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LANDFILL MINING IN THE FRAMEWORK OF INTEGRATED WASTE MANAGEMENT: CASE STUDY OF AN ITALIAN LANDFILL

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ABSTRACT

A remediation project involving landfill mining (LFM) was designed and is ongoing at the 40-year-old Villadose landfill in Rovigo, Italy. The original natural clay lining the bottom of the old landfill is being recovered and used as technical material. Meanwhile newly constructed landfill sectors, designed to contain more than four times more waste than previously are being filled with both excavated waste and fresh municipal solid waste. A laboratory scale experiment was conducted to simulate the expected landfill conditions and analyse the effects of different waste fractions on emissions. The fresh municipal waste although pretreated at a mechanical biological treatment plant shows a significant residual emission potential, in terms of TOC, and NH4. A landfill housing such quality of waste would not be expected to have achieved final storage quality by the end of its aftercare life. The joint disposal of this waste fraction and the substantially degraded excavated waste may contribute to shortening this timeline. This paper reports the landfill mining operation, an assessment of the emissions from the landfill simulation reactors and the implications for the expected landfill behaviour

1. INTRODUCTION

Sustainable landfills play the fundamental role of closing the loop of the materials which cannot be further reintroduced in the circular economy, by giving them back to the Earth (Cossu, 2016) in a controlled, stable, non-contaminating form. Paradoxically, the Not-In-My-Backyard (NIMBY) syndrome is still widespread within communities as landfills are seen to occupy valuable land, making it difficult for policy and decision makers to assign spaces for construction of new landfills. Moreover, finding suitable land that meets regulatory requirements for landfill use can be a significant challenge. On a more positive perspective, the solution to this problem could come from exploiting old landfill contaminated sites in need of remediation. Of the estimated 500,000 old landfills in Europe, approximately 10% meet the EU Landfill Directive requirements and are considered sanitary landfills (López et al., 2018). The landfill mining (LFM) of old landfill sites is often seen as an opportunity both for environmental protection from ongoing or potential contamination and for resource recovery, (Fadel et al., 2013; Jones et al., 2013; Quaghebeur et al., 2013). While material recovery from waste may not always be feasible due to the unrecoverable state of the excavated waste or the cost of recovery, recovery of soil, clay and airspace may almost always be achieved in a LFM project.

Krook et al., (2012) defined LFM as a process for extracting materials or other solid natural resources from waste previously disposed of in the ground. Indeed, LFM was initially conceived for material recovery as is the case of the very first case of LFM reported in scientific literature (Savage et al., 1993). However, the motivations for LFM evolved to include environmental protection and extension of landfill life. For this reason, landfills without constructed barriers, operated before the 1982 Resource Conservation and Recovery Act (issued by the Italian Environmental Protection Agency) can be considered potential sources of contamination and therefore must be remediated (Back et al., 2000).

Many recent reports of landfill mining in the literature are dedicated to evaluating the feasibility of enhanced landfill mining (ELFM) which is landfill mining for resource recovery either by waste-to-material or waste-to-energy (Mankhair et al., 2024; Mankhair & Chandel, 2024; Phyu et al., 2024; Saravanan & Dhinagaran, 2023). The feasibility of resource and energy recovery from landfilled waste is highly dependent on the waste quality, which in turn is affected by the habits of the population, effectiveness of waste segregation, the soil cover layer, the climatic conditions (López et al., 2018). Seemingly successful reports of ELFM are often in fact feasibility studies and they are related to

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landfills with high metal and combustible waste fractions. Such accounts are aimed at reporting physical characterization of the mined waste, grain size composition with relation to age of waste, determination of calorific value of combustible waste fractions, optimization of separation techniques for resource recovery, characterization of plastic waste for utilization as refuse derived fuel (Mankhair et al., 2024; Parida et al., 2024; Phyu et al., 2024; Saravanan & Dhinagaran, 2023; Tao et al., 2024). The LFM report of the Mont-Saint-Guibert landfill in Belgium for example focused on the recovery of material and energy from the fine fraction, defined as soil-like material obtained from mechanical processing that has a particle size range up to 4.5 mm (Parrodi, López, et al., 2019; Parrodi, Raulf, et al., 2019; Vollprecht et al., 2020). The Belgian landfill was used for the disposal of MSW, non-hazardous industrial waste and construction and demolition waste which explains the high exploitability of the fine fraction of waste. They however conclude like several other studies, that the implicated capital and operating expenditures continue to outweigh the revenues obtained by the valorization of recoverable fractions. In Italy, the high velocity railway line currently connecting Milan to Bologna in Italy, was designed to cross a landfill. Raga et al., (2015) report the full-scale LFM project which was funded within the context of another construction project and involving the excavation of a trench 400 m long and 80 m wide to remove approximately 200,000 tons of waste.

Landfills dedicated solely or primarily to the disposal of MSW have a low economic viability for ELFM which breeds the reluctance to carry out landfill mining projects. LFM with subsequent volumetric expansion provides a synergistic approach to overcoming the financial hurdles related to the execution of LFM projects. Most old landfills are simply pits which were filled with waste until ground level and then covered with soil. LFM provides an opportunity to construct sustainable landfills with state-of-the-art technology. These new landfills constructed in the space previously occupied by old landfills exploit the pit volume and go up to and beyond 20m above ground level. This increase in landfill volume allows the supplementary disposal of residual waste whose gate fees provide funding for the LFM. Moreover, this practice is a solution to the unavailability of land for new landfills and is applicable in densely populated areas across Europe and other parts of the world.

