affecting the biological processes in landfills can be grouped to: (1) factors related to the microbial environment (e.g., moisture, temperature, nutrients availability, and toxicity), and (2) factors related to the landfill site including: climate conditions (e.g., air temperature and precipitation), waste characteristics (e.g., particle size and composition), and site-specific settings (e.g., collection and injection systems). The BL concept is based on employing specific operational activities to control the influencing factors in a positive manner, e.g., applying leachate recirculation to optimize waste moisture. From the process control point of view, i.e., based on the feasibility of real-time manipulation, the first group of factors can be considered *controllable* inputs to the BL process, while the second group of factors is *uncontrollable*. The management techniques through which the *controllable* factors can be controlled are discussed below.



**Figure 2.** Data flow diagram of the bioreactor landfill ecosystem

### 1.1.1. Leachate recirculation

Moisture addition has been proved repeatedly to stimulate the methanogenic population in the landfill waste matrix. Leachate recirculation is considered the most effective method to

increase moisture content of waste in a controlled fashion, which could reduce the time required for landfill stabilization from several decades to two to three years [12]. Leachate recirculation has been proven to achieve better BL performance in terms of biogas production by several lab-, pilot-, and full-scale studies [13-17]. In full-scale applications, leachate recirculation at Trail Road landfill enhanced waste settlement and resulted in 30% airspace recovery, which was used for landfilling more waste [4]. In another full-scale study by [18], leachate recirculation achieved more rapid biogas production, increased settlement rates, and accelerated decreases in the concentration of certain contaminants in leachate. According to [19], moisture increase alone does not enhance methane production. It is the nutrients, inocula and buffers, which in addition to moisture, enhances biodegradation to the greatest extent. It was shown in [8] that added alkalinity, dissolved oxygen level, and presence of methanogenic bacteria in the recirculated liquid considerably influenced the hydrolysis rate and onset of methanogenesis. *Therefore, it is suggested that, not only moisture addition, but also the quality of the leachate affects the impact/outcome of recirculation significantly.* Hence, there are two main aspects of the recirculation process that can be controlled: the **quantity** and **quality** of the recirculated leachate.

The **quantity** of the leachate generated is site-specific and a function of water availability, weather conditions, characteristics of the waste, as well as the liner and cover design [10]. In order to achieve the benefits of leachate recirculation, leachate has to be recycled at optimal rates that achieve sufficient contact with waste. The effect of varying leachate recirculation rates was studied in lab simulations [13, 16, 17, 20]. These studies demonstrated that higher recirculation rates result in better BL performance in terms of biogas production. It was suggested that leachate recirculation should be adjusted according to the phases of waste stabilization [21]. This practice was applied successfully in [13] as well as [22] who varied the leachate recirculation rates in lab scale BLs based on 7 and 4 operational stages, respectively. Unsupervised high rate of recirculation may result in: (1) washout of large amounts of organic matter before the methanogenic phase, thereby reducing the biological methane potential, (2) production of leachate containing high concentrations of short chain fatty acids which either inhibits methanogenesis directly or by lowering the pH, (3) excessive accumulation of leachate within the landfill, which may breakout from landfill slopes, (4) increase of pore water pressure and decrease of the shear strength of the waste matrix which affect the geotechnical slope stability, (5) increase in the hydrostatic head on the base liner, leading to higher risk for ground water contamination, and (6) drop in the internal temperature of the landfill especially in cold regions. *Therefore, leachate recirculation rate has to be selected such that the desired moisture content levels, moisture movement, and supplements distribution are provided, and at the same time, the pre-mentioned issues are monitored and incorporated in the decision-making process.*

The **quality** of leachate is highly dependent on waste composition and operational phase [10]. Leachate has been reported to contain a wide range of inorganic and organic compounds including toxicants such as aliphatic/aromatic hydrocarbons and halogenated organics [23]. Typically, the concentration of constituents, including pollutants, in leachate decreases with the waste age. The large temporal variation in the biochemical characteristics of leachate - as produced - makes it sometimes unsuitable for recirculation. For example, the concentrations

of dissolved organic substances in young leachate are usually much higher than in older leachate. Continuous recirculation of young leachate in early phases of operation will increase the concentration of short chain fatty acids inside the BL which either inhibits methanogenesis directly or indirectly by lowering the pH of the system. Recently, researchers examined the use of different leachate (e.g., mature leachate from older landfill cells) for recirculation [16, 17, 21]. Alternatively, young and mature leachates were used interchangeably over four operational stages along the BL lifespan [22]. They used young leachate in phase I, then mature leachate in phase II and when the characteristics of produced leachate became suitable, they switched back to young leachate in phases III and IV. The same concept was applied by [20] who rotated the recirculated leachate between fresh waste and stabilised waste reactors until a balanced microbial population was established. Other studies combined leachate with water, as simulated rainfall, which simulated field conditions and diluted the leachate [13, 24]. The addition of supplemental water to the recirculated leachate in early operational phases could promote dilution of inhibitory substances and reduce leachate strength resulting in more favourable methanogenic conditions [25]. *Therefore, supplemental water can be used in combination with other leachate manipulation techniques – shown below - to correct certain process deviations, reduce the impact of detrimental substances, and/or enrich the concentration of other beneficial compounds.*

#### 1.1.2. pH Adjustment

Methanogenic bacteria are sensitive to pH, with an optimal range between 6.8 and 7.2, and could be inhibited by acidic conditions at pH less than 6.7. Therefore, pH of recycled leachate can have a significant effect on waste stabilization and methane production. This understanding of microbial ecology has promoted the addition of buffer to adjust the pH of leachate prior to recycling it back to landfill. Buffering as a control option may be best used in response to changes in leachate characteristics (i.e., a drop in pH or increase in volatile acids' concentration). Leachate recirculation with a buffering system to control the pH has been found to result in shorter acidogenic stage leading to earlier initiation of the methanogenic stage, and concomitant higher gas production [7, 8, 25].

#### 1.1.3. Bioaugmentation

Bioaugmentation or inoculation of the landfill has been investigated, usually through the addition of bio-solids from wastewater treatment facilities [1]. The optimal inoculum should provide suitable consortia and concentration of microorganisms, as well as nutrients such as nitrogen and phosphorus. It was stated in [23] that initiating fermentation in BLs can be promoted by addition of large amounts of methanogenic microorganisms in the form of effluent and sludge from an anaerobic sewage digester since the population of such microorganisms in fresh MSW is typically low. In [6], moisture saturation conditions was examined with digested sewage sludge, with fertilizer, and without additives. It was found that moisture and sewage sludge additions resulted in the shortest acidogenic phase and highest gas production. However, it has been suggested that any measured beneficial effects associated with the addition of biosolids may be due to buffering or moisture addition rather than inoculation [26]. Moreover, generic



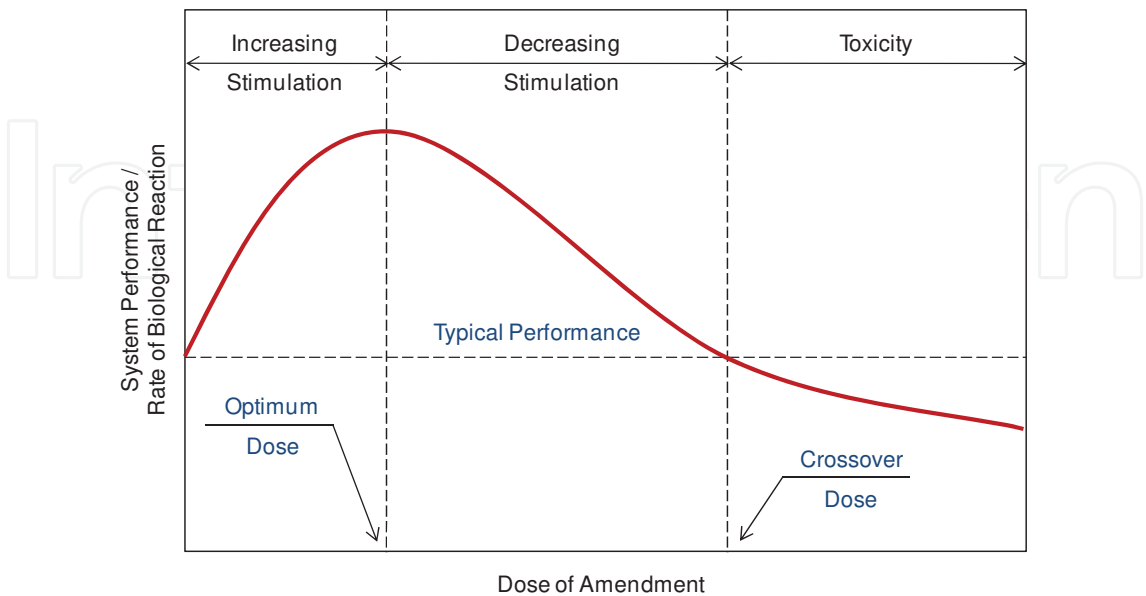
conclusions regarding the effect of sludge addition cannot be drawn, since different types and percentages of sludge might have been used in different experiments.

1.1.4. *Nutrients addition*

Nutrients required for anaerobic degradation of waste are generally low, and therefore, nutrients are expected to be available especially during early phases of biodegradation [7]. It was found that all the necessary nutrients and trace heavy metals are available in most landfills, but insufficient mixing and heterogeneity of the wastes may result in nutrient-limited zones [23, 27]. Experimentally, it was proven that the addition of nitrogen and phosphorous stimulated methane production, rapidly decreased organic concentration in leachate, and shortened the initial phase before methane generation commenced [1, 28].

