

Article

Respirometric Index and Biogas Potential of Different Foods and Agricultural Discarded Biomass

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Abstract: The biological stability of biomass is an important parameter for treatment plant design, process control or compost use. Measuring the biological reactivity of waste with the help of indicators such as respirometric indexes (RI) becomes an important tool to prevent the significant environmental impact of biodegradable wastes in accordance with European legislation. The aim of this paper is to show the importance of the RI technique as a tool to establish further uses of biomass such as fertilizer or biogas. The respirometric process length for different types of biomass (grape marc, apple pomace and olive pomace) was quantified. Higher moisture content seemed to favor the biological activity during the respirometric experiments and shorten the length of the process. The duration of olive pomace respirometry did not exceed 3 days, while the respirometric activity of apple scraps lasted approximately 2 days. The highest RI values were encountered for the apple pomace, $4888 \text{ mgO}_2 \cdot \text{kg}_{\text{VS}}^{-1} \cdot \text{h}^{-1}$. The majority of the discarded biomasses are categorized in the third class of stability materials in the course of degradation. This technique is important to detect the biodegradability of substrates, as well as to gain insight into the quantity and generation rate of biogas produced, information that is important from an engineering management perspective.

Keywords: respirometric index; biomass; anaerobic digestion; biogas; grape marc

1. Introduction

In the European Union's newly joined countries, biodegradable waste represents a significant portion of the total municipal solid waste (MSW). This could be a problem in terms of compliance with the European Council Directive on landfilling of waste [1] (Directive 1999/31/EEC) which requires member states to reduce the amount of biodegradable municipal solid waste (BMSW) in landfills, over a 15-year period, to 35% of the amount produced in 1995. This has led to strategies for segregation of the organic and non-organic waste fractions and BMSW treatment such as volume reduction, reutilization or energy recovery.

Furthermore, higher demand of agricultural products has led to the augmentation of wastes from food and agricultural industries. These agricultural wastes are not yet valorized in developing countries and represent an additional expense to be discarded by producers [2,3].

Although landfills are the most commonly used method for waste disposal [4], other biological treatment strategies can be applied to biodegradable and high moisture content wastes, such as

composting, bio-drying or anaerobic digestion [5]. Compost produced using organic wastes is used for amendment in agricultural soils due to high and stabilized organic matter content [6,7], whereas bio-drying process allows biodegradable waste to be re-used as refuse-derived products [8].

An important parameter in efficient design of treatment plants, process control or compost use is the biological stability of biomass [9]. This indicates the degree to which the biodegradable organic matter decomposes. Therefore, measurement of biological reactivity has become important as it allows the classification of treated and untreated MSW and derived products, prior to their disposal in landfills, on the basis of their potential impact [10].

One of the most commonly used methods for biological stability measurement is the respirometric index (RI), which has seen much interest in the specialized literature. The respirometric technique is an indirect, simple and efficient method of determining the degree to which the biomass organic fraction decomposes, in relation to two important biochemical phenomena: the biological activity and the substrate consumption [11].

The respirometric method is an oxidative exothermic process, operated by aerobic microorganisms which consume oxygen with simultaneous production of water and carbon dioxide [12]. As reported by [11], the respirometric index represents the quantity of oxygen consumed by microorganisms per unit of present volatile solids and over time.

The respirometric tests, based on the oxygen consumption measurement, can be categorized as static or dynamic methods [12,13], with measurements performed in the absence (static) or presence (dynamic) of continuous aeration of the biomass. The static methods performed at constant volume or at constant pressure have the disadvantage of limiting diffusion and dispersion of oxygen in the biomass and therefore slowing down the decomposition of the organic fraction [11]. In dynamic systems, the continuous aeration of the substrate guarantees an optimum oxygen concentration for the biological activity at each moment of time [12,14].

Worldwide, several methods for respiration index determination are used. In Italy and USA, Static Respiration Index is used, in the first case accompanied by the Dynamic Respiration Index—Di.Pro.Ve methods [14]; in the UK—the specific oxygen uptake rate (SOUR) is most commonly used; in Germany and Austria the AT4 index for respiration activity in 4 days is mostly applied [12,14]. According to the literature [15,16] the dynamic method presents several important advantages, such as: presence of continuous airflow during measurement which does not limit the oxygen transfer through the biomass layer; the possibility of working on large amounts of samples and on full-scale particle size; and the possibility of measurement of the airflow rate required to degrade waste under optimal conditions.

The maturity of compost is evaluated on the basis of growth potential and phytotoxicity of the vegetal species, while stability is a concept related simply to the microbial activity, in relation to the presence of degradable substrate. For the Italian dynamic respiration index (DRI) method developed by [10], the biological stability values reported for fresh and mature compost are 1000 and 500 $\text{mgO}_2 \cdot \text{kg}_{\text{VS}}^{-1} \cdot \text{h}^{-1}$, respectively. According to the European legislation framework, the achievement of either a Respiration Activity after four days (AT4) below 10 $\text{mgO}_2 \cdot \text{g}_{\text{DM}}^{-1}$ or a Dynamic Respiration Index below 1000 $\text{mgO}_2 \cdot \text{kg}_{\text{VS}}^{-1} \cdot \text{h}^{-1}$ shall deem that the material is not biodegradable waste [12].

Measuring the biological reactivity of waste with the help of indicators such as respirometric indexes is an important tool to prevent the significant environmental impact of biodegradable wastes, in accordance with the European legislation. The aim of this paper is to establish the biodegradability degree of different substrates and investigate the use of the respirometric index method as a tool for determining further uses of organic wastes. In addition, the biodegradability of the analyzed substrates was correlated with their biogas release potential through anaerobic digestion.

Anaerobic digestion plant operators often have to choose which biomasses to use, depending on the substrate digestibility and economical convenience. In this context, rapid methods for assessing biogas generation potential are needed. Anaerobic biogas potential (ABP) tests are reliable, but their

response time (21 days for the partial biogas production and 100 days for the total biogas production) is very long [9,17,18]. As the availability of organic matrixes on the market varies day by day, rapid evaluations of the ABP are needed. Studies from the literature assumed an indirect and faster method to evaluate the ABP through a respirometric approach [19,20]. The result can be considered satisfactory as a compromise between precision and speed of the assessment.