The case study presented in this report is that of the Villadose landfill in the municipality of Rovigo, Italy where LFM in conjunction with other containment remediation strategies have been underway for the past 22 years. It is a LFM project aimed at remediation and construction of new sectors for disposal of fresh residual waste. According to the 2023 balance sheet records, the gross revenue amounts to approximately € 49.2 million and the total costs, € 49.1 million resulting in a profit of about €100,000. More specifically, the revenue from management of residual waste amounts to approximately € 7.8 million, while the waste disposal and treatment costs € 4.4 million. The state of advancement of the project in terms of remediation effectiveness, recovered material and landfill service life extension is reported. Meanwhile, with regards to the management of the newly constructed landfill sectors, an assessment is made based on a laboratory bioreactor experiment in which the landfilled waste fractions are characterised and emissions of the different waste fractions are evaluated.

2. MATERIAL AND METHODS

2.1 Site Description and History

2.1.1 Site Description

The landfill under study is located in an open countryside, approximately 1 km from the town center of Villadose, in the municipality of Rovigo, (Veneto Region, Italy). The four landfill sectors: Taglietto 0, Taglietto 1, Taglietto 2 and Taglietto 3, (T0, T1, T2 and T3 respectively), were constructed and operated between 1980 and 1996 for the disposal of municipal solid waste (MSW) and residues from recycling activities classified as non-hazardous special waste. The T0 landfill spans for approximately 5.4 hectares. It is generally bordered by agricultural land, except on the northeast side where it shares a boundary with the T1 landfill, which spans for about 5 hectares. T1 is divided into six major cells – Cells 1,2,3,4,5 and Pipetta which is a colloquial termed coined for the shape of this sector. 150 meters northwest from the northern end of T1, are the two more recent landfills, T2 and T3, as well as the storage area for construction materials and the impermeabilized storage area for excavated waste. A site map is visible in Figure 1 although T2 and T3 are not visible in the image as they are located a few hundred metres from T0 and T1. The entire area is intersected by canals and ditches for water drainage, some of which are of considerable size.

Cultivation of T0 began in the early 1980s and was soon exhausted. In 1982, the disposal area was extended by the cultivation of T1. The year of closure is uncertain, but it is likely around 1985 when the landfill was described as "practically exhausted" in a document. T1 like T0 was covered with a layer of clayey soil of about 80 cm and dedicated to agriculture. T2 was constructed as a controlled landfill in 1985. The first 2 ha of the landfill were closed, covered with agricultural soil, and sown with soybeans in 1986. The remaining 4 ha were exploited from 1988 to 1990. From 1991 to 1996, T3 was cultivated and then closed in a similar manner.

2.1.2 History and discovery of contamination

The first concerns about groundwater contamination around the Villadose landfill arose in 1997, during a routine check of the existing monitoring wells. Some anomalies were found in the concentrations of some parameters. Especially problematic were the amounts of Boron, Arsenic and Chlorides, suggesting an ongoing contamination. Further analysis and investigation led the authorities to consider the T0 and T1 landfills as possible sources of contamination and hence prescribe LFM as remedial action.

Continuous groundwater monitoring has been ongoing from 2004 when management of the landfill changed hands from DANECO to Ecogest.srl – now Ecoambiente since 2012. The occurrence of contamination corresponds with the period when the landfill was established under

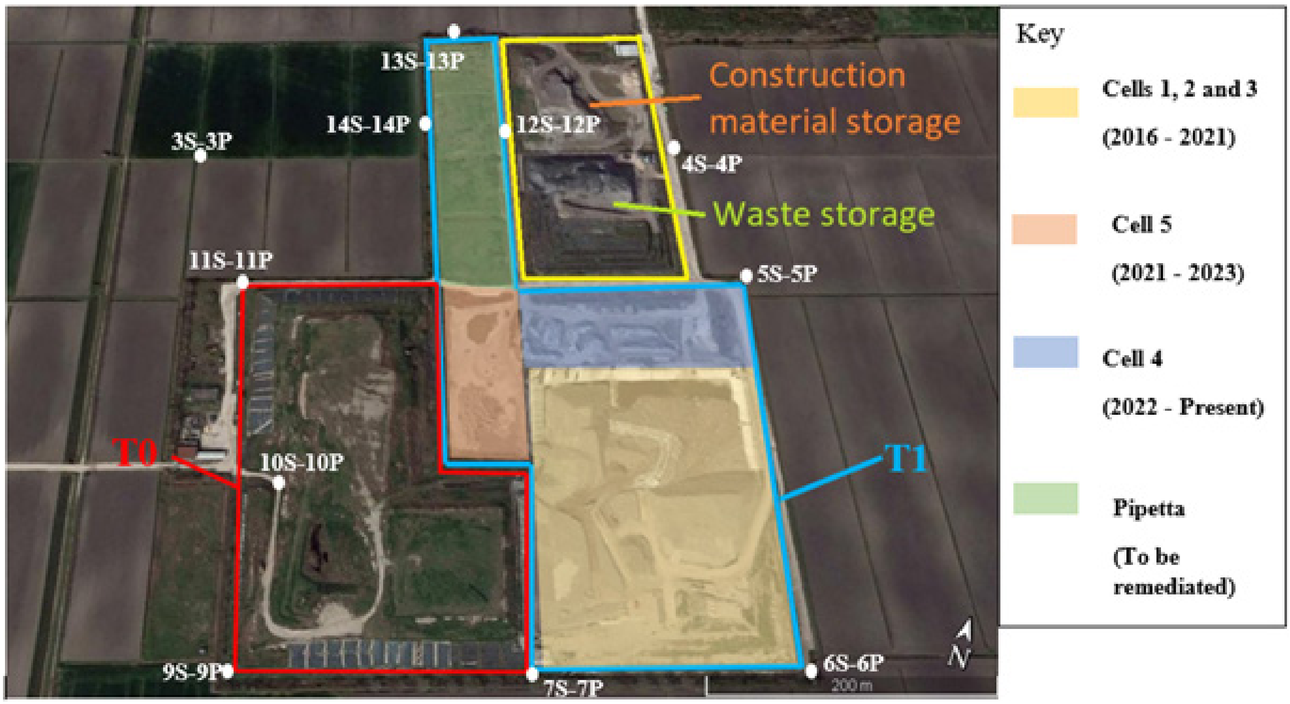

FIGURE 1: Map of Villadose landfill showing Taglietto 0 (T0), Taglietto 1 (T1) and its landfill cells, the temporary waste storage area the storage area for construction materials and the locations of the pairs of piezometers. T2 and T3 are not visible as they are located a few hundred metres from T0 and T1.