1.2. **Identification of control problem**

While most studies reported process improvements associated with leachate recirculation and manipulation processes, other studies found the contrary, such as toxicity and souring conditions. The results reported in many studies are different, and sometimes contradicting, since the same substance can be useful or harmful depending on its dose. This can be explained by the general effect of increasing salt concentration in anaerobic systems shown in Figure 3. A substance which is essential to a biological process can stimulate the bacterial growth at low concentrations. However, as concentrations increase above optimal, the rate of microbial activity decreases until the process is inhibited. Similarly, this trend can describe the effects of adding leachate and other amendments on the BL performance. In addition to the dose, other factors may affect the results: (1) operational factors, such as the type and characteristics of amendments, and (2) operational phase and progressive evolution of the BL.



**Figure 3.** Effect of adding amendments on BL performance (modified from [29])

In conclusion, specific growth needs of the BL bacterial consortia changes with time, concomitantly the required leachate characteristics are continuously changing such that leachate as produced in its original form may not always be ideal for recirculation. The goal of the present research is the development of a real-time monitoring and expert decision making system that can adjust both, leachate characteristics and rates of recirculation according to the ecological requirements of each operational phase to provide the optimum conditions for waste biodegradation in BLs.

## 2. The proposed control system

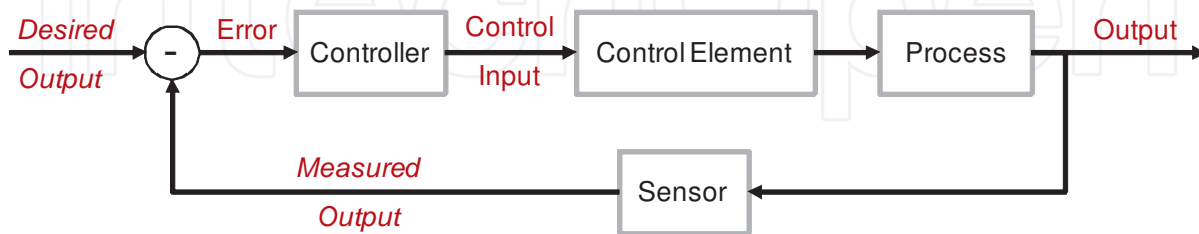
The main real-time control tool in an anaerobic BL is leachate recirculation combined with amendment addition to provide both optimal moisture content and distribution of essential additives. The pH of the recirculated leachate can be adjusted by adding buffer, while inoculum in the form of anaerobic digested sludge, can be used both as a buffer and a rich source of methanogenic bacteria. At later BL operational phases, nutrients can be added as needed to supply the nutritional needs of the bacterial consortia. Supplemental water can be added to dilute concentrated leachate (as a remedy for toxicity) and to account for any shortage in available recyclable leachate for moisture control. The rate of application of any of these amendments can be decided based on measurable parameters in the leachate as well as the specific requirements of each BL operational phase. In conjunction with recirculation, certain parameters such as pore water pressure, landfill internal temperature, and hydrostatic head on the liner must be monitored and considered as they are influenced by recirculated leachate, and can affect BL operation.

### 2.1. Control scheme

The biological processes occurring in the landfill are largely anaerobic. Similar to anaerobic digesters, the landfill ecosystem is sensitive to environmental conditions such as pH, temperature, moisture, toxic compounds, and presence of oxygen. In fact, much of what is known or assumed concerning processes in landfills has primarily come from experiences with anaerobic digesters [10]. For this reason, the required control for an anaerobic BL is analogous to that of an anaerobic digester, with the latter more easily to control being a well-mixed reactor [7]. There are various control schemes that can be applied in managing biochemical systems. The most widespread control schemes are: feedback, feed-forward, and open-loop. Feedback control is a control mechanism that uses information from measurements to manipulate a variable so that the desired result is achieved. Alternatively, feed-forward control mechanism predicts the effects of measured disturbances and takes corrective action to achieve the desired result. On the other hand, the open-loop controller does not utilize feedback to determine whether the input achieved the desired goal or not, and can neither engage in machine learning nor correct any errors that it could make. Thus far in landfill sites, process control is accomplished, if ever, based on a non-feedback scheme. Therefore, the present study aims at applying feedback control in the management of BLs.



In feedback control, the variable being controlled is measured and compared with a target value. The difference between the measured and desired value is called the *error*. Feedback control manipulates inputs of the system to minimize this error. Figure 4 shows a generic component block diagram of an elementary feedback controller. The output of the system is measured by a *sensor* and the *control element* represents an actuator or control device. The *error* in this system would be the *Measured Output - Desired Output*.



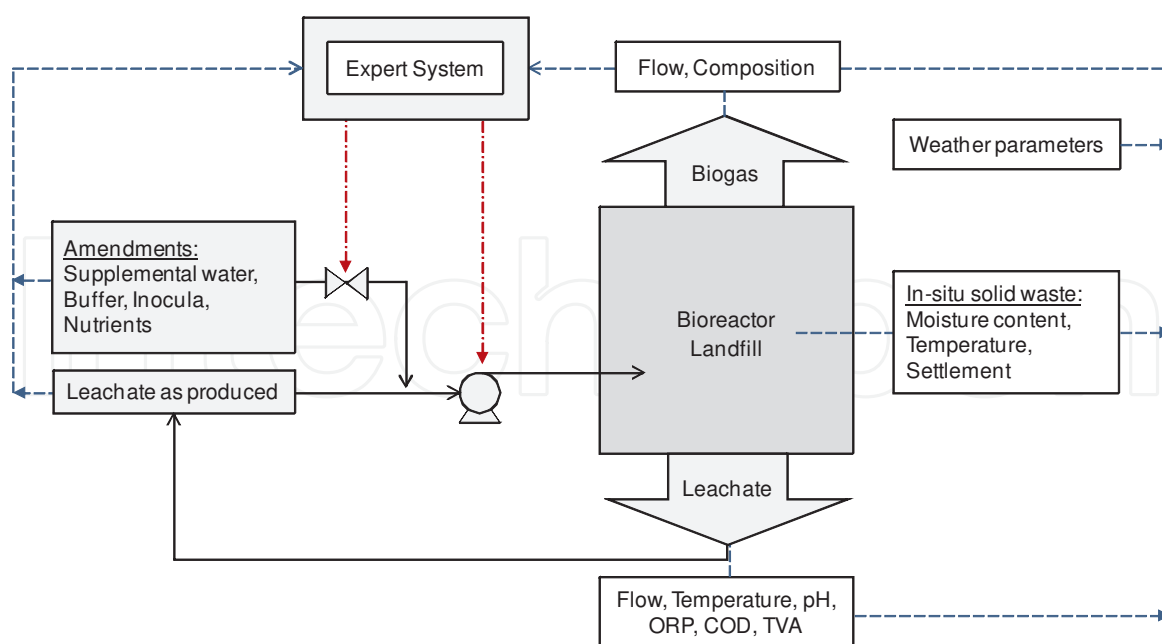
**Figure 4.** Block diagram of a basic feedback control loop

The potential advantages of feedback control lie in the fact that it obtains and utilizes data at the process output [30]. Therefore, the controller takes into account unforeseen disturbances in the process. Feedback control architecture ensures the desired performance by altering the inputs immediately once deviations are observed regardless of their reason. Thus, it reduces operator workload by eliminating the need for human adjustment of the control variable. An additional advantage is that by analyzing the output of a system, unstable processes may be stabilized. Feedback controls do not require detailed knowledge of the system and, in particular, do not require a mathematical model of the process. The controller can be easily duplicated from one system to another.

On the other hand, the time lag in the system is potentially the main disadvantage of feedback control. A process deviation occurring near the beginning of the process will not be recognized until the process output. The feedback control will then have to adjust the process inputs in order to correct this deviation. This results in the possibility of substantial deviation throughout the entire process [30]. The system could possibly miss process output disturbances and the error could continue without adjustment resulting in a steady state error. When the feedback controller proves unable to maintain stable closed-loop control, operator intervention is then required. Finally, feedback control does not take predictive control action towards the effects of known disturbances, and depends entirely on the accuracy with which the controlled output is measured.

## 2.2. Control framework

The proposed Sensor-based Monitoring and Remote-control Technology (SMART) system features software and hardware interacting components that provide real-time monitoring and expert control of BLs. Figure 5 shows a general diagram of the control system. The dashed lines indicate the sensory data, while the dot-dashed lines represent the commands.