One other significant use of biogas potential estimation is the assessment of methane as a greenhouse gas and environmental impact of organic waste sent to landfills. In accordance with the European legislation, MSW to be landfilled can be characterized through respirometric tests correlated with biogas emissions monitoring to determine its biological stability.

The present paper also proposes to determine the biogas potential production (ABP) from biodegradable waste using the Dynamic Respirometric Index values [19,20] obtained during the laboratory tests carried out with the AIR-nl method in the engineering laboratories at the University of Trento.

2. Materials and Methods

2.1. Selected Biomass

Six different types of biomass were analyzed in this work, generated by agricultural activities or food industries: four types of grape marc (GM), apple pomace (AP) from apple processing industry and olive pomace (OP). Special attention was given to the wine-making industry wastes, due to the great availability of grapes worldwide and to the large quantities of wastes generated [21,22].

The grape marc used was collected from different wine producers and distilleries in Northern Italy, Trentino alto Adige. One of the products analyzed derived from white (W) grapes after the pressing and wine making process; the second product is represented by grape marc from red (R) grapes generated through the same wine making process. The other two types of grape marc are represented by the remains from the distillation process of white and red grapes. The waste derived from the wine making process was referred to as fresh grape marc (FGM), while the waste obtained from the distillation process was called exhausted grape marc (EGM) [23].

The apple scraps represent a waste product in the apple processing industry for food, fruit juices or ciders production. AP consists of peels, residues from pulp, seeds and petioles. Because of high moisture content (more than 50%), apple scraps are best suited for energy recovery through biological methods, such as aerobic and anaerobic processes.

Olive pomace is a by-product of olive oil extraction process consisting of skins, pulp residues and fragments of pits. Among the main uses of OP are extractions for cosmetics, food products or agricultural land fertilizer. Currently, treatment of olive residues is performed by separating water, hulls and the pulp from the pits [24].

Primary and proximate analysis was performed on all six biomasses. Samples from each of the materials were collected and shredded prior to characterization. The samples were kept in a heated oven at 105 °C for 24 h to determine the biomass moisture content and for 40 min at 800 °C to measure the volatile solid content. Using a Calorimeter C200 the high heating value of the dried samples was determined. The elemental analysis of the products was performed with an Elemental Analyzer EA3000 and the chlorine and mercury content was established for further classifications as derived fuels. The outcome of these experiments is presented in the Results section of this paper.

2.2. Experimental Setup

The respirometric reactor used was built during a Ph.D. thesis at the University of Trento, Italy [9]. The project was based on a typical sealed respirometer for sludge treatment, in which a probe monitors the progressive decrease of oxygen, from a maximum value near saturation to a minimum set value, chosen for preventing limiting conditions. When it reaches its inferior value, a small compressor automatically starts to re-circulate the air within the reactor. In this way, the oxygen variation curve can be translated into a detailed respirometer diagram which is not limited in time.

The respirometer (Figure 1) is made out of a steel reactor hermetically closed (volume 18 L), in which a plastic recipient with perforated bottom is placed. Temperature is measured continuously by a thermocouple (0–50 °C). The reactor is insulated, connected to a thermostat (maintained at 30 °C) and completely enclosed in a thermal container in which all the components of the air re-circulating circuit are housed.

The aeration and analysis system is composed of a double pneumatic circuit: the first circuit for the continuous measurement of oxygen concentration which transports a lower flow rate of air, and the second circuit which allows the aeration of the sample transporting a higher air flow rate (18 L·min⁻¹). In the first circuit a humidifier was placed to avoid the excessive decrease of sample moisture, while in the second circuit a container with silica salts is placed to dehumidify the air passing through the sample. The system is connected via a control unit for data acquisition to a computer that records temperature and oxygen concentration data within the reactor at regular intervals of 1 min.

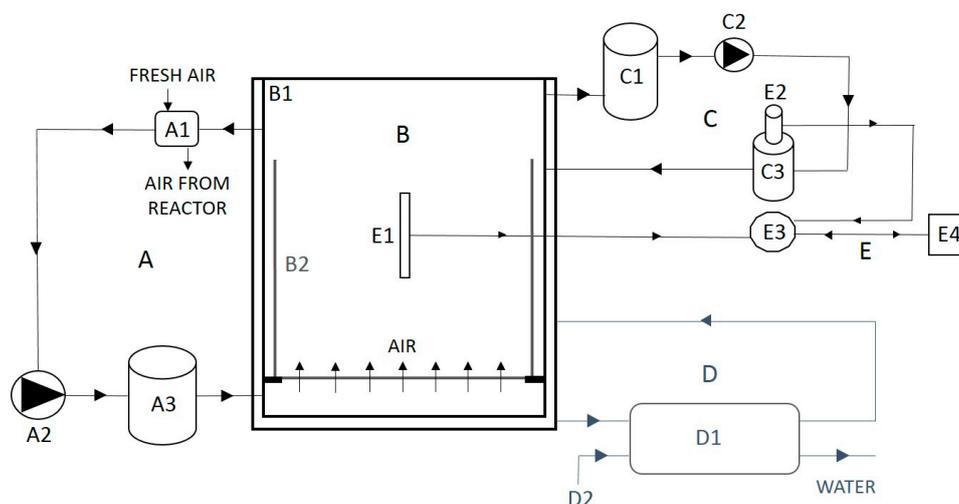


Figure 1. Respirometer AIR-nl 2002 schematic. A: Main pneumatic circuit; A1: Air recirculation electro valve; A2: Pump; A3: Humidifier. B: Reactor; B1: Sealed chamber for temperature control; B2: container with perforated bottom. C: Secondary pneumatic circuit for O₂ measurement; C1: Dehumidifier; C2: Micro pump; C3: Measuring cell. D: Circuit of thermoregulation; D1: Heater; D2: Cooling device. E: Transmission/Data acquisition; E1: Temperature probe; E2: Oxygen probe; E3: Acquisition/control unit; E4: Computer [20].