less stringent legislation for environmental protection. There are 11 pairs of groundwater monitoring wells (see Figure 1) that reach into the shallow and the deep aquifer, labelled; 3s-3p, 4s-4p, 5s-5p, 6s-6p, 7s-7p, 9s-9p, 10s-10p, 11s-11p 12s-12p, 13s-13p and 14s-14p (where s - shallow and p - deep). The stratigraphy of the area where the Villadose landfill is located is such that:

- 0 m to -2 m: Sandy loams (widely used for agricultural activities)
- 2 m to -6 m: Clay and silty clay
- 6 m to -8 m: Sand and silty sand (shallow aquifer)
- 8 m to -10.5 m: Compacted silty clay (locally known as the caranto layer)
- 10.5 m to -20 m: Sand and silty sand (deep aquifer)

The compact clay of the caranto layer was previously considered sufficient for the protection of the deep aquifer. However, geoelectrical surveys revealed the presence of a permeable discontinuity in this layer and microfractures that promote ionic exchange between the shallow aquifer (initially contaminated with leachate) and the deep aquifer.

Additionally, the aquifer has low hydraulic gradients and is subject to flow reversals at certain times, resulting in stagnation. However, the movement of groundwater is generally considered to be South/South-East. Indeed, groundwater parameters from the "upstream" piezometers 3s,3p, compared to the rest of the piezometers indicate that the landfill is the likely source of aquifer contamination.

T2 and T3 landfills, younger than the other two, were considered not dangerous, as their construction had been regulated by more restrictive legislation.

2.1.3 Preliminary remediation measures

In 2002 the Province of Rovigo approved the remediation project of the area. The remediation consisted in the LFM of the T0 and T1 areas. However, the landfill site's proximity to agricultural land necessitated a more rapid and immediate intervention. As a preliminary remediation measure, an embedded bentonite clay retention wall, 50 cm wide and 12.5 m deep, (and therefore past the caranto layer) was constructed around the perimeter of T0 and T1 to isolate them from the surrounding aquifers.

Results of geotechnical studies showed the need to contain the infiltration of leachate into the excavation area from the adjacent portions of the landfill and of groundwater from the bottom. For this reason, steel diaphragm walls were constructed within the areas of the T1 landfill. The diaphragms installed using the "vibrojet" technique to a depth of 12.5m, divide T1 landfill into nine landfill cells namely: Cell 1A, Cell 2A, Cell 1/2B, Cell 3A, Cell 3B, Cell 4A, Cell 4B, Cell 5 and "Pipetta".

2.2 Landfill mining operation

LFM of T0 began in 2004 with the excavation of waste deposited in the 1970's. A controlled landfill was constructed in compliance with Italian Legislative Decree No. 36/2003 on waste landfilling. The new landfill was used for the disposal of excavated waste as well as of residual waste after on-site mechanical biological treatment (MBT). The supplementary disposal of residual waste provides funding for the LFM and results in thicker landfill cells.

T0 was subjected to a temporary capping intervention in 2013 after closure. The elevation levels of the landfill were reshaped to regulate the infiltration of meteoric water. T0 is equipped with biogas wells connected to a flare which regularly extracts and burns the biogas generated. Leachate is collected and treated offsite. Geoelectric, geophysical, and geotechnical analyses were carried out to determine the necessary technical characteristics for the realisation of the final stage of remediation which is the capping which is underway at the time this paper is being written.

LFM operations on T1 commenced in 2015 and are ongoing at the time of writing of this paper. Cells 1, 2 and 3 were excavated, constructed and operated between 2016 and 2021; Cell 5 between 2021 and 2023; Cell 4 is under construction at the time of writing of this paper and; Pipetta is still to undergo remediation. Results of geotechnical investigations revealed waste buried at varying depths between -3.5 m and -4.0 m. Excavation was performed to a depth of -4.5 m in some cells and -5 m in others to ensure complete removal of waste and potentially contaminated soil while maintaining a safe distance from the aquifer. Leachate generated during excavation is pumped out and exported for treatment offsite.

As is the case for many old landfills, material recovery is not performed at this site because it is not economically feasible. However, the topsoil and bottom clay are recovered. For each cell, prior to the excavation of the waste, the temporary capping soil is removed. This soil is classified as uncontaminated due to its position above the waste and is stored for reuse as engineering material at the landfill. After removal of the waste, the bottom clay is removed until the design excavation depth is reached. This clay is considered waste until chemical analysis prove that there are no exceedances of threshold concentration values. The reclaimed soil classified as CER 170504 in the European waste catalogue) is stored in numbered heaps of approximately 1,000 m^3 each. Each heap is sampled for subsequent chemical analyses, the results of which, for the most part, have shown compliance with the limits set in Table 1, Column A, of Annex 5, Part Four of Legislative Decree 152/2006 and subsequent amendments and additions, as communicated by Ecoambiente S.r.l. to the Province of Rovigo and ARPAV Rovigo. The soils are then transferred to the support area for their use as engineering materials in addition to temporary capping soil.