**Figure 5.** Schematic of the SMART control system

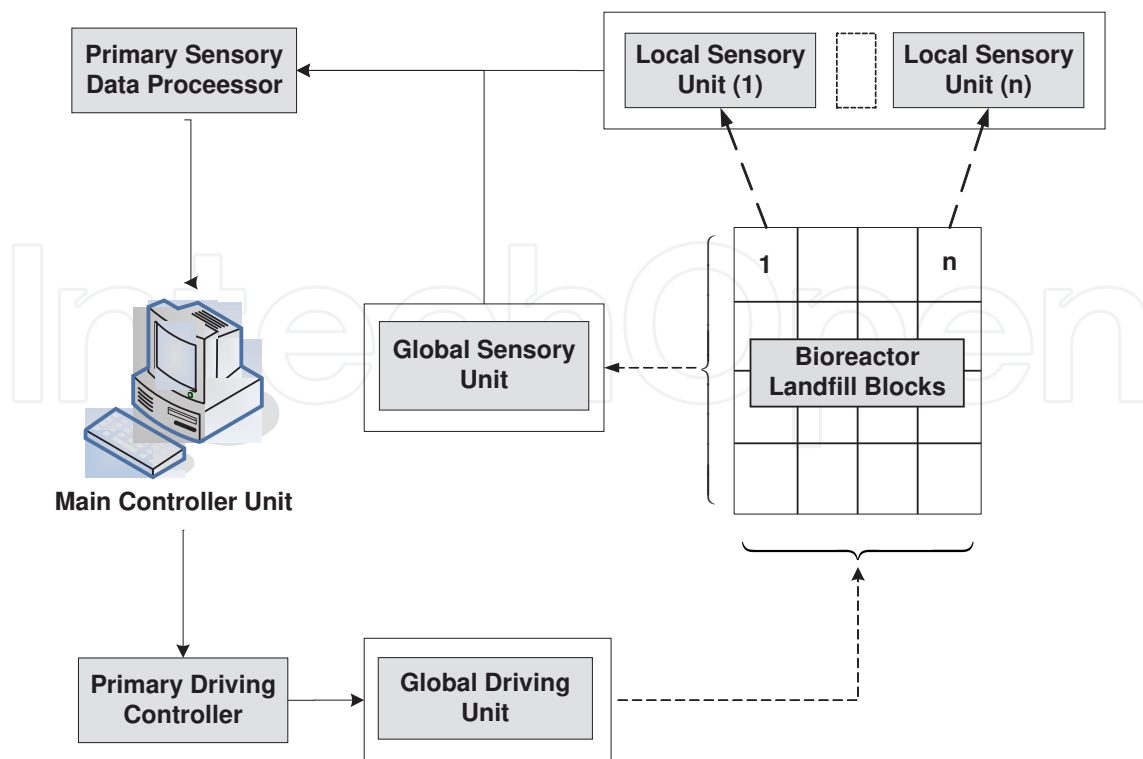
The control system has a geographically and functionally distributed architecture in which the BL is divided into basic blocks. Each block has its own local sensory data acquisition and control units. In addition, global sensory units are to provide measurements for the landfill body altogether as one block. All these local and global components are connected and remotely controlled by a global data processing and decision making unit. The controller continuously monitors two types of sensory data: process parameters (such as moisture and temperature), and returned feedback from performance indicators (such as biogas production and settlement). The decision made by the control algorithm is transmitted to the actuators, after authorization from the site operator, to inject the computed volumes of the selected amendments in order to manipulate the characteristics of the recirculated leachate. This batch control process runs continuously along the lifetime of the BL cell.

### 2.3. System components

The SMART system incorporates six interacting components: (1) Local Sensory Unit, (2) Global Sensory Unit, (3) Primary Sensory Data Processor, (4) Main Controller Unit, (5) Primary Driving Controller, and (6) Local Driving Unit. The main components of the system are shown in Figure 6, and described in detail below.

#### Local Sensory Unit (LSU)

The LSU is placed in each block, i.e.,  $n$  sensory units for the  $n$  blocks. Each unit includes a set of analog sensors which quantify the values of different system parameters, such as temperature and moisture content, in the corresponding block. The installed units form a three dimensional grid in order to show the spatial dynamic status of the main parameters within the BL. All LSUs are designed to send the measured data to the Primary Sensory Data Processor.



**Figure 6.** Main components of the SMART control system

**Global Sensory Unit (GSU)**

The GSU provides global measurements for the landfill body altogether as one block. These measurements include the parameters that are impractical to be determined for each block individually such as leachate characteristics, settlement, hydrostatic head on the liner, as well as biogas quantity and quality. Other examples of global measurements are the weather condition parameters such as air temperature, wind speed and direction, humidity, solar radiation, precipitation, and evaporation. All GSUs are connected to the Main Controller Unit through the Primary Sensory Data Processor.

**Primary Sensory Data Processor (PSDP)**

The PSDP is responsible for analyzing the acquired data from the Local and Global Sensory Units, and arranging them in a new frame to be delivered to the Main Controller Unit. Although this work could be done by the Main Controller Unit, employing an intermediate device here provides more modularity and flexibility to the system by providing an interface between the software of the Main Controller Unit from one side, and the LSUs from the other side.

**Main Controller Unit (MCU)**

The MCU is considered the driving brain of the control system. It receives the measured data (inputs), processes them within the developed expert system, and makes the control decision. The operator is prompted with the decision made by the MCU in order to evaluate it, and then approves it to be sent to the Primary Driving Controller in the form of quantified commands.

The operator can overwrite the decision to deal with any unexpected problem or unconsidered scenario in the expert system. The control program was programmed on the LabVIEW™ graphical programming platform (National Instruments, USA). The control program and expert system of MCU are discussed in *Section 2.5*.

### **Primary Driving Controller (PDC)**

The PDC receives the commands from the MCU and distributes it to the different Local Driving Units. Basically, it is a device that de-multiplexes the received data set which holds the commands for all the driving units, and then delivers the commands to each unit separately. This unit combines analog/digital conversion, signal conditioning, and signal connectivity.

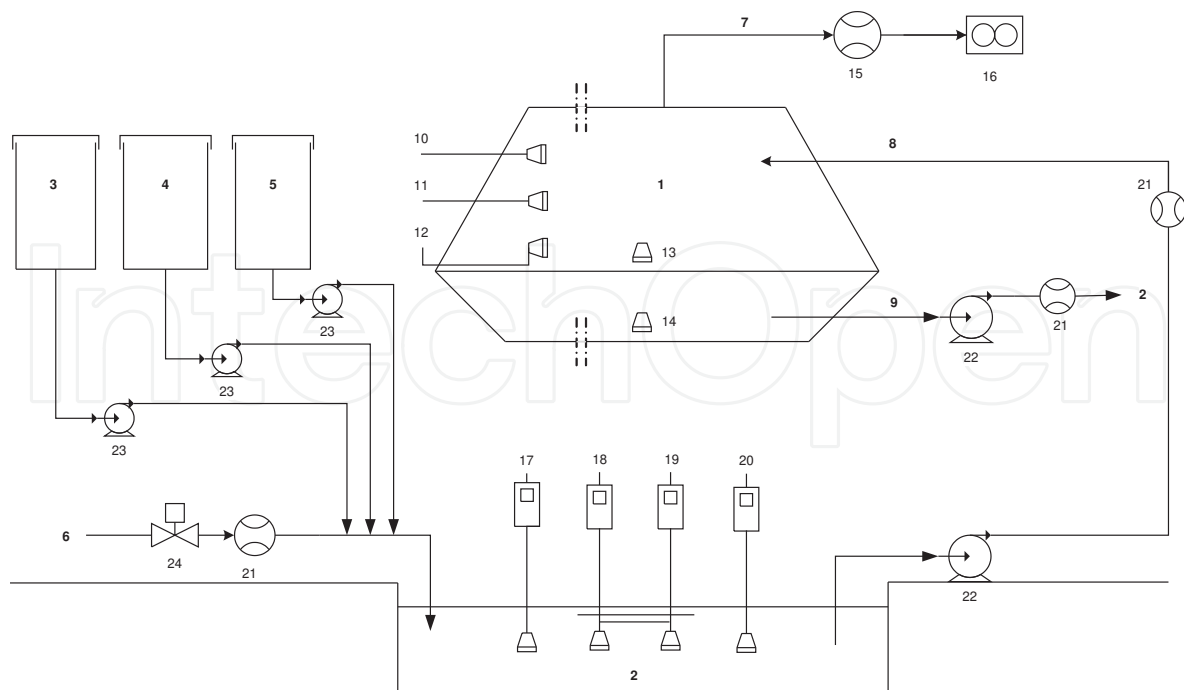
### **Local Driving Unit (LDU)**

The LDU receives the commands and performs the required action by driving the corresponding actuator (motorized valves and/or pumps). Similar to the LSU, each of these units is responsible for controlling a single block, i.e.,  $n$  driving units for the  $n$  blocks. Each actuator receives from the PDC the exact quantity required of the amendment it controls.

## **2.4. Instrumentation**

In order to build the on-line monitoring and real-time control system of SMART, all sensors and control elements must be adaptable to automatic operation and because of the aggressive environment of landfills, instruments have to be durable, chemical and corrosion resistant, and robust (especially against overburden pressure). Typical sensor requirements to monitor in-place waste, leachate, and biogas for a generic block in the SMART system are shown in Figure 7. In this instrumentation system, sensors are controlled remotely by the PSDP, whereas the final control elements are controlled by the PDC. The PSDP/PDC unit transmits/receives the input/output signals via standard communication protocols (such as RS-232 or RS-485) to/from the MCU.

In-place waste is monitored by LSU bundles which are evenly distributed in the BL body forming a three-dimensional grid. Each bundle measures moisture content, temperature, and water pressure (Figure 7, objects 10-12, respectively). Electrical resistivity and capacitance (frequency domain) technologies are suitable technologies for moisture measurements, and are compatible with automated monitoring systems. Waste temperature can be measured using thermocouples or thermistors, with the latter built into most commercial moisture and pressure sensors. However, thermocouples are still the preferred stand-alone temperature monitoring devices because they are reliable, inexpensive and the higher accuracy of thermistors is not needed in landfill applications. Thermocouples of types T (-250 to 350°C) or K (-200 to +1350°C) or J (-40 to +750°C) are widely used in landfill applications. Pore water pressure is measured using vibrating wire or solid state piezometers. Settlement is measured using settlement plates, whereas hydrostatic head on the liners is monitored by differential pressure transducers (Figure 7, objects 13 and 14, respectively). Landfill biogas flow is metered and totalized onsite using turbine or thermal dispersion flow meters (Figure 7, object 15). Biogas is analyzed for carbon dioxide and methane with dual wavelength infrared gas analyzers, whereas, oxygen is monitored via a zirconium dioxide sensor (Figure 7, object 16).