During the respirometric experiments, the temperature and oxygen volumetric percentage of the system are continuously monitored. The aim of the respirometric test is to measure the respirometric activity referred to as respirometric index (RI), which quantifies the O₂ consumption rate of the decomposing bacteria. The RI refers to the volatile solids (VS) unit present initially in the sample.

Data measured with the O₂ probe represents a volumetric percentage. In order to convert the percentage of O₂ into mgO₂, it was assumed that the air behaves like an ideal gas. Applying the Gay-Lussac law for ideal gases, Equation (1) is obtained:

$$n_{O_2} = \frac{p \times V_{O_2}}{R \times T} = \frac{p \times V \times \%O_2}{R \times T} \text{ [mole]} \quad (1)$$

The process takes place at constant atmospheric pressure. Knowing the number of O₂ moles and O₂ molecular mass, the number of mgO₂ was determined (2):

$$mgO_2 = p \times V \times \frac{\%O_2}{R \times T} \times 32 \times 1000 \quad (2)$$

The average value of decreasing slope is expressed as function of time and represents the value of specific respirometric activity ($\text{mgO}_2 \cdot \text{h}^{-1}$) which is further divided to the volatile solids present in the system, meaning to the kg_{VS} of the sample (3).

$$\text{RI} = \frac{p \times V}{T} \times 32 \times 1000 \times \left(\frac{\% \text{O}_{21}}{T_1} - \frac{\% \text{O}_{22}}{T_2} \right) \times \frac{1}{\text{VS}} \times \frac{1}{\Delta t} \quad (3)$$

where p —pressure [atm] equal to the atmospheric pressure; V —free volume expressed in liters; 32 is the molecular mass of oxygen [$\text{g} \cdot \text{mol}^{-1}$]; vs —is the volatile solids content [kg]; Δt —time [h]; $R = 0.0821 \text{ l} \cdot \text{atm} \cdot \text{mole}^{-1} \cdot \text{K}^{-1}$ —gas constant; 1 and 2 indicate the points where the calculus was performed.

Equation (3) calculates the specific RI ($\text{mgO}_2 \cdot \text{kg}_{\text{VS}}^{-1} \cdot \text{h}^{-1}$). The processing of data acquisition during the respirometric experiments was done with the InNet software version (University of Trento, Trento, Italy, 2002) [20].

Three types of results are obtained after performing the respirometric experiments:

- RI—respirometric index variation in time (hourly) for each type of material;
- RI_{24} —average of instant values of RI, obtained in the most intense 24 h of biological activity;
- RI_{max} —the maximum values registered during the tests.

2.3. Biogas Methodology

The test estimating the partial biogas produced lasts 21 days, while estimating the total biogas generation could last up to 100 days [9,18]. One type of analysis proposed in the literature [19] estimates the biogas potential of a substrate based on its respirometric index. This calculation would shorten significantly the time necessary for the biogas potential test and would decrease the operation costs of an anaerobic digestion plant for 100 days.

The equation that determined the anaerobic biogas potential derived from the value of dynamic respirometric index is [19]:

$$\text{ABP} = (34.4 \pm 2.5) + (0.109 \pm 0.003) \text{DRI} \quad (4)$$

The ABP and DRI are expressed as $\text{Nl} \cdot \text{kg}_{\text{DM}}^{-1}$ and $\text{mgO}_2 \cdot \text{kg}_{\text{DM}}^{-1} \cdot \text{h}^{-1}$, respectively. This expression was developed by RICICLA Group Di.Pro.Ve from the University of Milan, by studying 46 samples from MBT full-scale plants.

In general, the dynamic method to which the Italian regulations refer to is the Costech method, developed by Di.Pro.Ve (University of Milan).

Given that Equation (4) uses the $\text{DRI}_{\text{Di.Pro.Ve}}$ and in our case the RI was obtained with the Trento method (with AIR-nl reactor), the University of Trento has made a tranche of experimental tests following both methods in order to find a correlation that makes the two DRI comparison possible. The main difference between the two methods is the temperature control during tests. The method developed by the group RECICLA does not control temperature. The data recorded by the Costech respirometer should be reporting oxygen consumption at the reference temperature of 30°C , the temperature set in our AIR-nl respirometer. The University of Trento group proposed an expression of correlation valid in the range of 20 to 40°C [12]:

$$\text{DRI}_{30^\circ \text{C}} = \text{DRI}_T \vartheta^{(30^\circ \text{C} - T)} \quad (5)$$

where T —instantaneous temperature at which the measurement is performed (measured by the probe inside the substrate) and ϑ —reference constant, equal to 1.08.

From this study [12] another Equation of first approximation without accounting for the role of temperature has been made available, allowing the correlation of the two DRI_{24} values.

$$\text{DRI}_{24\text{Costech}} = 0.7086 \text{DRI}_{24\text{AIR-nl}} \quad (6)$$

The value of DRI_{24} is preferred to the value of DRI, since it was determined as the average integral over a period of 24 h during the maximum oxygen consumption. DRI_{24} is less affected by any peak oxygen consumption of limited duration in the respirometric path [20]. As it is less affected by error, the value of DRI_{24} was used to determine the ABP.

3. Results

3.1. Primary Characterization

The results of the primary and proximate analysis performed are presented in Table 1.

Table 1. Primary and proximate analysis.

Sample	Volatile Solids ^{db} (%)	Moisture (%)	Gross Heating Value ^{db} (kJ·kg ⁻¹)
WFGM	98	65	20,494
RFGM	98	59	20,274
WEGM	98	60	21,707
REGM	98	54	18,494
AP	90	75	16,966
OP	80	68	12,425

^{db} Dry basis.

