Two-stage anaerobic co-digestion of jam washing water and a mix of fruit and vegetable wastes

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In recent years, biomass wastes have gained interest as renewable and carbon-neutral feedstocks to face the exhaustion of fossil fuels and climate change. Moreover, their exploitation accomplishes the circular economy principles (Shanmugam et al., 2021). These substrates can be degraded through sequential biological processes producing energy carriers such as hydrogen (H_2) and methane (CH_4). The first is obtained through dark fermentation (DF) where microorganisms decompose organic substrates into a gas phase (H_2 and CO_2) and volatile fatty acids (VFA). DF is one of the stages composing anaerobic digestion (AD) through which biomass is biologically converted into biogas (CH_4 and CO_2). Even if DF is an interesting approach to produce H_2 at reduced capital and operational costs, the H_2 yield is low, and the technological readiness level does not exceed 5 (Buffi et al., 2022; Ubando et al., 2022). Besides, a C-rich residue is generated from DF which can act as feedstock in the following AD. Coupling DF and AD is a rather innovative approach called two-stage anaerobic digestion (TSAD) which presents several benefits compared to DF or AD alone as the simultaneous production of two energy carriers, a satisfying exploitation of biomass carbon, and a higher CH_4 yield from the AD stage (Lembo et al., 2022; Nathao et al., 2013). As TSAD involves biological processes, among operative conditions, nutrient balance plays a key role in assuring proper microbial activity. Carbon (C), nitrogen (N), and phosphorus (P) can be balanced through co-digestion which consists of mixing substrates with different chemical and physical compositions to reach an optimal macro and micronutrient content (Hussain et al., 2015). The pH of the system can be also controlled through this technique together with a reduction or total avoidance of clean water use by properly choosing biomasses (Esposito et al., 2012). This work aims to present an original two-stage anaerobic co-digestion coupling fruit and vegetable residues and an innovative substrate which is the washing water employed to clean jam production equipment. The latter is an unconventional feedstock that is currently discharged in sewerage but is suitable in TSAD where its high fructose and glucose content act as a simple-biodegradable substrate for microorganisms while its high water content can be crucial in reaching an optimal total solids content (TS) in a wet digestion. H_2 and CH_4 productions have been evaluated to demonstrate the feasibility of this innovative biomass mixture which from wastes become feedstock, by circular economy principles.

- Experimental activities were performed at a laboratory scale. Jam washing water and inoculum were collected from local companies near Torino (Italy) while fruit and vegetable residues were collected from household waste. Substrates and inoculum were characterized through elemental analysis, total solids (TS), and volatile solids (VS) evaluation. The initial series of tests focused on DF of the two substrates involving the use of a thermally pre-treated inoculum (TS=7%) at 60°C for 30 minutes to create an environment unsuitable for microbial survival, prompting H_2-producing microorganisms to form spores. The experiments were conducted in batch configurations using 250 mL bottles (working volume of 200 mL). Each bottle was connected to a 1 L gas bag to collect the generated biogas. The experimental conditions included a mesophilic temperature (35°C), feeding the reactor with a total solid percentage (%TS) up to 6% and an initial pH of 6. Four configurations, each performed in duplicate, were selected depending on substrate-to-inoculum ratio and thermal pre-treatment on the substrate (60°C, 30 minutes), as shown in Tab.1. DF was conducted for a period of three days, chosen on previous DF experiments and averaging the values present in literature (Nathao et al., 2013; Zhang & He, 2014). Before initiating the experiments, nitrogen (N_2) was introduced into each bottle to completely remove oxygen. The volume of gas produced was monitored everyday by emptying the gas bags and measuring the extracted gas volume. Gas composition analysis was conducted using gas chromatography. Additional analyses were carried out on the DF digestates, including pH measurements, total solids (TS), volatile solids (VS), and elemental analysis.

Tab.1 Number, name, and process conditions of the four configurations tested during dark fermentation experiments.