**Figure 7.** Schematic instrumentation diagram of the SMART system: (1) bioreactor landfill cell; (2) leachate storage facilities; (3) buffer tank; (4) inocula tank; (5) nutrient tank; (6) water supply; (7) collected biogas flow line; (8) recirculated leachate flow line; (9) collected leachate flow line; (10) moisture sensors; (11) thermocouples; (12) piezometers; (13) settlement plates; (14) pressure transducers; (15) gas flow meter; (16) inline gas analyzer; (17) liquid thermistor; (18) pH probe; (19) ORP electrode; (20) ammonia-selective electrode; (21) liquid flow meters; (22) pumps; (23) dosing pumps; and (24) electrically actuated valves.

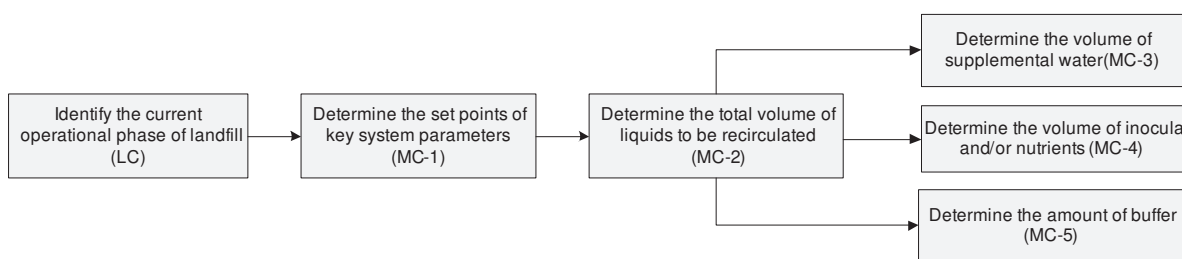
Collected leachate is analyzed for major parameters such as chemical oxygen demand (COD), volatile fatty acids (VFA), oxygen reduction potential (ORP), and pH. The pH, ORP, and ammonia are measured by inline double-junction temperature-compensated pH, ORP, and ion-selective electrodes, respectively connected to a transmitter (Figure 7, objects 18-20, respectively). Online analyzers for COD and VFA are commercially available, however due to their high capital and maintenance costs as well as the slow reaction time in landfill processes, determination of these parameters by standard offline analytical methods is still the most economic and practical approach, and therefore is used in SMART. Leachate flow rate and cumulative flow are measured via Coriolis mass flow sensors equipped with totalizers (Figure 7, object 21). On the control side, GDU units include electrically actuated double-diaphragm or peristaltic pumps, and diaphragm valves that can safely handle particulate-laden and corrosive liquids (Figure 7, objects 22-24, respectively).

## 2.5. Expert system

The control program receives the measured data (inputs), processes them within the MCU expert system, makes the control decision, and sends it to the LDUs in the form of quantified commands. The expert system is designed to determine the required volumes of leachate, make-up water as well as bioaugmentation and nutritional amendments necessary to provide the BL microbial consortia with their optimum growth requirements. It was assumed that the

chemical/biochemical characteristics of the effluent leachate are representative of the conditions within the whole BL waste matrix. Regulating the characteristics of the recirculated leachate alters the characteristics of the waste matrix through which it percolates, in a gradual stepwise manner, over a number of cycle times. It is the premise of the system to identify the current operational phase of the controlled bioreactor, and accordingly determines quantities of leachate, buffer, supplemental water, and inoculum/nutrition amendments required to provide the landfill microbial consortia with their growth needs.

The data flow diagram and hierarchy of the developed control program are shown in Figure 8. The structure of the program is composed of multiple cascading mathematical calculations (MCs 1-5) based on a main logic controller (LC). The control sequence in Figure 8 is repeated every operational cycle. The LC is discussed below (why a logic controller is needed? which method should be used? how the model is developed?), and then the mathematical calculations are presented.



**Figure 8.** Dataflow diagram of the control program

### 2.5.1. Logic controller

Bioreactor landfills undergo the typical waste decomposition phases of sanitary landfills (in the order of: *initial/aerobic*, *transition*, *acid formation*, *methane generation*, and *final maturation* phases) but in a shorter time frame [7, 9, 31]. The determination of the current operational phase of the BL is vital because the bacterial consortia change significantly throughout the BL lifetime, and accordingly so do the conditions for their optimal growth. In order to stimulate the decomposition process and consequently biogas generation, those requirements have to be adequately provided. Practically, the identification of the dominant operational phase of the BL at a given time is challenging especially because of factors such as the heterogeneity of the waste which may cause system parameters not to follow their normal expected trends. Moreover, since landfills receive waste continually over several years, these progressive phases occur simultaneously, but in different neighbouring locales. The temporal and spatial dimensions of each phase depends on many factors such as waste characteristics, landfill design, operational strategy, and environmental conditions, that can be characterized by changes in various physical and biochemical indicator parameters.

In recent years, intelligent control of large-scale industrial processes has brought about a revolution in the field of advanced process control [32]. Knowledge-based techniques, such as fuzzy logic which uses linguistic control rules capturing the know-how of the experienced



human operators, proved to be robust and reliable solutions for dealing with complex and ill-defined processes, such as those encountered in the operation of a BL. In fact, no conventional controller could efficiently operate such a complex process because it is practically impossible to predict its behaviour especially with the heterogeneity of waste. Fuzzy logic has been applied successfully to control various biological treatment systems such as anaerobic digesters [33], biological reactors [34], and wastewater treatment plants [35].

Therefore, the objective was to employ the modeling capabilities of fuzzy logic in developing a knowledge-based controller that determines the operational phase based on quantifiable input parameters of leachate and biogas, while taking uncertainty issues into consideration. The selected input variables include the leachate's COD, total volatile acids (TVA), pH, ORP, and methane content (%CH<sub>4</sub>) in biogas, whereas, the single output variable is an index that defines the current operational phase of the BL, hereafter named the *Phase Index*.

### Model development

The **first step** in the design of a Fuzzy Logic Controller (FLC) is to build the *data base* which contains the membership functions defined for each input and output variable. Each variable is expressed by linguistic terms (fuzzy sets) within its predefined range (universe of discourse). The degree of truth of a fuzzy set A is defined by a membership function  $\mu_A$ , which is represented by a real number in the interval [0, 1] depending on the degree at which it belongs to the set. This is different from conventional numerical sets where an element either belongs or does not belong to a particular set (membership = 0 or 1). This distinctive feature is advantageous for controlling biological ecosystems, like the BL, where the change in input variable does not cause the controlled process to shift abruptly from one state to another. Instead, as the variable changes, it loses its membership in one fuzzy set while gaining membership in the next. This is a logical approach to account for the fact that a part of the BL may be in a particular operational phase, while adjacent parts may be in other phases.

Membership functions (MFs) can have different shapes such as triangular, trapezoidal, bell-shaped (Gaussian), or wave-shaped (Sigmoid). In the present FLC, fuzzy sets were defined by trapezoidal and/or triangular (special case of the trapezoidal shape) MFs where the uncertainty in each variable is represented by the most likely interval (i.e., the range at membership degree = 1.0) and the largest likely interval (i.e., the range at membership degree = 0.0) as shown in Figure 9. These intervals facilitate the interpretation of overlapping and disagreement in the compiled data ranges. The membership value is constant in the most likely interval [b, c], and increasing linearly from 0 to 1 between (a & b) and decreasing linearly from 1 to 0 between (c & d), thus providing the trapezoidal shape. For the special case of the triangular MF, the only difference to the trapezoidal MF is that the most likely interval [b, c] is a single point.

Figure 10 shows the MFs defined for a sample input (ORP) and the single output (*Phase Index*). The linguistic labels (fuzzy sets) used to describe the ORP values are *positive* (P), *zero* (Z), *negative* (N), and *very negative* (VN). The '*Phase Index*' variable was defined by the basic phases that typically characterize the BL lifespan; *aerobic* (A), *transition* (T), *acid formation* (AF), and *methane generation* (MG).