The products have high moisture content, making them suitable for respirometric treatment. As expected, the highest moisture is present in fresh grape marc (compared to exhausted grape marc), in apple scraps and in olive pomace. The energetic content of the analyzed dried discarded biomasses is quite high and their use as potential fuels could be very advantageous for power generation. The highest heating value was achieved by grape marc, which is similar to different types of wood in terms of energy and volatile solids content.

The elemental analysis of the dried selected biomass is presented in Table 2.

Table 2. Elemental analysis of biomass samples.

Sample	N (%)	C (%)	H (%)	O (%)	Cl (mg·kg ⁻¹)	Hg (mg·kg ⁻¹)	C/N
WFGM	2.34	48.43	6.74	40.49	<50	0.014	20.7
RFGM	2.29	50.23	6.24	39.24	<50	<0.05	21.9
WEGM	1.71	49.99	6.48	39.82	<50	0.001	29.23
REGM	2.36	43.83	6.41	45.40	<50	0.002	18.57
AP	0.85	42.97	7.11	39.07	<50	<0.0005	50.5
OP	2.05	57.83	8.32	11.80	411	<0.05	28.2

The elemental composition of the analyzed samples and of grape marc in particular is similar to wood biomass, specifically to different types of conifers.

For an efficient anaerobic digestion, the feedstock C/N ratio is an important parameter. According to some sources [25], the optimum C/N ratio varies from 15 to 30, while for other authors [26,27] this range was set from 25 to 30. All the discarded biomasses fall into the same range for C/N ratio, except for the apple pomace which presents lower nitrogen content. As a result, these wastes could be suited for anaerobic treatment and biogas production, when looking only at their C/N ratio.

The Cl and Hg content are important to establish the bio-waste class as solid recovered fuel (SRF). In the UNI CEN/TS 15359 [28], the SRF is classified in 5 categories according to three specific parameters (GHV, Cl and Hg). The first one takes the meaning as economic parameter, the second one as technical parameter and the latter as environmental parameter. The importance of Cl as a technical parameter is due to its intrinsic properties. Even a small presence in the feedstock leads to problems in plants, especially due to its corrosive behavior.

3.2. Biological Stability

For each type of biomass, three respirometric tests were performed to better emphasize the obtained results, due to the heterogeneity of some of the materials. Because the RI testing methodology does not allow for each test choosing a pre-fixed sampling rate at constant moments in time, the statistical analysis was performed only after setting a common x -value for the three replicates. The data from each Test 1–3 was interpolated to determine a new common time value and the average RI variation with standard deviation bars is presented below for each type of material analyzed.

The results for the RI and RI_{24} variation are presented in Figures 2–7.

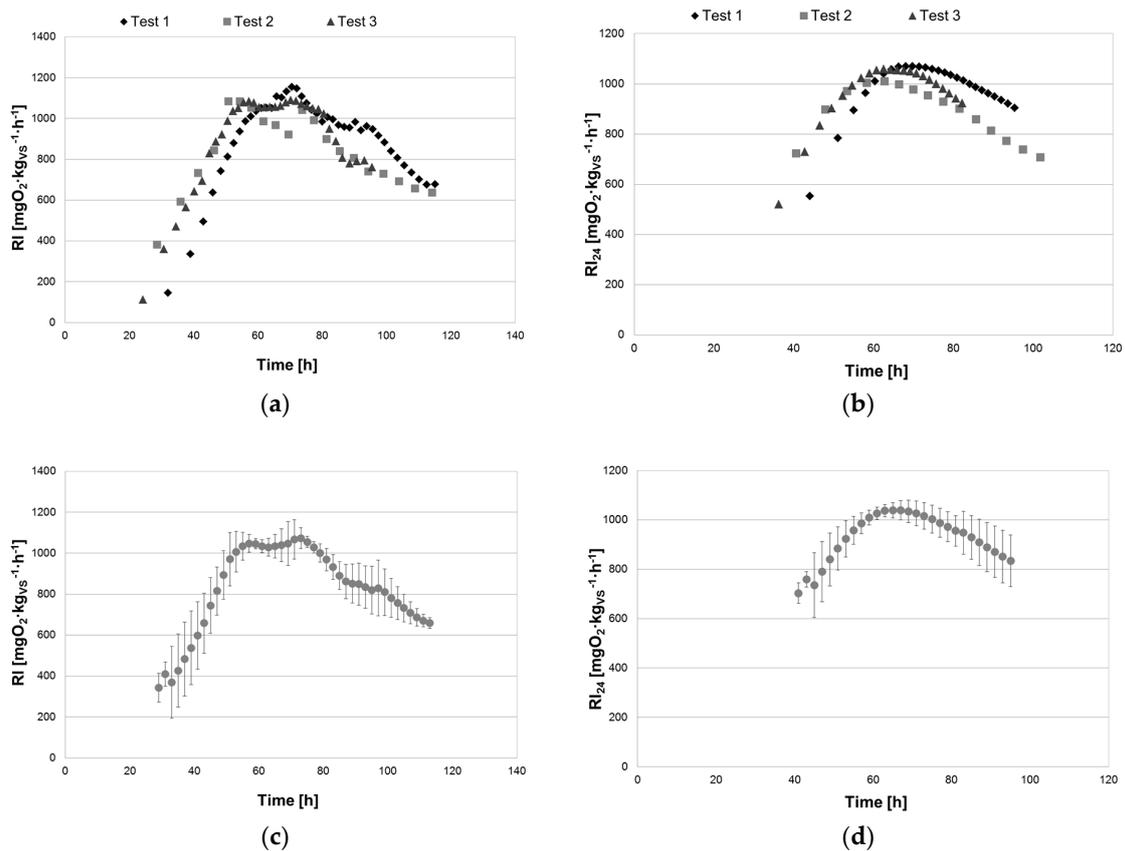


Figure 2. WFGM respirometric variation: (a) WFGM RI 3 Tests variation; (b) WFGM RI₂₄ 3 Tests variation; (c) WFGM RI variation; (d) WFGM RI₂₄ variation.