2.3 Waste logistics, sampling and characterisation

The logistics of the waste are organised such that excavated waste and residual waste pretreated at the MBT plant are immediately disposed of in new landfill sectors. At the MBT plant, the waste is shredded and then sieved in a trommel screen with 100 mm diameter openings, which separates the waste into an oversieve light fraction (particle size > 100 mm) and an undersieve fine fraction (particle size < 100 mm). The light fraction is sent directly to the landfill. The undersieve is biostabilised under aerobic conditions in a procedure similar to composting for approximately four weeks. The resulting material is soil-like with fragments of undecomposed waste and is used as daily cover at the landfill. Based on records of landfilled waste, new landfill sectors typically contain the light fraction of residual MSW, excavated waste, and the biostabilised fraction in the proportions 70%:20%:10% respectively. The two fractions of MBT waste are displayed in Figure 2b and 2c.

Samples of excavated waste (Figure 2a) were collected from two different landfill sectors and at varying depths using an excavator. After removing the topsoil layer, roughly 200 kg waste was placed on a geotextile onsite and homogenised for sampling using the quartering method, then about 60 kg were transported to the lab. Once at the lab it was and characterised by means of fractional composition and grain size composition analysis. The waste was shredded to a size £ 6cm, then quartered further to obtain the samples for the reactors. The sample analysed is assumed to be a representative composition of the old waste. The waste was classified according to particle size (>100 mm, >50 mm, >20 mm and <20 mm) and according to the following composition: plastic, glass, metal, textile, cardboard and wood, stones, and others.

Solid waste analysis were carried out to establish the initial waste quality. Analyses of Total Solids,Volatile Solids and Moisture Content (standard IRSA-CNR 29/2003, vol 1, n. 2090a mod), Total Organic Carbon (with Shimadzu total organic carbon analyser device), and Respiration Index after 4 days (RI_4 with Sapromat respirometer) were performed on the <50 mm fraction of the excavated waste (LFM) and on the following categories of residual waste: Stabilised fine fraction; Paper and Cardboard, Plastic, Textile and Others.

FIGURE 2: a - Excavated waste; b - Light fraction of MBT waste; c - Stabilised fine fraction of MBT waste.

2.4 Lab-scale bioreactor experiment

2.4.1 Experiment setup

Four plexiglass reactors, each 106 cm high with a diameter of 24 cm (Raga & Cossu, 2013), were set up to evaluate and compare the degradation of the different waste fractions. Each reactor was equipped with the following systems: an aeration system composed of a vertical perforated PVC tube running down the centre of the reactor with an inlet on the reactor lid which connects to a Prodac Air Professional pump 360; a leachate recirculation and collection system composed of a system of pipes, taps and a peristaltic pump (Heidolph Peristaltic Pump Drive 5001); a temperature regulating system comprised of a heating jacket used to maintain the internal temperature at 35°C±2° and Thermo Systems TS100 temperature probes installed inside the reactor; a biogas monitoring system comprised a gas outlet valve fitted on the lid of the reactor which then connects to an LFG 20 analyser. The LFG 20 is a portable analyser which permits simple and precise measurements of CH_4, CO_2 and O_2 in a sample drawn by an internal pump at 200 mL/min. Figure 3 shows the conceptual diagram and an example of the reactors used.

The reactors were filled with the following waste fractions:

- Reactor 1 - OW: Old Waste excavated from old landfill sectors;
- Reactor 2 - NWL: New Waste Light fraction which is the oversieve from the MBT plant;
- Reactor 3 - NWS: New Waste Stabilised fraction which is the aerobically stabilized undersieve from the MBT plant.
- Reactor 4 - MW: Mixed Waste which is a mixture of all the fractions.

The ratio of each waste fraction in the MW reactor was NWL 70%: OW 20%: NWS 10% which is the estimated ratio of waste landfilled in the new landfill sectors. The OW and NWL were sorted to remove stones, electronic parts, glass bottles and large metallic fractions. Then they were subjected to size reduction (4 – 6 cm) for homogeneity and to downsize real landfill conditions to laboratory scale conditions. The NWS, having a homogeneous particle size ≤2mm, remained unaltered. A 10-cm thick gravel layer was placed at the bottom of each column as a drainage layer.

2.4.2 Reactor management

In March 2023, the reactors were filled with the waste samples. The reactors were filled with water by connecting a funnel to the water addition/leachate recirculation inlet until fill capacity of the waste, then with an additional 5 L of water to allow recirculation. The system was kept under anaerobic conditions and recirculation was performed once a week with the help of the Heidolph Peristaltic Pump Drive 5001 which was set to rotate at 60rpm for 20 min allowing 5l of water to be recirculated. Leachate samples were collected and analysed for pH, TOC and NH_4^+ every month. TOC was measured using the Shimadzu TOC analyser which gives results as the mean of a triplicate analysis while NH_4^+ was measured by the UV-Vis spectrometric