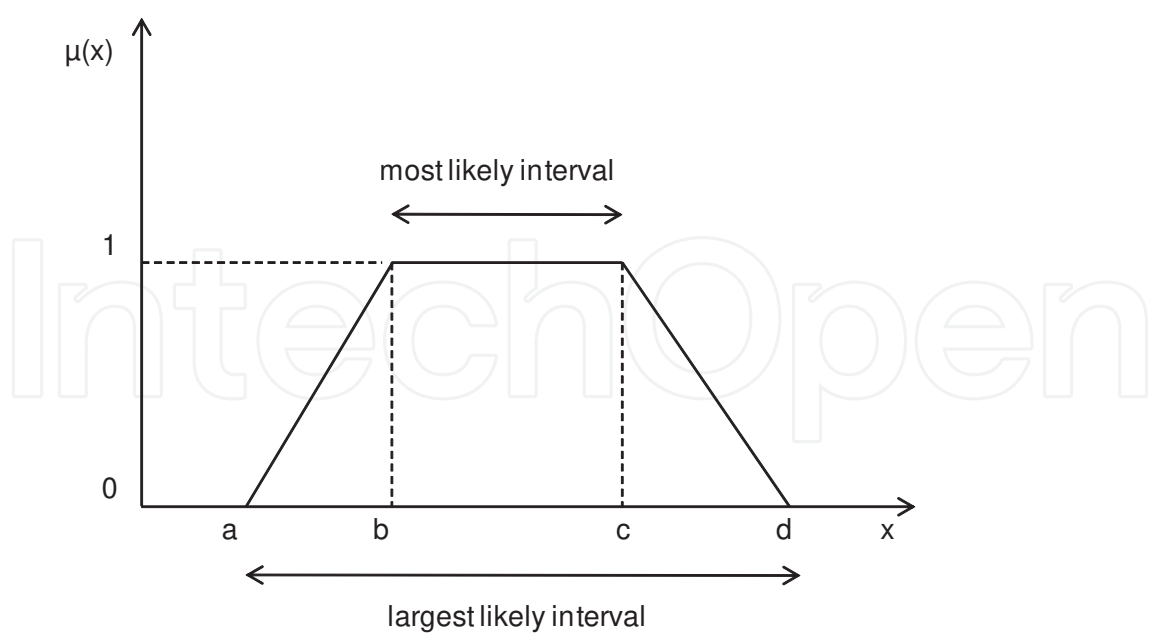


Figure 9. Typical trapezoidal membership function

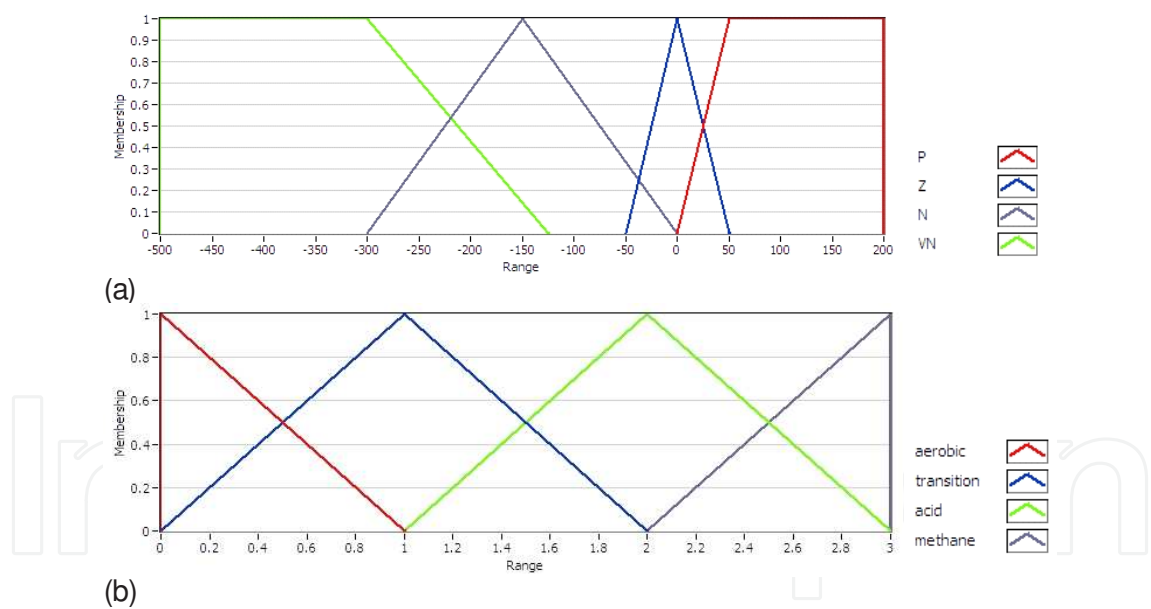


Figure 10. Membership functions for: a) ORP, and b) Phase Index

The **second step** in the design of FLC is developing the *rule base* for the controlled process. The *rule base* consists of fuzzy rules which are stated as IF–THEN statements that define the system behavior and predict the output variable. A typical fuzzy rule can include several variables in the antecedent (IF part) and consequent (THEN part) of the rule. If a rule has more than one antecedent, a fuzzy operator such as AND, OR, or NOT, is used to connect them, and to determine how to calculate the truth value of the aggregated rule antecedent. In the present

FLC, five basic statements (rules) were created to define the expected operational phase based on different quantifiable parameters. The probabilistic-type of the OR operator, which uses the probabilistic sum of the degrees of membership of the antecedents, was applied in the formulated rules. The following is an example of the developed rule base statements:

IF ‘ORP’ is ‘VN’ OR ‘pH’ is ‘HN’ OR ‘COD’ is ‘H’ OR ‘TVA’ is ‘I’ OR ‘%CH<sub>4</sub>’ is ‘H’  
THEN ‘Phase Index’ is ‘MG’

In the above rule, VN, HN, H, I, H, and MG are fuzzy sets that denote *very negative*, *high neutral*, *high*, *intermediate*, *high*, and *methane generation*, respectively. The complete fuzzy rules as well as parameters of membership functions defined in the FLC are presented in [36].

**Example:** Based on the compiled knowledge base, when the ORP of the leachate is -250 mV, it has a 0.3 membership in the “*negative*” fuzzy set, and a 0.7 membership in the “*very negative*” fuzzy set (see Figure 10a). This allows the single input (-250 mV) to be processed with multiple rules, i.e., the fuzzy rules that include “*negative*” and “*very negative*” ORP in their antecedents. Although all the invoked rules influence the output, the rules with higher truth values (“*very negative*” in this case) have the greatest effect. This weighing system helps in dealing with the uncertainties in the landfill ecosystem, as well as simplifying the complexity of the controlled process.

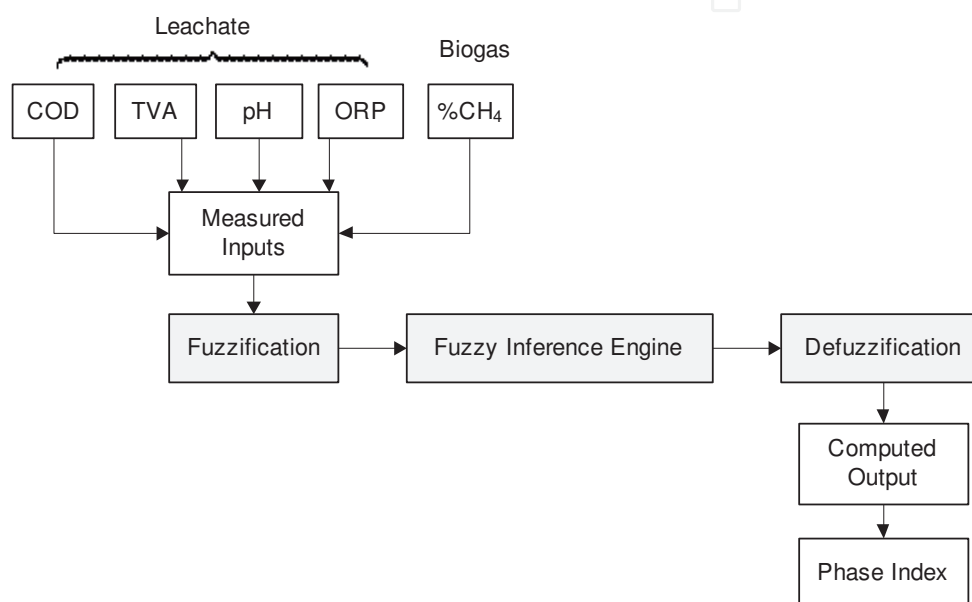
The data base and rule base represent the knowledge components based on which the FLC makes the decision. The knowledge was compiled from information presented in [7, 37-39]. Table 1 shows the reported ranges of the input system parameters in the compiled studies.

Parameter	Study	Phase II Transition	Phase III Acid Formation	Phase IV Methane Generation	Phase V Maturation
COD, mg/l	[7]	20 - 20,000	11,600 - 34,550	1,800 - 17,000	770 - 1,000
	[38]	-	15,000 - 41,000	1,000 - 41,000	-
TVA, mg/l	[7]	200 - 2,700	1 - 30,730	0 - 3,900	0
	[38]	-	7,000 - 15,000	10,000	0
pH	[7]	5.4 - 8.1	5.7 - 7.4	5.9 - 8.6	7.4 - 8.3
	[38]	-	5 - 6	5.6 - 7.1	-
	[37]	-	5.8 - 6	6 - 7.8	7.1
%CH <sub>4</sub>	[38]	-	0	0 - 50	40
	[37]	-	-	23 - 62	-
ORP, mV	[38]	50 - (-50)	50 - 0	0 - (-125)	-
	[39]		(-100)	(-300)	-

**Table 1.** Ranges of selected system parameters at the main operational phases

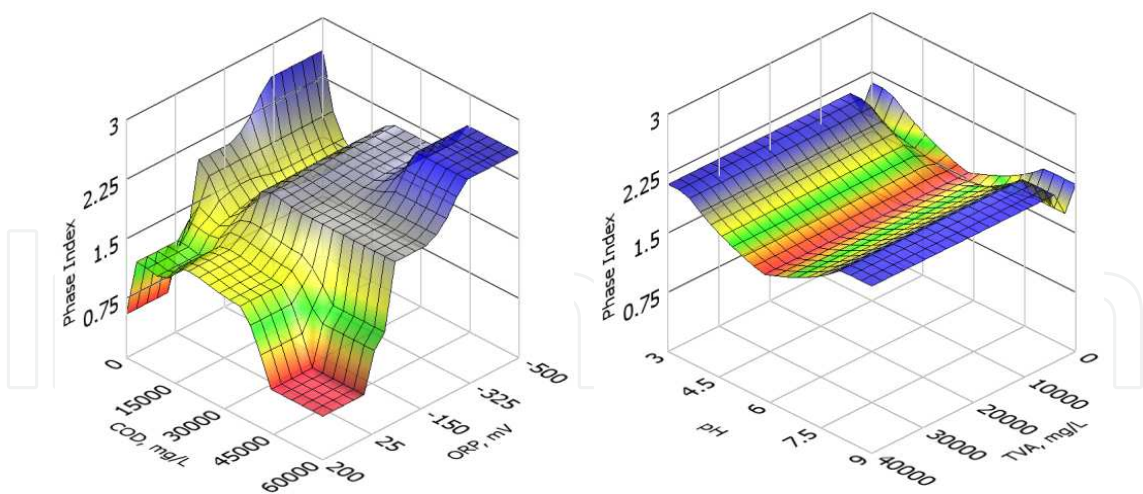
The data base and rule base are incorporated in the typical FLC components, shown in Figure 11, which includes: (1) *fuzzification unit*, (2) *inference engine*, and (3) *defuzzification unit*. The

*fuzzification unit* converts the input variables into fuzzy sets using the predefined membership functions. The *inference engine* then processes the fuzzy inputs based on their relevant fuzzy rules, and determines the fuzzy output(s). As mentioned above, the *inference engine* invokes more than one rule, which results in having different memberships in multiple output fuzzy sets. In the present LC, the *inference engine* uses the product implication method in which each output MF is scaled down at the truth value of the corresponding aggregated rule antecedent. The output from this step is an irregular area under the scaled-down membership functions. Finally, the *defuzzification unit* incorporates a number of fuzzy sets in a calculation that gives a single numeric value for each output.