No. Configuration	Configuration Name	Thermally treated substrate	VS substrate: VS inoculum
1	BIO/INOC	No	1-1
2	2BIO/INOC	No	2-1
3	BIOTERM/INOC	Yes	1-1
4	2BIOTERM/INOC	Yes	2-1

Then digestates were employed as substrate for the following AD step, carried out in the same laboratory set-up. The substrate-to-inoculum ratio was fixed at 1 in all 4 configurations using an inoculum at TS=6% while the initial pH was 7. As illustrated before, biogas volume and composition were analyzed together with digestate properties. The experiment was conducted for nineteen days, chosen on previous AD experiments and averaging the values present in literature (Paudel et al., 2017).

- H_2 and CH_4 production are shown in Fig.1. Regarding DF experiments, the highest H_2 yield, 0.05 Nm^3/kg_{VS}, was comparable to the values present in the literature. It originated from the configuration where the substrate-to-inoculum ratio was fixed at 1 and substrates were thermally pretreated because, after the treatment at 60°C, the substrate structure was partially degraded and became more accessible to microorganisms. The configurations with a substrate-to-inoculum ratio equal to 2 showed a lower H_2 production probably because microorganisms were not enough concentrated to properly degrade the substrate. AD experiments show an opposite trend as configurations fed with digestate originated from substrate-to-inoculum ratio 2:1, produced the highest CH_4 quantity accounted for 0.128 Nm^3/kg_{VS}, slightly lower than the average values present in literature. Configurations that produced more H_2, were characterized by a lower CH_4 yield as in the first stage probably a higher content of organic matter was decomposed into H_2 and CO_2, reducing carbon still available for the second stage.

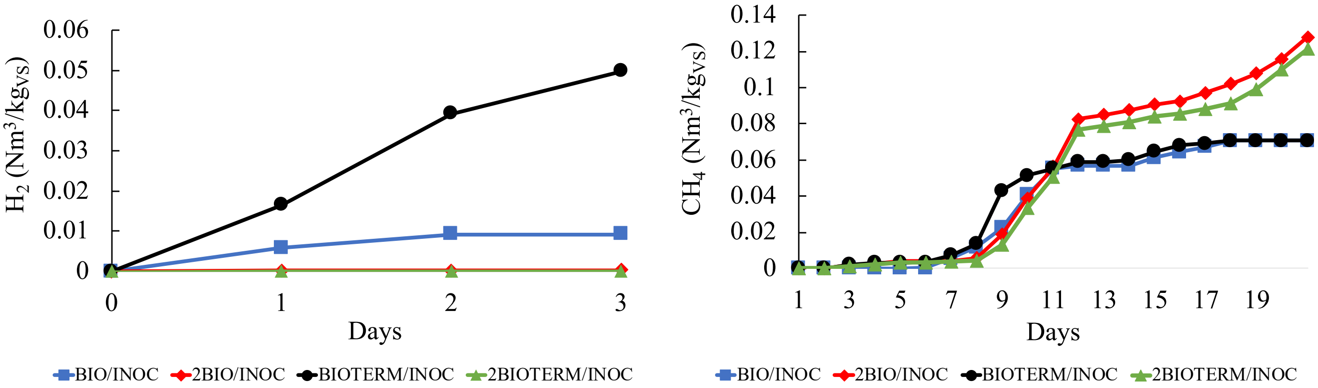

Fig.1 Hydrogen production from the DF stage for three days and CH4 production from the AD stage for 19 days.

- Fruit and vegetable wastes and jam washing water seem to be promising substrates in biological processes to produce H_2 and CH_4. On the other hand, H_2 and CH_4 production does not present values exceptionally higher concerning other substrates digestion. Further studies may be performed to optimized process conditions and to test the system in continuous configurations to achieve higher energy carriers' production. Moreover, a preliminary study on techno-economic and environmental analysis will be done through plant design and calculation of fixed and operative costs to assess the feasibility of the process at industrial scale and its impacts.

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