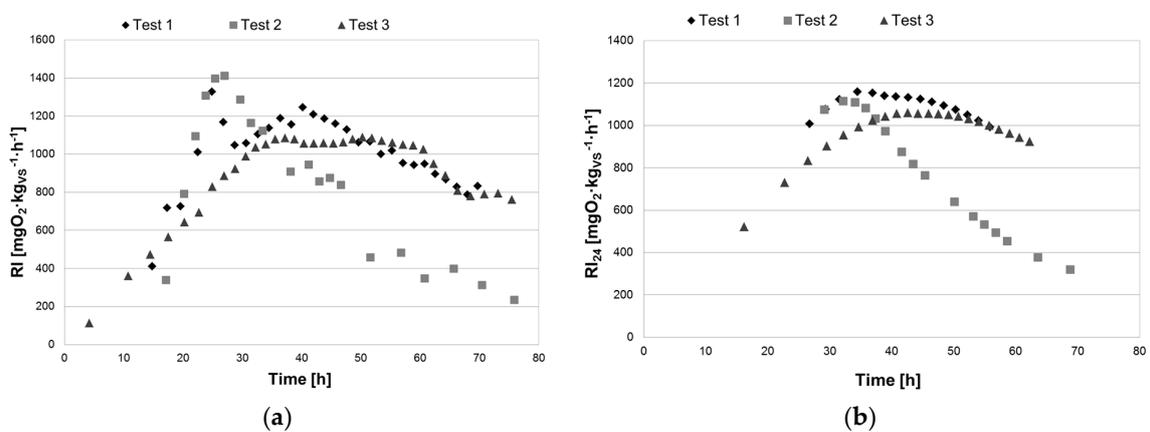


Figure 3. Cont.

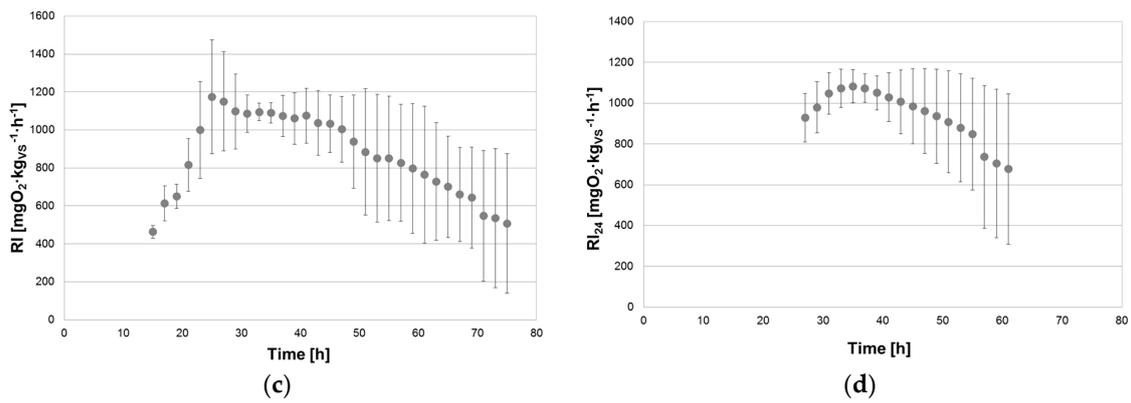


Figure 3. RFGM respirometric variation: (a) RFGM RI 3 Tests variation; (b) RFGM RI₂₄ 3 Tests variation; (c) RFGM RI variation; (d) RFGM RI₂₄ variation.