**Figure 11.** Typical structure of a fuzzy logic controller

In order to help visualize the non-linear characteristics of the *Phase Index*, surface plots were generated by varying two variables while the other variables remained constant. This can generate an infinite number of response surface, however if grouped for each pair of inputs, the number of possible groups of response surfaces becomes equal to the combination  $C(n, 2) = n! / 2! (n - 2)!$  where  $n$  is the number of input variables. In the present FLC, 10 groups of response surfaces can be established for the 10 possible pairs of input variables. Figure 12 shows the response of the output variable '*Phase Index*' to changes in two pairs of the input variables, namely ORP and COD as well as TVA and pH, at the average defined value for the other input variables. The non-linear variation of the response intensity for the different values of input variables is considered one of the main advantages of the fuzzy logic system. Moreover, SMART's numeric representation for the operational phase offers a unique feature being able to obtain the transitional stage of the controlled BL. For example, when the '*Phase Index*' is equal to 2.7, this means that the bioreactor is transitioning from the acid formation phase (2.0) to the methane generation phase (3.0). The value (2.7) indicates also that the BL microbial ecosystem is closer to the methanogenic stage.



**Figure 12.** Response surfaces for two pairs of inputs: 1. COD/ORP (left), and 2. TVA/pH (right)

2.5.2. Mathematical calculations

As shown in Figure 8, the program sequence starts with the logic controller (LC) which identifies the current operational phase of the BL based on quantifiable characteristics of the generated leachate and biogas. The output of LC is a real number in the interval [0, 3] that expresses the BL operational phase, where 0 is the aerobic phase and 3 is the methanogenic phase. The output from LC is the input to the first mathematical step (MC-1).

Target set points

In MC-1, set points of pH (leachate), Carbon/Nitrogen (C/N) ratio (leachate), and moisture content (solid waste matrix) are computed based on the BL operational phase determined from LC. Table 2 shows default set points used in the present study for the two main BL operational phases. It should be noted that these set points may vary depending on several site-specific factors such as holding capacity of waste matrix, degree of compaction, and waste composition.

Parameter	Medium	Phase III Acid Formation	Phase IV Methane Generation
pH	Leachate	5.5-6.5	6.8-7.2
C/N ratio	Leachate	10	15
Moisture content, %	Waste Matrix	50	60

**Table 2.** Set points of process parameters at the Acid Formation and Methane Generation phases

MC-1 applies linear interpolation between the predefined parameter values (shown in Table 2). The parameter setpoint ( $S$ ) at a given phase ( $P$ ) can be calculated as follows:

$$S_p = S_i + [(S_{i+1} - S_i) \times (P - i)] \tag{1}$$

Where  $P$  is the computed phase from LC,  $i$  is the integer part from the computed *Phase Index*  $P$ ,  $S_i$  is the setpoint at phase  $i$ , and  $S_{i+1}$  is the setpoint at phase  $i+1$ .

### Recirculation volume

MC-2 computes the total required volume of recirculated liquids to raise the water content of the waste matrix from its current level to the desired setpoint. The liquid volume is calculated as follows:

$$V_{liquid} = \left( \frac{S_{mc} \times w}{\rho_{water}} \right) - (\theta \times V_{waste}) \quad (2)$$

Where  $V_{liquid}$  is the total required volume of liquids to be added in a cycle ( $m^3$ ),  $S_{mc}$  is the setpoint for the gravimetric water content (calculated in MC-1),  $\theta$  is the measured volumetric water content,  $\rho_{water}$  is the water density ( $t/m^3$ ), and  $w$  is the bulk weight of the waste ( $t$ ).

### Supplemental water addition

One of the main benefits of supplemental water addition is to dilute elevated concentrations of pollutants in leachate which may inhibit the microbial consortia in the waste matrix. The primary inhibitors in MC-3 can include, but are not limited to, ammonia-nitrogen, VFA, and their free unionized fractions, as well as alkali cations. The concentrations of selected inhibitors are used to compute a factor ( $D$ ) for the required dilution (i.e., dilution water as a fraction of the liquid recirculated).  $D$  is calculated as the greatest of individually calculated dilution indices required to bring each of the potential inhibitors, if any, to its nontoxic range, as follows:

$$D = \text{Max} \left( 1 - \frac{C_{target}}{C_{inhibitor}} \right) \quad (3)$$

Where  $C_{inhibitor}$  is the concentration of an inhibitor in leachate ( $g/m^3$ ), and  $C_{target}$  is the nontoxic concentration of that inhibitor ( $g/m^3$ ). The required supplemental water volume can then be calculated by multiplying the volume of leachate produced in previous operational cycle by the dilution factor.

### Nutritional requirements

Next, MC-4 determines additional nutrient requirements using the set point for C/N ratio as well as the concentrations of TOC and TN of the generated leachate. The addition of a nitrogen source to the BL is controlled according to the C/N ratio. The volume of nutritional source is calculated as:

$$V_{nutrients} = \frac{\left( \frac{TOC}{S_{C/N}} \right) - TN}{TN_{nutrients}} \times V_{liquid} \quad (4)$$



Where  $V_{nutrients}$  is the required volume of the nutritional source ( $m^3$ ),  $S_{C/N}$  is the setpoint calculated for the C/N ratio,  $V_{liquid}$  is the volume of liquid calculated in MC-2 ( $m^3$ ), and TN, TOC and TN nutrients are the concentrations of total nitrogen of diluted leachate, total organic carbon of diluted leachate, and total nitrogen of the nutritional source to be used, respectively ( $g/m^3$ ).

### Buffering requirements

Next, the required amount of buffer is calculated in MC-5. The buffer salt is used to adjust the pH and provide external source of alkalinity to the system. MC-5 calculates the required bicarbonate alkalinity to be added to the leachate regardless of the resultant pH. The buffer is added to provide the difference between the required alkalinity ( $CO_2$ /water buffering system) and the available alkalinity in the system. The available bicarbonate alkalinity can be calculated as:

$$BA = ALK - 0.83 \times f \times VFA \quad (5)$$

Where  $BA$  is the bicarbonate alkalinity ( $mg\ CaCO_3/L$ ),  $ALK$  is the total alkalinity ( $mg\ CaCO_3/L$ ),  $VFA$  is the concentration of the volatile fatty acids ( $mg/L$ ),  $0.83$  is a unit conversion factor (Equivalent weight of  $CaCO_3$ /Equivalent weight of  $VFA$ ), and  $f$  is a factor for the percentage of  $VFA$  titrated at the pH endpoint of the alkalinity test. On the other hand, the required alkalinity ( $RA$ ) for the  $CO_2$ /water buffering system can be calculated as:

$$RA = K_1 \times K_H \times P_{CO_2} \times E_{CaCO_3} \times 10^{S_{pH}} \quad (6)$$

Where  $RA$  is the required concentration of bicarbonate ion for  $CO_2$  neutralization ( $g\ CaCO_3/L$ ),  $K_1$  is the ionization constant for carbonic acid,  $K_H$  is the hydration equilibrium constant,  $P_{CO_2}$  is the partial pressure of  $CO_2$  in the system (fraction of  $CO_2$  in the composition of air),  $S_{pH}$  is the target pH as computed in MC-1, and  $E_{CaCO_3}$  is the equivalent weight of  $CaCO_3$ . The added alkalinity is the difference between the required and available alkalinity in the system. The volume of buffer to provide the required alkalinity can be calculated as:

$$V_{buffer} = \frac{[RA - BA] \times E_{buffer} \times V_{liquid}}{C_{buffer}} \quad (7)$$

Where  $V_{buffer}$  is the required volume of buffer,  $E_{buffer}$  is the equivalent weight of buffer salt,  $C_{buffer}$  is the concentration of buffer salt in solution, and  $V_{liquid}$  is the volume of recirculated liquid. The amount of buffer to be added should be equal or greater than the amount required to bring the pH up to the setpoint calculated from MC-1.

### 3. Application and evaluation of SMART

The new concepts proposed and incorporated in SMART were demonstrated in a real operational prototype. Specifically, the concept of temporal determination of the BL operational phase as the starting step for initiating the other subsequent computations to determine the various amendments to be added to manipulate the leachate recirculated. Concomitantly, the main objectives of this research phase were to: (1) implement the software and hardware components of SMART on a pilot-scale prototype, and (2) evaluate the system viability to control the BL versus a conventional open-loop leachate control (OLLC) scheme, in which recirculation rate is fixed and the leachate quality is not changed.