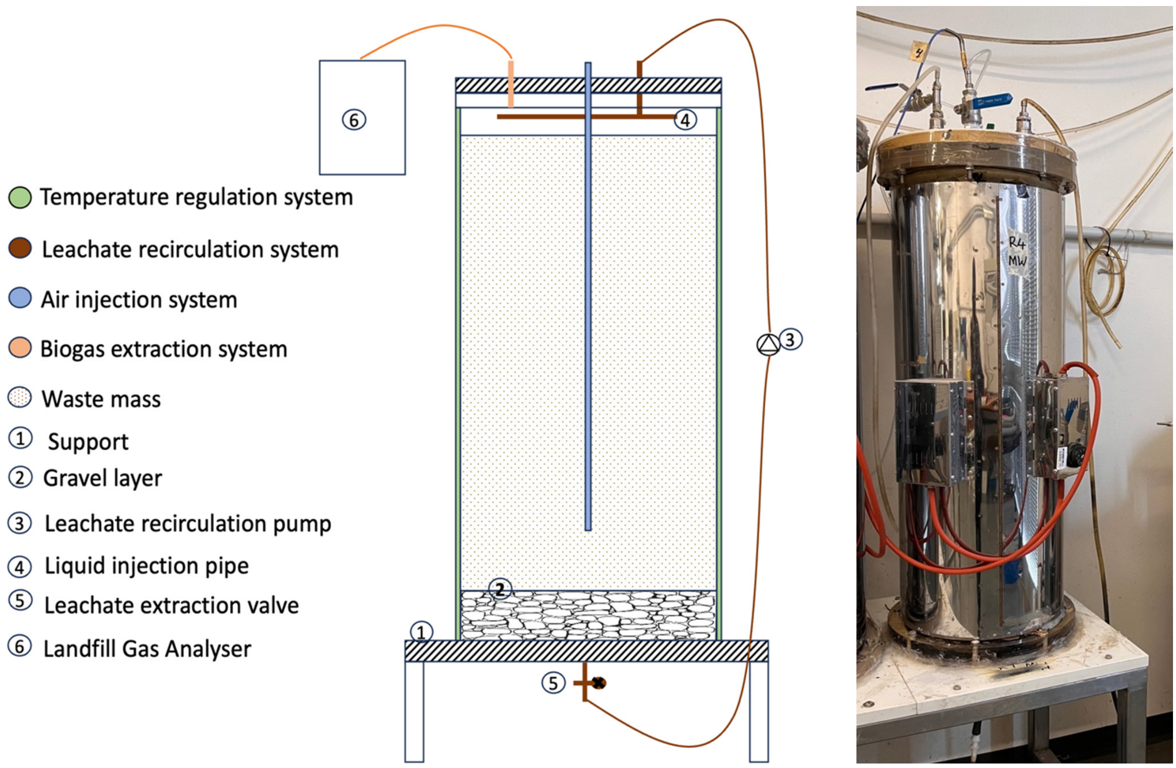

FIGURE 3: Left - Schematic representation of experiment setup; Right - Image of reactor used in experiment.*The air injection system was closed off to maintain anaerobic conditions.

method which gives results as the mean of a quadruplet analysis. The experiment lasted for 281 days.

3. RESULTS

3.1 Waste characterisation results

The material composition of the excavated waste reported as percentages by wet weight with a standard deviation of ±5% is outlined in Table 1. The material with particle size <20 mm termed undersieve was mostly composed of soil-like material resulting from degradation of organic fractions as well as soil which was used as daily cover. This fraction had a percentage of 28.5%, which is much lower percentages previously reported in other studies, where soil-like fractions range from 40% to 80% (Hogland et al., 2004; López et al., 2018; Quaghebeur et al., 2013; Somani et al., 2018). The water content of the waste likely resulted in the compaction of soil-like particles into thick clayey fragments which merged with the waste to form indistinguishable fractions, classified as others. The excavated waste was not dried as done in studies dedicated to physical characterisation of waste, reason for the low percentage of fines perceived. It is closely followed by plastic with 22.1% and then others or undistinguishable fractions with 21.14%.

Results of the analysis on the excavated waste fractions show that they are in a state of advanced degradation, being over 40 years old. RI_4 value of 2.61 mgO_2/gTS, is only slightly higher than the final storage quality values suggested in the Guidelines for sustainable landfills, issued by the Lombardy region (Cossu et al., 2020), equal to 2 mgO_2/gTS. Average TOC values for excavated waste are lower than those for MBT waste while the plastic and textile fractions of MBT waste contained the highest residual organic carbon.

3.2 Laboratory results

3.2.1 Biogas quality

Biogas was only monitored qualitatively and results are expressed as percentages with a ±1% error margin and are reported in Figure 4. The quantification of biogas was impeded because the reactors were not perfectly airtight allowing biogas to leak out and some measure of oxygen to seep in.

The biogas generated by OW started off at 11% in terms of CH_4 but immediately dropped to approximately 0.2% and did not exceed 0.9% for the rest of the experiment. The CO_2 was similarly low, attaining a maximum of 14.1% but generally remaining in the range 6.5%-12.5%. This low reactivity is concurrent with the assessment that old anaerobic landfills are not expected to pose a long-term problem in terms of biogas emissions as landfills are expected to have a biogas exploitation potential for a duration of approximately 30 years (Rada et al., 2015).

NWL was principally composed of slowly degrading material such as of plastics and textiles as was reflected in the CH_4 which was generally at varying degrees below 3% and with an average CO_2 14.5%. Correspondingly, the pH remained in the acidic range 5.5-6.1, which is suboptimal for methane generation - in fact, from day 114, onwards, the pH fell below 6 and remained as such.

The highest CH_4 percentage for NWS (51.3%) was recorded on day 67 with a corresponding 31.5% CO_2. However, between day 74 and day 88, the CH_4 was in the order of 3%-12%. After this, the percentage progressively dropped below 1% until the end of the experiment. A similar decline was observed in the CO_2. From day 185 till the end, the CO_2 recorded was between 4% and 10%, meanwhile prior to that the average CO_2 recorded was approximately 13% despite the optimal conditions for biogas production. This indicated removal of the residual emission potential by further stabilisation of the previously aerobically stabilized biodegradable waste fraction.