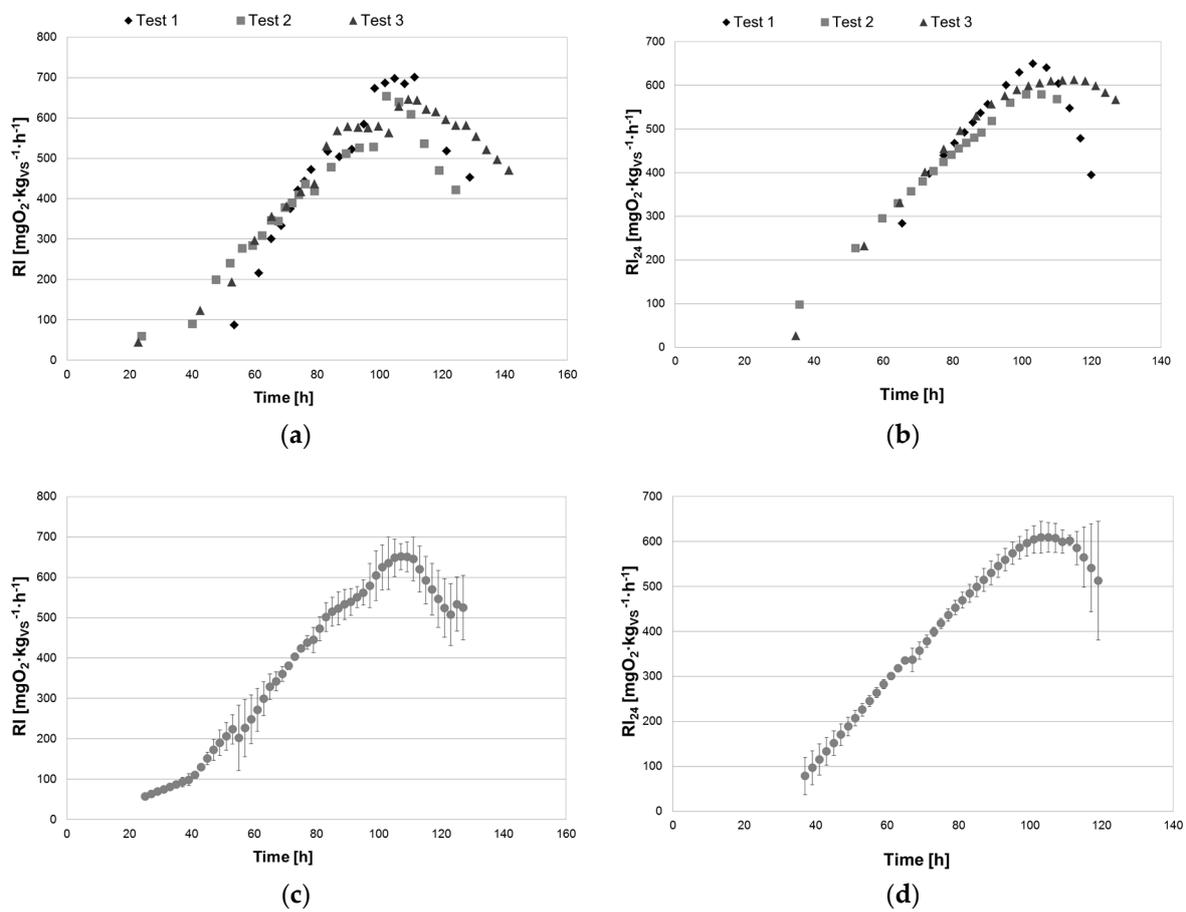


Figure 4. WEGM respirometric variation: (a) WEGM RI 3 Tests variation; (b) WEGM RI₂₄ 3 Tests variation; (c) WEGM RI variation; (d) WEGM RI₂₄ variation.

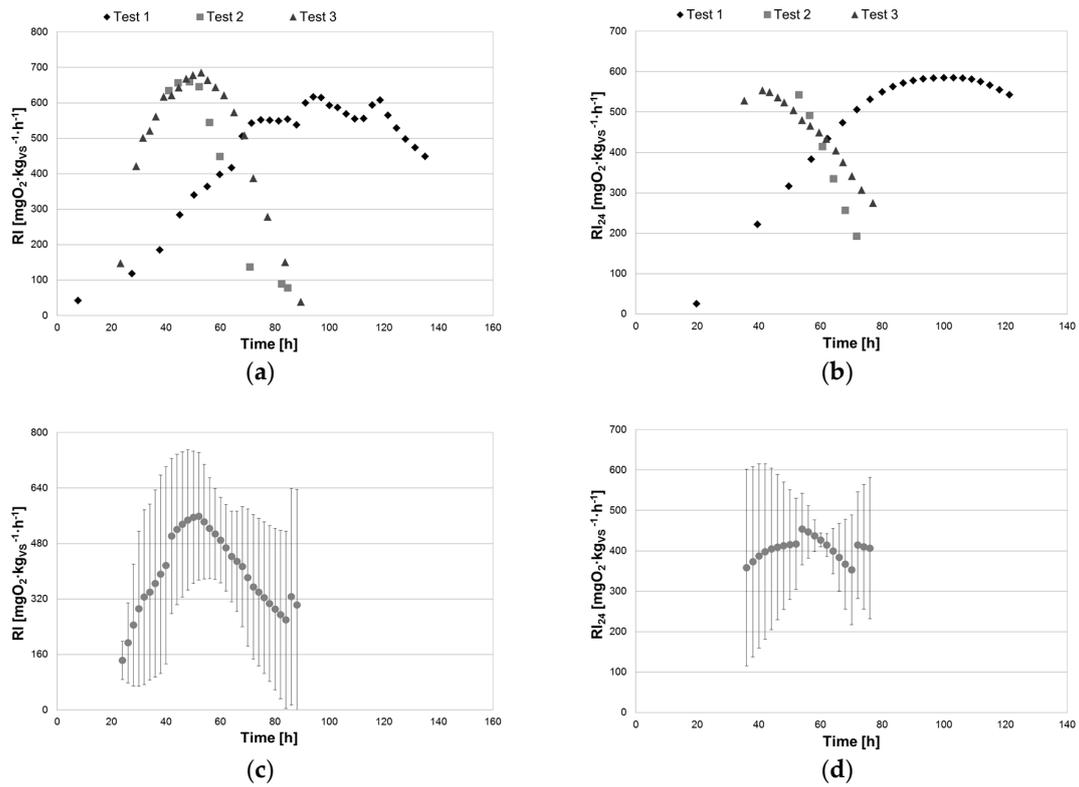


Figure 5. REGM respirometric variation: (a) REGM RI 3 Tests variation; (b) REGM RI_{24} 3 Tests variation; (c) REGM RI variation; (d) REGM RI_{24} variation.