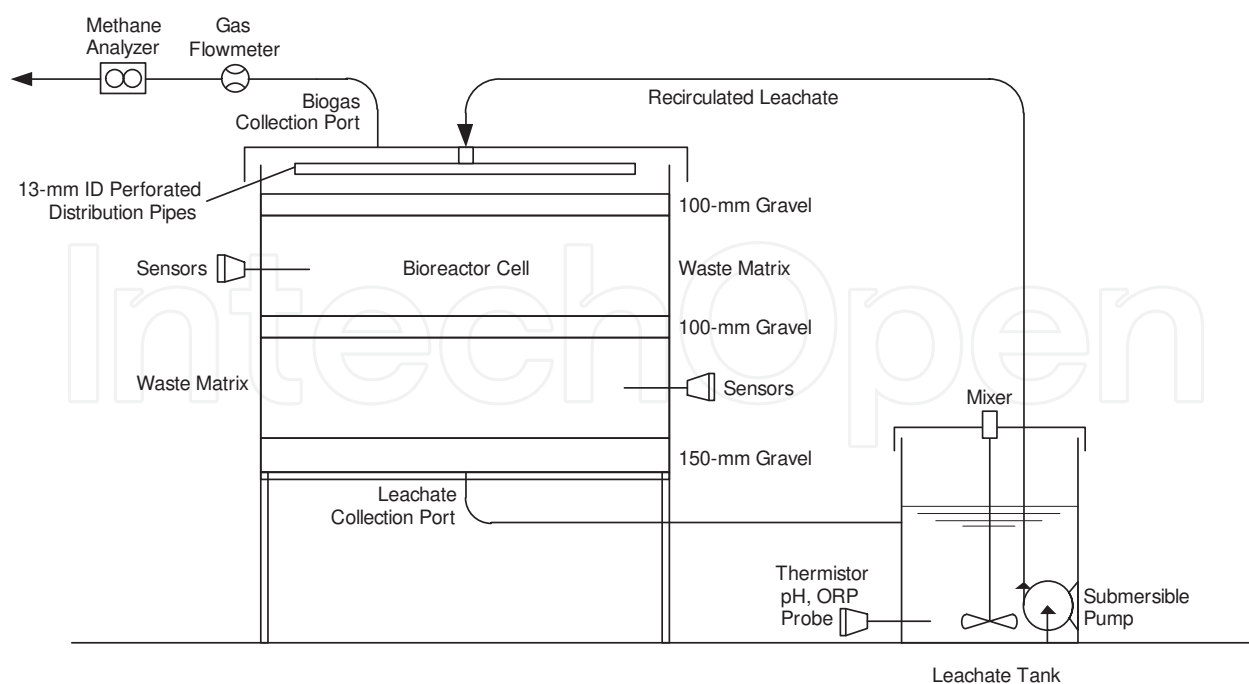
#### 3.1. Experimental setup

Experimental work was conducted on two bioreactor setups; Cell-1 and Cell-2. Figure 13 shows the configuration of a single bioreactor cell (675 litres volume) with its leachate collection and recycling tanks. An equal mixture of residential and food wastes were thoroughly mixed while loaded to the bioreactor cells. The average total organic fraction and water content of the mixed waste was 73%, and 48%, respectively. Each bioreactor cell was equipped with three type-T thermocouples measuring temperature in different radial positions at three equidistant vertical levels in the waste matrix. In addition, three moisture sensors were placed at the same monitoring spots in order to measure the volumetric water content using frequency domain technology. The biogas generated went through a micro-turbine wheel flow meter, followed by an inline infrared methane analyzer. Leachate was collected by gravity from a lower outlet port connected to a collection tank with a mechanical mixer. This tank also received the flow from the amendments' tanks through tube lines with actuated solenoid valves (SMART-controlled). The recirculated leachate was manipulated by adding amendments such as inoculum (anaerobic digester sludge), nutritional source (plant fertilizer), buffer (sodium bicarbonate), and supplemental water. After mixing with amendments, leachate was recycled in a cyclic batch mode using a submersible pump (SMART-controlled).

After loading the bioreactor cells, the first nine months were used to examine the communication and synchronization between system components, as well as test run of the system. By the end of this period, Cell-2 has already started producing methane and surpassed Cell-1 in terms of all performance and evolution parameters. In order to effectively assess the system, SMART was applied on Cell-1 (the inadequately performing cell) for four months so as to evaluate the performance. In parallel, Cell-2 was running according to an OLLC scheme, at a constant rate of leachate recirculation equal to a predetermined percentage (8%) of the initial volume of waste matrix. The discussion is presented in two main sections: (1) assessment of the control actions made by SMART, and (2) evaluation of the system performance through its effect on leachate and biogas.

#### 3.2. Evaluation of SMART control decisions

There has been no consensus in the literature on the optimal leachate recirculation rates in BLs, and the reported rates are extremely diverse to over 400 fold [17]. It was also found

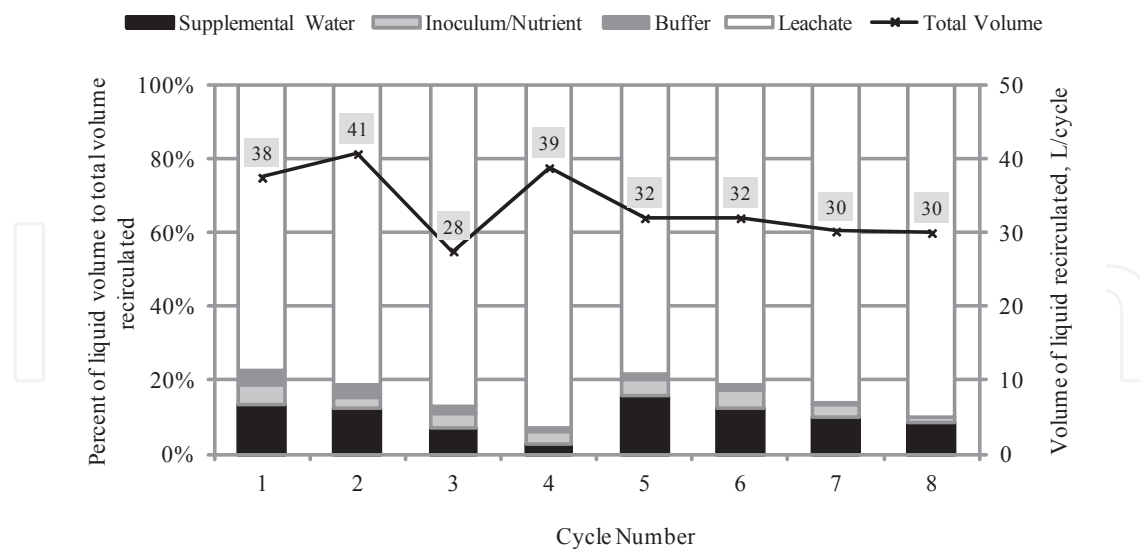


**Figure 13.** Configuration and instrumentation of the prototype bioreactor cell

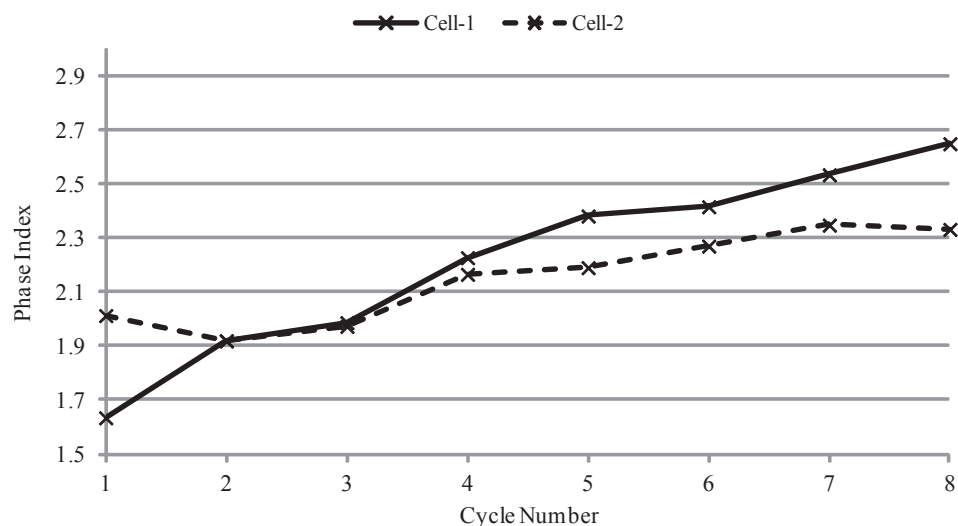
that higher recirculation rates do not necessarily achieve better performance of the BL [1, 24]. Alternatively in SMART, recirculation rates vary based on the site-specific and real-time conditions, and so every BL is controlled according to its own evolution. Figure 14 shows the different recirculated volumes of leachate as determined by SMART for Cell-1, as well as the various fractions of leachate, water, buffer, and sludge in the recirculated liquid in each cycle. It can be observed that the calculated volumes of leachate and other amendments did not follow a predictable trend, and they varied significantly over time ( $34 \pm 7$  L/cycle). However, the volumes of amendments followed a decreasing trend that seemed to restart every four operational cycles (1-4 & 5-8).

### 3.2.1. System evolution

The *Phase Index*, determined by the logic controller, for the two cells is shown in Figure 15. The progress of Cell-1 surpassed that of Cell-2 which was also evolving but at slower rate. It can be seen that, while at the beginning of this test, Cell-2 was ahead of Cell-1 with a PI of 1.6 (Cell-1) versus 2.0 (Cell-2), the SMART-controlled Cell-1 was able to catch up and actually surpassed Cell-2 in four operational cycles. It is clear that since Cell-2 was running with an open-loop control scheme, the improvement in the evolution pattern of Cell-1 can be mostly attributed to the implementation of SMART. The fuzzy logic controller was able to track the BL evolution by identifying the operational phase at any time based on multiple parameters of leachate and biogas. The computed *Phase Index* described the transitioning progress between the main phases of BL, which enabled the interpolation of the evolving growth requirements for the bacterial population inside the BL, and led to successful transition from one phase to another.