Only mixed waste had biogas with a significant CH_4 and CO_2 percentage, starting off at 80% CO_2 and 6.5% CH_4 on day 24, after which the composition stabilised to an average of 7% CH_4 and 17% CO_2 between day 69 and day 85. Steadily, the composition increased to the maximum emissions of 44% CH_4 and 40% CO_2 for 100 days before progressively to 20% CH_4 and 25% CO_2 around day 238. The decline in biogas composition was accompanied by a similar decline in organic carbon release in the leachate phase as the biological stability was improved over time. From the graph, the NWL and MW have a similar biogas composition

TABLE 1: Composition of excavated waste and particle size distribution.

	Excavated waste composition (kg)								
Sieve diameter (mm)	**> 100**	**%**	**> 50**	**%**	**> 20**	**%**	**< 20**	**Weight (kg)**	**%w/w**
Plastic	6.80	52	3.18	39.2	1.68	10.2	-	11.60	22.1
Glass	-	-	1.11	13.68	5.70	34.67	-	6.81	12.95
Metal	0.05	0.34	1.99	24.53	0.20	1.20	-	2.24	4.26
Textile	0.36	2.75	0.32	3.94	0.22	1.30	-	0.90	1.71
Cardboard & Wood	1.20	9.18	1.06	13.07	0.45	2.73	-	2.71	5.16
Stones	2.20	16.84	-	-	0.00	-	-	2.20	4.19
Others	2.46	18.79	0.45	5.54	8.19	49.81	-	11.1	21.14
Undersieve (<20mm)	-	-	-	-	-	-	14.95	14.95	28.5
Total	13.06	100	8.11	100	16.44	100	14.95	52.50	100.0

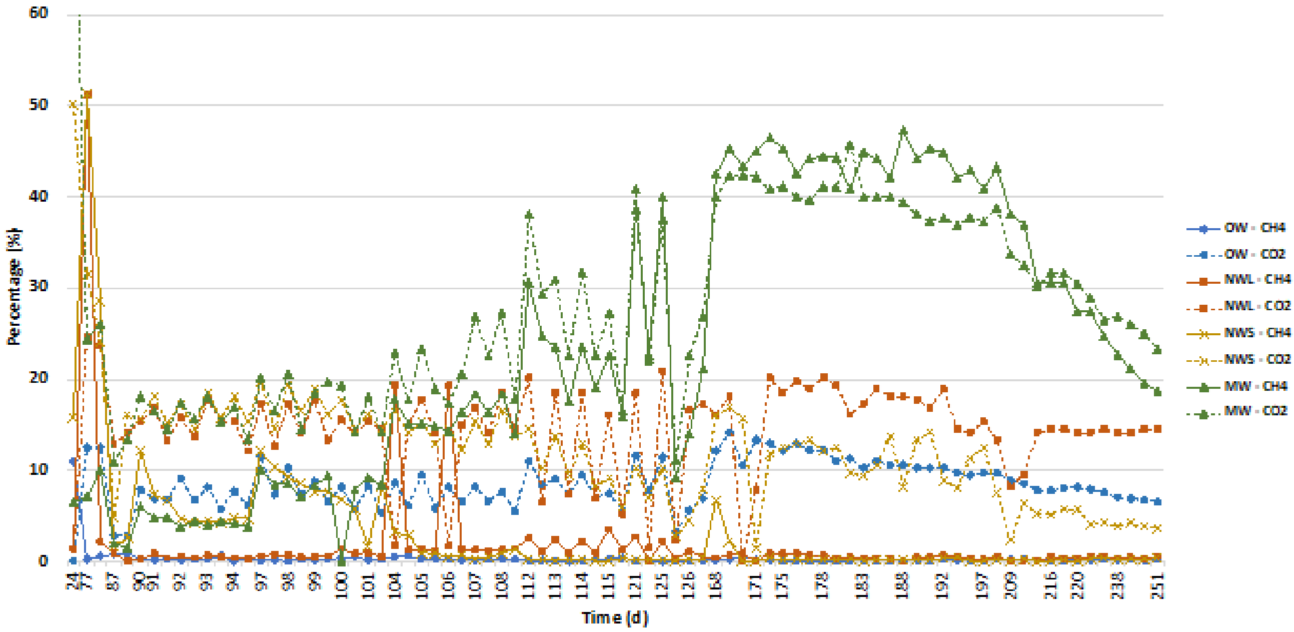

FIGURE 4: Variation in biogas composition. Where OW – Old Waste, NWL- New Waste Light, NWS- New Waste Stabilised and MW – Mixed waste.

trend up until day 110 when MW begins to release gas with more than twice the methane content while NWL proceeds on the same stable slope.

3.2.2 Leachate quality

The evolution of the leachate pH, TOC and NH_4^+ are reported in Figure 5 (a, b and c respectively). The readings have a standard deviation of ± 0.01, ± 0.006 mg/L and ± 0.02 mg/L respectively. The OW leachate started out at a slightly acidic pH of 6.25, progressed to a range between neutral and moderately alkaline (7.05-7.3) by day 58 and remained as such for the entirety of the experiment. Consistently, the TOC values of the OW leachate were virtually stable throughout the experiment, indicating that the initial reactivity of the OW was quite low and the waste fraction was near stabilisation at the study inception as similarly reported in studies involving excavated waste (Hrad et al., 2013; Warith & Takata, 2004). The NWS fraction predictably behaved in a manner similar to the old waste in terms of pH and TOC as it had been aerobically stabilized prior to the start of the experiment. The NWS nevertheless proved to be more reactive with a TOC going from 3400 mg/L to 1400 mg/L. On the other hand, the NWL fraction proved to be the most reactive waste fraction as its leachate was the most acidic with a minimum pH of 5.51. Likewise, the TOC of the NWL leachate increased from around 2000 mg/L on day 10 to around 10000 mg/L on day 58. The TOC of the MW leachate followed the same trend but progressively dropped to approximately 900 mg/L by the end of the experiment while that of the NWL only dropped to around 6000 mg/L. The reactivity of the MW undoubtedly is a result of the of the NWL contribution (of 70% by wet weight), implying that the enhanced degradation of this waste fraction results from the action of the OW or the NWS or both.