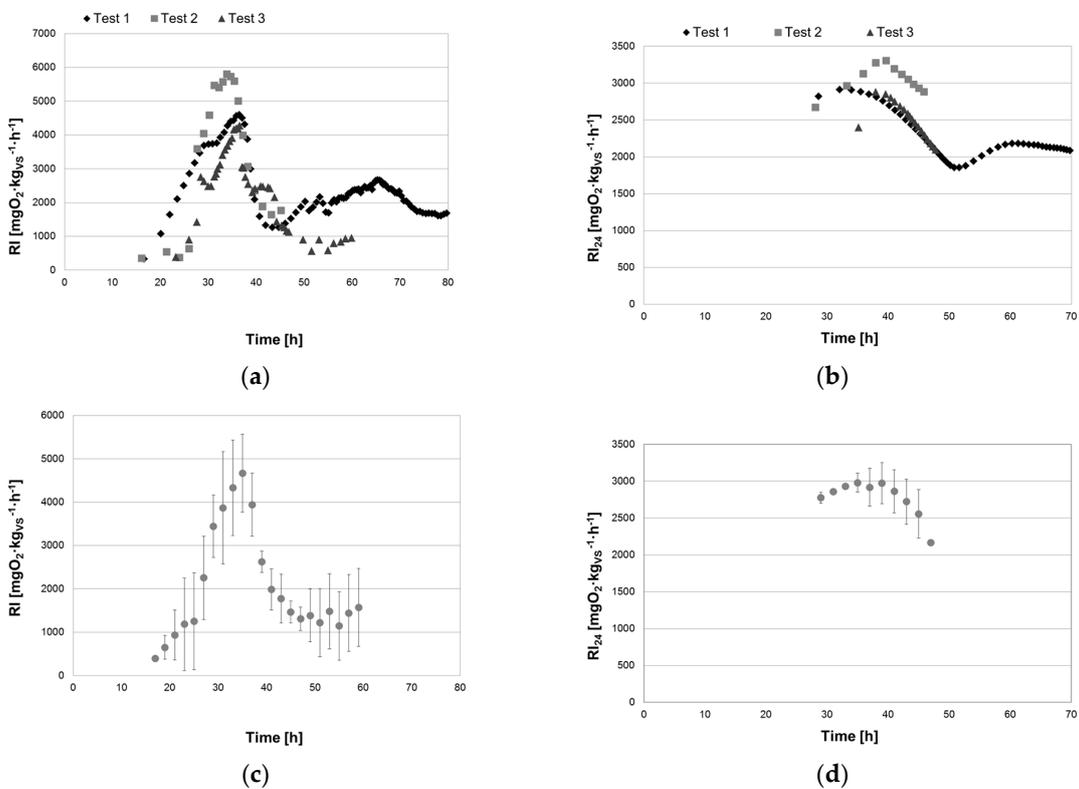


Figure 6. AP respirometric variation: (a) AP RI 3 Tests variation; (b) AP RI_{24} 3 Tests variation; (c) AP RI variation; (d) AP RI_{24} variation.

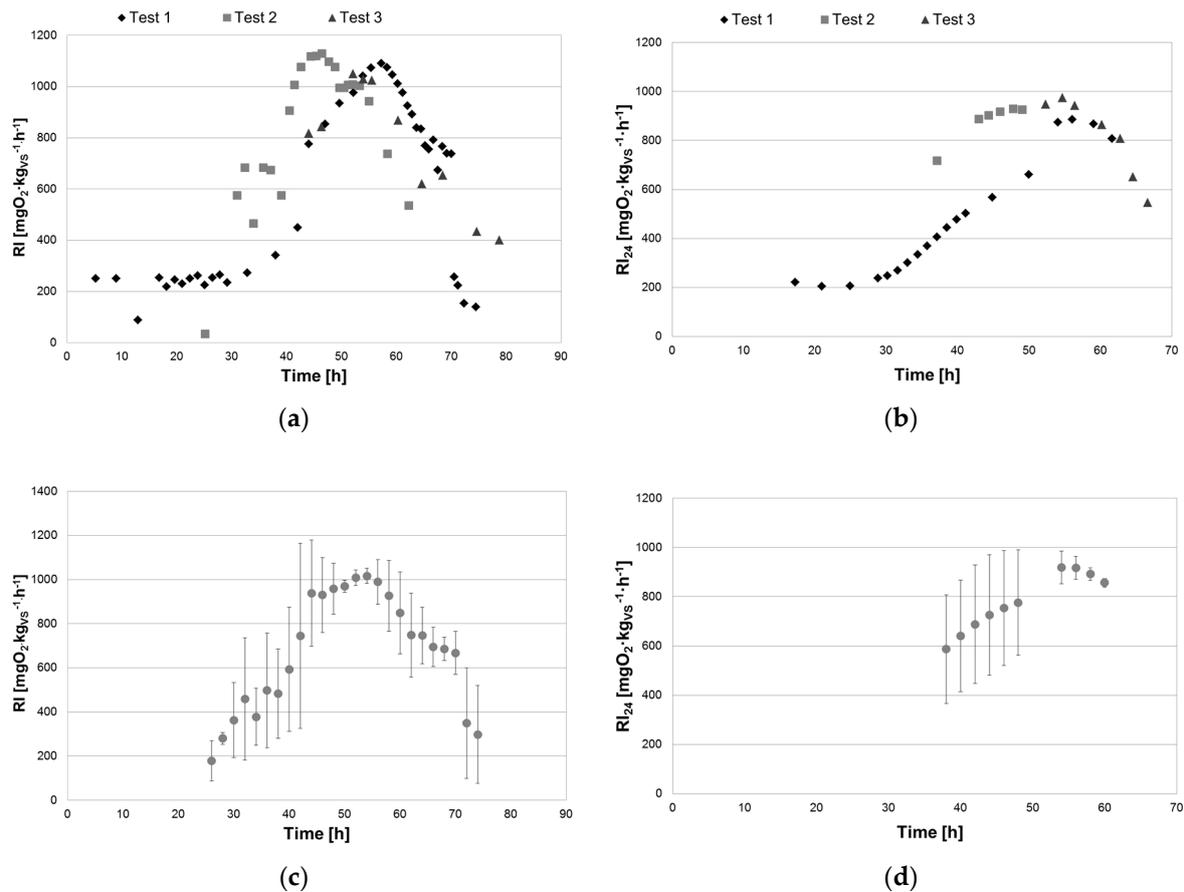


Figure 7. OP respirometric variation: (a) OP RI 3 Tests variation; (b) OP RI_{24} 3 Tests variation; (c) OP RI variation; (d) OP RI_{24} variation.

The aerobic process occurring during the respirometric index determination has different time lengths for the six types of materials. As expected, differences appeared between the WGM and RGM, due to the different technologies of producing white and red wine [29]. If average length of a test for WFGM was 4–5 days, in the case of RFGM the average was 3 days. For the exhausted grape marc the necessary amount of time for a process run was comparatively higher than all the other types of biomass; as a result, the biological activity of WEGM was measured over 5–6 days, and during 4–5 days for REGM. This shows that the wastes coming from distillation process require a longer period of time for aerobic degradation, leading to higher energy consumption by the biomass aeration equipment.

Interestingly, the difference in white and red grape processing is noticed in the start of the respirometric activity as well. Though the biological activity of RFGM and REGM is measured by the respirometric tests from the first hours of the process, the WFGM and WEGM do not show any periods of activity in the first 20 h. The fact that the white grape marc reacts more slowly to aerobic processing is also observed in the maximum RI values achieved, which are offset by approximately 40–60 h compared to the red grape marc RI maximum.

Shorter periods of time for process run were registered for OP and AP. The duration for OP tests did not exceed 3 days, while for the AP the treatment period was measured for approximately 2 days. These results are possibly connected to the discarded biomasses moisture contents. Higher moisture content favors the biological activity and shortens the length of the process, but a deeper analysis on the porosity role could help.