**Figure 14.** Cyclic recirculated liquid volumes and amendment fractions in Cell-1



**Figure 15.** Progress of the Phase Index of Cell-1 and Cell-2

### 3.2.2. Control strategy

During the operation period, the operator had to interfere occasionally so as to insure the control actions address all potential problems. This man-computer interaction was crucial due to: (1) the instability and unexpected behavior of the BL system, in part due to its complexity and nonlinear responses, and (2) the fact that the reasoning of the fuzzy logic is limited to its knowledge base. Therefore, applying a semi-automated control strategy, rather than a fully automated one, was found to achieve more stable performance of the system. In this control strategy, SMART collects and analyzes the data, performs the computational effort to deter-

mine the optimum operational strategy, and then aids the site operator to apply the final operational decision through the computer interface.

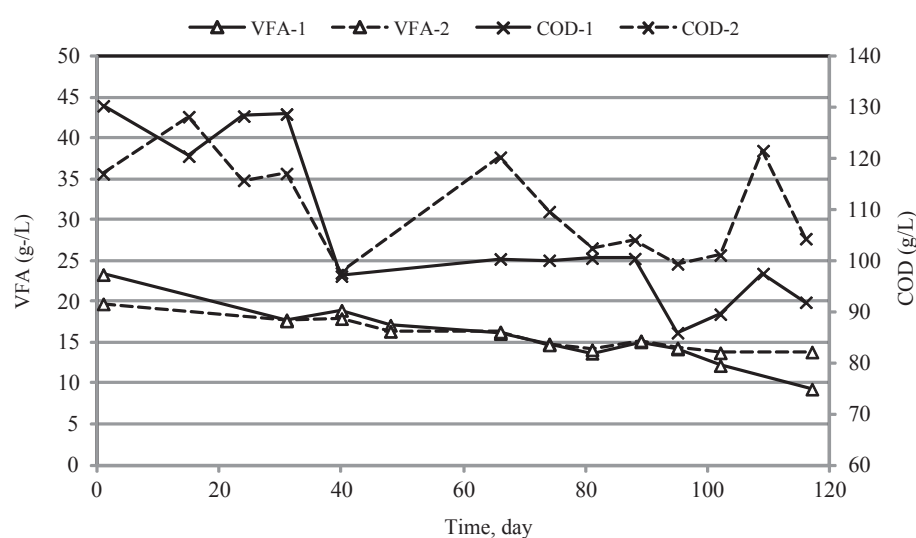
### 3.2.3. Feedback control scheme

The control actions determined by SMART were based on multiple leachate and biogas parameters acquired from previous cycles. The response time of the BL ecosystem, i.e., time from changing a system parameter to when its effect (feedback) on system performance is detected, was found to be sufficient to facilitate the application of the feedback control scheme. The BL performance was significantly improved with the application of closed-loop control (in Cell-1) as opposed to an open-loop strategy (in Cell-2).

## 3.3. Evaluation of process parameters

### 3.3.1. Organic matter

The development of oxidizable organic concentration in the leachate produced is plotted in terms of COD and VFAs in Figure 16. The average degradation rate of COD in Cell-1 (controlled by SMART) was 330 mg/L.d compared to 110 mg/L.d in Cell-2. The COD concentrations in leachate from Cell-2 were fluctuating and the final COD was about 10% less than the initial concentration (from 116 to 105 g/L). After 40 days, COD concentration in leachate from Cell-1 was consistently less than that of Cell-2 which shows that the implementation of SMART had a positive effect on the degradation of organic matter.



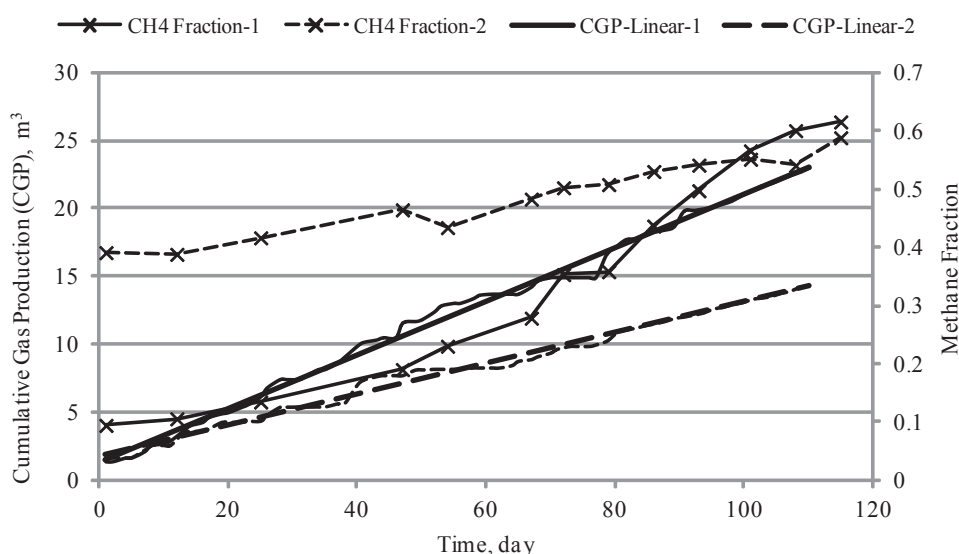
**Figure 16.** Evolution of organic concentration of leachate from Cell-1 and Cell-2

As shown in Figure 16, the conversion of VFAs to methane was increasing slowly resulting in lower and mostly similar concentrations of VFA in leachate from both cells. However at day 95, the VFA concentration in Cell-1 started to drop, leading to an overall conversion rate of 120 mg/L.d compared to 50 mg/L.d in Cell-2. The last recorded VFA concentration was less than

10 g/L in leachate from Cell-1 compared to 14 g/L in Cell-2. It is therefore clear that the SMART control system stimulated the methanogenic activity which gradually consumed the produced VFAs, until the conversion rate of VFA became greater than the production rate (starting from the 95<sup>th</sup> day).

### 3.3.2. Biogas production

The CH<sub>4</sub> fractions of the biogas produced from both cells are shown in Figure 17. The performance of Cell-1 in terms of the rate of increase of the CH<sub>4</sub> fraction was improved. SMART was successful in leading the cell through the transitional stage from acid formation to methane generation. The CH<sub>4</sub> content increased from 10 to 62% in Cell-1 in a four-month period, while Cell-2 continued to increase but at slower rate going from 40 to 58%. Based on the equations of the trend lines fitted to the actual data of cumulative production in Figure 17, the rate of increase in methane production in Cell-1 was 1.7 fold higher than that of Cell-2. By the end of operation, the cumulative biogas production reached 23 and 14 m<sup>3</sup> which corresponds to a specific production of 61 and 35 L/kg of waste in Cell-1 and Cell-2, respectively.



**Figure 17.** Development of methane production and methane content in the biogas produced

### 3.4. Future aspects and potential implications

The implementation of a sensor-based control strategy in full-scale BL faces two main issues: (1) instrumentation of the system, and (2) the heterogeneity of the waste matrix which affects the degree to which the measurements are representative. While in-situ measurements of leachate and biogas are well established, the main instrumentation problem is the subsurface monitoring for in-place waste, such as: moisture content and temperature. The difficulty arises from the following issues: (1) instrument failure is most likely to occur since no specialized sensing technologies and installation procedures exist for landfill application, (2) installation



techniques are very challenging and obstruct daily site operations, (3) cables are subject to physical damage due to heavy equipments, differential settlement, and aggressive environment, and (4) cable conduits create pathways for lateral breakout of leachate and gas. It is clear that, with all these operational issues, current monitoring techniques are neither robust nor efficient. The solution for these issues can be realized via two approaches: (1) using non-intrusive surface methods for subsurface monitoring; e.g., for moisture measurements: seismic waves [40], ground penetrating radar [41], and fiber optics [42], or (2) using wireless communication techniques to eliminate the huge capital cost and operational problems associated with conventional wired techniques [43]. Both approaches can also solve the heterogeneity problem in a way that: in the first approach, a three-dimensional image of moisture distribution can be produced, and in the second approach, more wireless sensors can be used to give higher resolution data. In addition, soft computing methods can be used to deal with the uncertainty in measurements, and by using adaptive systems, monitoring and control programs can learn and adapt to the controlled BL.

Given the rapid development in both instrumentation and full-scale applications of BLs, it is expected that robust subsurface monitoring techniques will appear in the near future. However, research in the area of advanced BL process control like the present research, has to move in-parallel and not to wait until a flawless method to measure subsurface parameters is ready. In fact, process control research can motivate the search for robust and reliable sensory equipment. Therefore, SMART can be currently applied in full-scale BLs if some technical modifications of in-situ monitoring are considered, e.g., monitoring in/out liquid to/from the BL can effectively replace the in-situ measurements of moisture content by means of continuously conducting a real-time water balance.

## 4. Conclusions

The present work developed a control framework in which an expert system is responsible for the operation of BLs. The main control objective of the system was to optimize the performance of the BL by manipulating the quantity and quality of leachate recirculated so as to supply the microbial consortia inside the BL with their optimal growth requirements. The proposed control framework and guidelines were described, and an assessment was conducted for a SMART-controlled pilot-scale BL in order to examine the applicability, feasibility, and effectiveness of the technology. The following conclusions were drawn:

1. The control system successfully determined the quantity and quality of recirculated liquid based on the BL operational stage and multiple process leachate and biogas parameters.
2. The performance of the BL was significantly improved with the application of closed-loop control as opposed to an open-loop strategy.
3. Leachate manipulation techniques, such as buffering, bioaugmentation, and supplemental water addition, were proven to be potentially effective control tools that are able to adjust/optimize the leachate characteristics.

4. Recirculating variable calculation-based amounts of leachate and other amendments resulted in a positive influence on the overall performance of the BL system.
5. The pilot-scale implementation of SMART demonstrated the feasibility of the system. Since all the incorporated hardware components are commercially available, the system can be readily scaled-up to a larger scale application.

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