4. DISCUSSION

From the biogas and leachate quality results we can surmise that the OW which was buried for over 40 years, had undergone the peak degradation which is expected to occur in the early stages of the landfill. The leachate quality is characteristic of old landfill leachate, showing more stabilisation in terms of pH than the leachate from a 20-year-old landfill in Ontario, Canada (Warith & Takata, 2004), but nevertheless having similarly insignificant ammonia concentrations. The carbon released via the leachate phase amounted to 0.35 g C which is 0.08 g C/kgDM. Literature values for similar experiments range from insignificant carbon release via leachate (Brandstätter et al., 2015) to 0.7 g C/kgDM (Wu et al., 2016).

The highest NWS CH_4 concentrations were detected within the first 67 days after which concentrations tailed-off to below 1% by day 153 as the MBT likely allowed for a reduction of the non-methanogenic phase and of the landfill gas generation potential (Gioannis et al., 2009). The TOC concentrations decreased from 3400 mg/L to 1400 mg/L, releasing 5.6 g of organic carbon equivalent to 0.08 g C/kgDM like the OW, reflecting the effects of the biological stabilisation. Correspondingly, the NWL fraction unexpectedly contained the highest pollution potential although it was mostly comprised of plastics and textiles which are known to have a slow degradability, not often evident within the timeframe of a laboratory experiment (Elagroudy et al., 2009; Xochitl et al., 2021). NWL and NWS come from the MBT plant, which treats waste belonging to category CER 19.12.12 of the European waste catalogue, described as “other wastes (including mixed materials) from mechanical treatment of non-hazardous waste”. Warith & Takata, (2004) also studied the anaerobic degradation of fresh MSW as discarded in residential

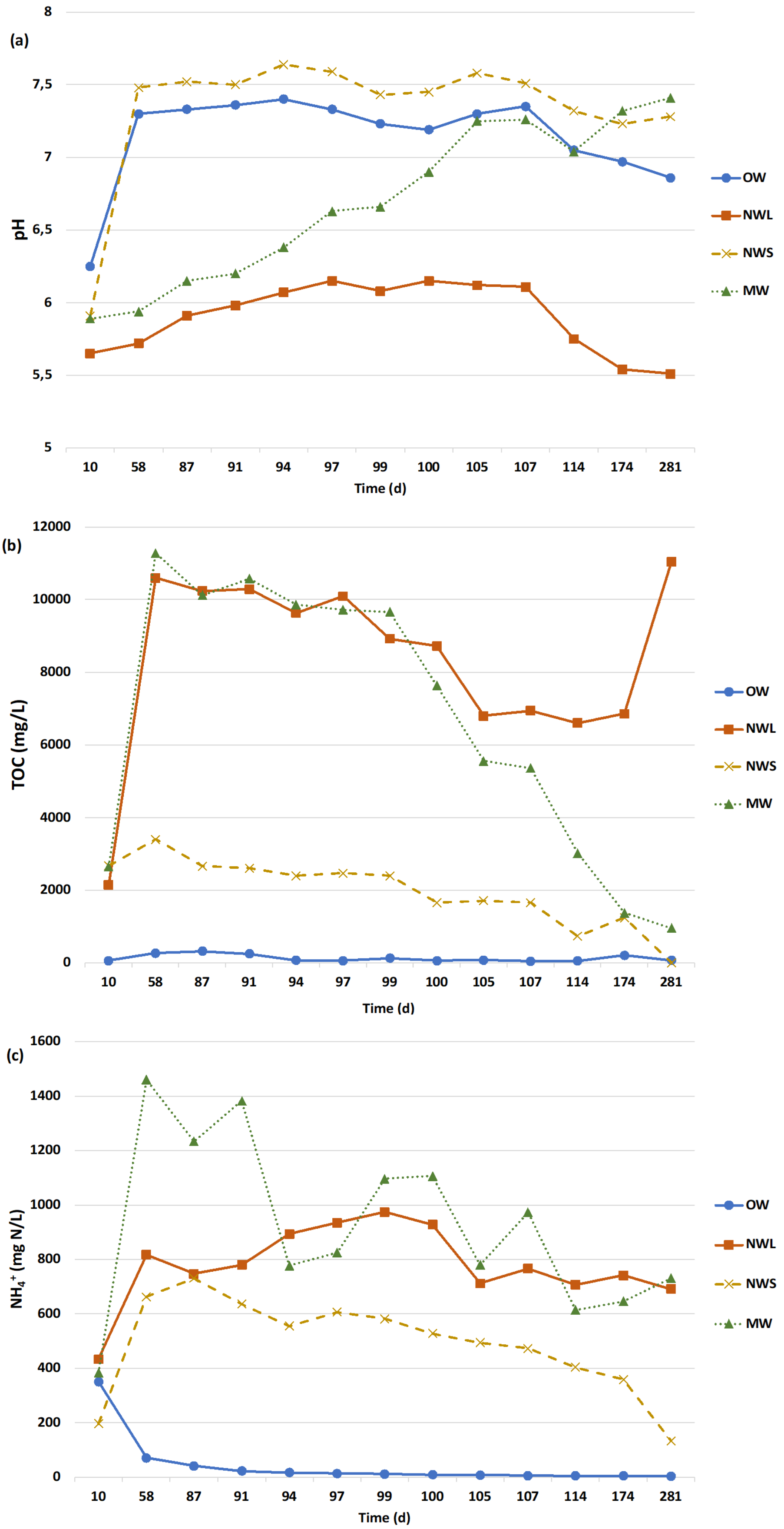

FIGURE 5: Evolution of pH (a); Total Organic Carbon (b); and Ammonia Nitrogen (c) in leachate. Where OW – Old Waste, NWL- New Waste Light, NWS- New Waste Stabilised and MW – Mixed waste.