The differences which appear between tests performed on the same type of material, especially grape marc, are due to the heterogeneous character of the materials. The grape marc consists of seeds, skins, stalks and pulp in different proportions [30]. The tests which have distinct lengths of time for

the same material can be explained by the load into the reactor of material containing more or less biodegradable matter. Therefore for establishing the RI value for each type of discarded biomass, an average of the three tests and the maximum values encountered are presented in Table 3.

Table 3. Maximum values of RI and RI₂₄ for the six biomass samples.

Sample	RI Max (mgO ₂ ·kg _{VS} ⁻¹ ·h ⁻¹)	RI ₂₄ Max (mgO ₂ ·kg _{VS} ⁻¹ ·h ⁻¹)
WFGM	1109 ± 40	1046 ± 32
RFGM	1276 ± 167	1110 ± 50
WEGM	665 ± 29	613 ± 35
REGM	652 ± 34	560 ± 22
AP	4888 ± 804	3031 ± 236
OP	1089 ± 40	929 ± 44

The highest registered values were encountered for apple pomace, which has by far the greatest biological activity. The lowest values were recorded for the exhausted grape marc, obtained from the distillation process. These values are comparable to the ones found in the literature for aerobic processes applied to organic fractions, in similar operating conditions [31,32]. According to classifications found in other research studies [16] values of dynamic RI above 3000 mgO₂·kg_{VS}⁻¹·h⁻¹ are considered to be fresh material and belong to class I of stability; values over 2000 mgO₂·kg_{VS}⁻¹·h⁻¹ belong to class II, while between 1000–2000 mgO₂·kg_{VS}⁻¹·h⁻¹ materials are considered to be in the course of biological decomposition and belong to class III. For class IV, 500–1000 mgO₂·kg_{VS}⁻¹·h⁻¹ the materials are moderately stable, while for values below 500 mgO₂·kg_{VS}⁻¹·h⁻¹, which represent class V, the substrate is considered biologically stable.

The only material belonging to class I of stability (the least stable) is the apple pomace, which had the highest RI value of 4853 mgO₂·kg_{VS}⁻¹·h⁻¹. The majority of the discarded biomasses are in the third category, as materials in the course of degradation. Therefore, WFGM, RFGM and OP need a pre-treatment method for biological stabilization before agricultural use. The white and red exhausted grape marc is less biodegradable (belonging to class IV), but cannot be considered stable and stored or used as fertilizer (compost) as it is. According to literature sources, the value of 593 ± 341 mgO₂·kg_{VS}⁻¹·h⁻¹ corresponds to bio-stabilized wastes [33].

3.3. Biogas Potential Estimation

The results for ABP, derived from the values of RI₂₄ using Equations (4)–(6) are presented in Table 4.

Table 4. ABP values for analyzed samples.

Samples	ABPmax (Nm ³ ·t _{VS} ⁻¹)	ABPmin (Nm ³ ·t _{VS} ⁻¹)	ABPmax (Nm ³ ·t _{t,q} ⁻¹)	ABPmin (Nm ³ ·t _{t,q} ⁻¹)
RFGM	125.81	115.98	51.36	47.35
REGM	80.56	73.16	35.90	32.60
WEGM	86.35	78.64	33.64	30.64
WFGM	120.72	111.17	41.02	37.77
AP	281.58	263.13	65.10	60.84
OP	119.86	109.66	30.9	27.99

The results of ABP were calculated at standard conditions (p = 1 atm and T = 0 °C) and expressed as the m³ of biogas ton produced per ton of feedstock VS, as typically done in the literature [34].

The results obtained are comparable with other studies from the literature [35–41]. For example Battista et al. [35] determined experimentally 5.40–14.10 m³·t⁻¹ biogas produced from different samples of olive pomace. In another study [36], the authors performed the ABP test on Italian white and red grape marc and obtained values of 245.32 m³·t_{VS}⁻¹ and 144.97 m³·t_{VS}⁻¹, respectively. The white grape marc ABP values calculated in this paper are significantly lower, however the same authors [36] show

ABP values for white grape marc skins of $142.37 \text{ m}^3 \cdot \text{t}_{\text{VS}}^{-1}$ and $128.34 \text{ m}^3 \cdot \text{t}_{\text{VS}}^{-1}$ for white grape marc stalks. Dinuccio et al. [37] found the specific biogas yield of grape marc to be $139 \text{ m}^3 \cdot \text{t}^{-1}$ and $64 \text{ m}^3 \cdot \text{t}^{-1}$ for grape stalks. This confirms that the heterogeneity and specific characteristics of the material play an important role in the repeatability of the ABP tests. When handling heterogeneous materials such as the ones studied in this paper, the success of running a continuous process depends on the reliability and swiftness of the feedstock characterization methods.

It should be noted that not all the biomass studied has a good ABP, in particular the exhausted grape marc with values below $100 \text{ m}^3 \cdot \text{t}_{\text{VS}}^{-1}$. For WEGM and REGM other types of energy recovery processes could be applied. It could be possible to send these biomasses to a drying and pelletizing facility and then to thermal treatment for power generation. Moreover, the proposed approach allows for optimizing co-treatment strategies with source-separated food waste from MSW, specifically in the case of anaerobic digestion followed by post-composting; indeed, as a result of RI, the data generation and the calculation of ABP, it is possible to decide in which step of treatment a biomass should be added to be co-treated: in the case of low ABP it should be sent directly to the post-composting stage, while in the case of high ABP, additional information (e.g., lignin content, C/N ratio) could be added to be sure about the compatibility in co-digestion.

4. Conclusions

This study emphasized the significant information which can be obtained by using respirometric index methods and proves that the correlation of ABP and RI is a useful method to determine in a shorter amount of time the value of biogas production potential. This method would improve the processing time from 21–60 days to just 1–4 days to conduct a respirometric test. Therefore, plant operators could use this method to optimize the feedstock for biogas generation.

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