Toronto and in contrast to the NWL in this study, they obtained a leachate with a neutral pH by the end of the experiment, as well as stable and lower ammonia concentrations within the range of 500 mg/L. In a study by Siddiqui et al. (2013), the biodegradation of the dry fraction of MBT waste with a composition similar to the NWL in this study was evaluated. The TOC concentrations of the leachate towards the end of their study, (about 650 mg/L), was more than 10 times lower than the NWL leachate TOC (> 6000 mg/L), although this could be attributed to the fact that they added anaerobically digested sewage sludge to ensure the presence of viable methanogenic bacteria and to accelerate the initiation of methanogenesis. The acidic pH and the biogas composition in the NWL reactors (av. CH_4 1.2%, av.CO_2 14.5%) are an indication that methanogenic conditions were probably not achieved in this reactor. A plausible reason is that plastics and textiles being the principal carbon sources did not provide enough organic matter to support methanogenic bacteria. Oxygen seepage could have also contributed to this phenomenon as regrettably, the reactors were not perfectly airtight throughout the experiment. Regardless, the TOC release from the NWL via the leachate amounted to around 20 g C (4.8 g C/kgDM).

The MW fraction which was mostly composed of NWL material showed a faster stabilisation than the NWL, probably due to the action of the microbial consortium supplied by the OW: indeed, only 15 g C were released through the leachate (2.8 g C/kgDM), 1.7times less than in NWL although the MW released more carbon in the gas phase as seen in Figure 4. One previous research exploited the wide microbial spectrum contained in old waste for the treatment of high strength leachate by passing leachate through an "aged refuse biofilter" (Youcai et al., 2002). In a similar laboratory scale research, leachate from an anaerobically digested mature landfill site was recirculated into a young landfill site to accelerate waste stabilisation (Erses & Onay, (2003). In this study on the other hand, the microorganisms contained in OW which have a strong decomposition capability for refractory organic matter (Youcai et al., 2002), are exploited for the degradation of fresh waste in the MW reactor. The practice at the Villadose landfill of executing landfill mining with the joint disposal of old waste with new waste in new landfill sectors may therefore contribute to accelerating waste stabilisation.

The newly constructed landfill sectors are managed as traditional landfills which pose a challenge in terms of removal of long-lasting recalcitrant organics and ammonia which does not have a degradation pathway in anaerobic systems (Grossule et al., 2018). This management strategy may therefore be an overlooked opportunity to improve leachate quality and shorten the aftercare phase of the landfill by managing them as aerobic or semi-aerobic bioreactor landfills. Aeration has been known to lower the leachate carbon and nitrogen values, improving the leachate quality resulting in subsequent financial savings for secondary treatment. The positive effects of aeration on waste stabilisation have been shown in several studies (Ahmadifar et al., 2016; Huo et al., 2008; Lavagnolo et al., 2018; Morello et al., 2017; Nag et al., 2016) and will be investigated in a subsequent experiment designed by the authors, to determine the optimal and minimal aeration rate necessary for the enhanced stabilisation of mixed waste.

5. SUMMARY AND CONCLUSIONS

This paper reports the description of a landfill remediation case study in Rovigo, Italy. Essentially, the supplementary disposal of residual waste provides funding for the landfill mining and the potential for volumetric expansion provides an opportunity to construct sustainable landfills with state-of-the-art technology. A landfill simulation experiment was conducted on the disposed waste fractions to analyse the effects of different waste fractions on emissions. Three reactors were filled with distinct waste streams from landfill sectors: Old Waste (excavated from the old landfill), New Waste Light (oversieve fraction from the mechanical-biological treatment plant), and New Waste Stabilised (undersieve fraction aerobically stabilized at the same plant). A fourth reactor, simulating real landfill conditions, was filled with Mixed Waste, containing the three waste fractions in proportions similar to those at the Villadose landfill.

According to the results of the anaerobic lab-scale bioreactor tests on the disposed waste fractions, the leachate quality is characteristic of municipal solid waste landfill leachate with some disparities in the behaviour of the New Waste Light. The Old Waste shows an advanced state of degradation, the New Waste Stabilised is similarly stabilised and these two fractions appear to have an enhancing effect on the degradation of the New Waste Light. The practice of re-landfilling old waste with fresh residual waste therefore accelerates waste stabilisation.

A limitation in this study was the inability to quantify the carbon emitted via the gas phase possibly due to gas losses in the reactors or minor air infiltration preventing the establishment of perfectly anaerobic conditions. The absence of Nitrates and Nitrites was however an indication of predominantly anaerobic conditions. The findings in this research are preliminary. More experiments combining old waste from different MSW landfills and fresh residual waste need to be carried out to better understand the dynamics of the enhanced degradation and to optimize the kinetics, such as by correlating microbial composition with the synergy. This case study is relevant both for old landfills with no viable prospect of resource recovery and for those with a significant recovery potential. Recovery of materials in ELFM creates space which can be used for the re-landfilling of unrecoverable waste in conjunction with fresh residual waste, solving the problem of shortage of land for landfilling. The resulting landfill with enhanced degradation of fresh residual waste may achieve final storage quality in a shorter time than landfills dedicated solely to the disposal of fresh MSW. Aerobic degradation of Mixed Waste within the context of co-disposal of old and fresh waste also has to be investigated and the authors are currently conducting a study to evaluate the extent of this enhancement under aerobic conditions.

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