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Prospect of kitchen wastes for biomaterials and biogas production in a biorefinery approach

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ABSTRACT

A biorefinery approach to obtain biodegradable biomaterials from hospital kitchen wastes (HKW) was proposed before the anaerobic biogas production. Two mixtures corresponding to mixed pre and postconsumption HKW from different diets were used. The lunch+snack (L + S) mixture was rich in proteins (49.8 ± 2.1 %) whereas that from dinner+breakfast (D + B) was rich in carbohydrates (60.3 ± 1.9 %). A two-stage hydrothermal processing was proposed for solubilizing first starch (yield 9.8 ± 0.5 %) and then protein. The recovered starch mixed with the waste solids from the hydrothermal processing and glycerol (mass ratio 8:20:2.5) were used to prepare gelled biomaterials stable for 3 months without microbial contamination. The soluble protein fraction, containing structural and muscle proteins with high nutritional value, was successfully proposed as biostimulant for sunflower. The waste solids exhibited biomethane potential (283.86 ± 45.02 and 279.34 ± 50.94 mL CH_4/g VS for D + B and L + S) non significantly different from that of the untreated HKW (244.48 and 295.78 mL CH_4/g VS for R_D + B and R_L + S). The proposed processing allows the product diversification during the valorization of a model kitchen waste into biomaterials, plant growth stimulants and bioenergy.

1. Introduction

Kitchen wastes (KW) are food losses generated during food preparation and postconsumption in households and restaurants, canteens, hospitals, hotels, caterings, etc. This unused fraction represents a worldwidely available, heterogeneous, biodegradable waste, which could be an outstanding source of high valuable products and a renewable biomass for biorefineries (Carmona-Cabello et al., 2018; Sindu et al., 2019; Mahjoub and Domscheit, 2020; Esteban-Lustres et al., 2022). Management of postconsumption food wastes, which account for more than half of food waste, requires advances in both social and technical aspects for the implementation of standards for disposal, recycling, and valorization (Pour and Makkawi, 2021). The currently applied management strategies are based on thermal (gasification, incineration and pyrolysis) and/or chemical and biochemical (anaerobic digestion and composting) transformations (Xie et al., 2022; Prepilkova et al., 2023). Biofuel production could alleviate the dependence on fossil fuels (Pour and Makkawi, 2021; Dhalsamant et al., 2023; Lahiri et al., 2023) and anaerobic digestion is a common solution to produce biogas and a digestate for fertilization purposes, or biohydrogen (Mohanakrishna et al., 2023).

Recent trends aim to advance on environmental sustainability and circular bioeconomy to promote resource efficiency (Gál et al., 2025) following a holistic valorization (Pour and Makkawi, 2021; Patel et al., 2024). The search for novel products will aid in this purpose and it is favoured by the diverse composition of KW providing potential for

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transformation into materials and energy (Mahjoub and Domscheit, 2020; Pour and Makkawi, 2021), and bioconversion into biobased biopolymers, chemicals, or biopharmaceuticals (Mahjoub and Domscheit, 2020; Sharma et al., 2025). From a recent meta-analysis across multiple regions, byproducts, and valorization pathways, more economic benefits from valorization than from traditional disposal are expected, but the cost viability varies with regional economic and technical context (Tariq et al., 2025).

A chemical, thermal, mechanical or thermochemical, and/or biological pretreatment is needed to promote bioconversion (Dhiman and Mukherjee, 2021), i.e. to enhance the accessibility before microbial conversion of food and kitchen waste to high valuable products (Esteban and Ladero, 2018). Different strategies have been reported to enhance the anaerobic digestion of KW. Wang et al. (2024) used a Fe_2O_3-modified digestate biochar to enhance the methane yield and to reduce volatile fatty acid concentration. Zhang et al. (2024) reported that liquefaction of kitchen and food waste enhanced methane production. Alkali pretreatment of KW combined with bentonite treatment at 25 °C promoted the dissolution of organic matter and enhanced anaerobic digestion (Hu et al., 2024). The biohydrogen production can be improved by high pressure, thermal, alkaline, acid, ultrasound, enzymatic, and microwave assistance, which enhanced both proteins and carbohydrates solubilization (Gallipoli et al., 2020; Kannah et al., 2020).

Hydrothermal treatment with both sub and supercritical water can be used for the fractionation of waste with high moisture content without previous dehydration and avoiding the use of chemicals. It is rapid and efficient for the extraction of a wide range of products from preconsumption residues and for hydrolysing macromolecules (Marcet et al., 2016). The application of a thermal pretreatment before the anaerobic digestion has been described. Hydrothermal treatment (100–180 °C) facilitates the solubilization of the organic matter, to raise the potential of methane and process rate, and the treated product can be sterilized (Carrere et al., 2016). Xie et al. (2022) confirmed that a hydrothermal processing of KW at short time (5–30 min) and relatively moderate temperatures (60–100 °C) favoured the removal of oil and salt before biomethane or bio-hydrogen production, and increased the volatile fatty acid concentrations. A higher severity process, hydrothermal liquefaction, can be proposed for producing an alternative fuel (Dhalsamant et al., 2023). Li et al. (2013) reported that a thermochemical pretreatment increased methane yields from grease/oil and synthetic kitchen waste co-digestions and Li et al. (2016) observed that a pretreatment up to 120 °C for 15–120 min increased the methane production efficiency and rates. Zhu et al. (2015) found that a pretreatment of KW at 150 °C during 60 min favoured the solubilization of organic fractions potentially bioconverted to volatile fatty acids and the floatable oil amounts. However, the need for an adequate selection of the treatment temperature can be illustrated with a few examples. Despite the hydrothermal treatment of KW at 175 °C for 60 min improved the initial methane production rate, the methane production decreased (Liu et al., 2012). The hydrothermal pretreatment of kitchen wastes may induce Maillard reactions beyond a certain temperature of 140–160 °C (Ajay et al., 2021). The hydrothermal treatment at 140 °C was optimal to enhance the hydrogen and methane co-production with organic fraction from restaurant waste (Ding et al., 2017) and was a critical temperature for the production of melanoidin from homemade food wastes 140 °C (Yang et al., 2025).

The valorization of KW is often challenged by heterogeneity and variability in the type and composition and high moisture content (Sindu et al., 2019; Engelberth, 2020). In a previous study, a blend of pre- and post-consumption hospital kitchen residues was used as model system providing a predictable and regular composition, which was confirmed for the different diets prepared. The wastes from dinner+breakfast (D + B) from seven different diets was in the range 27–33 % d. b. protein and 52–65 % carbohydrates and the wastes from lunch+snack (L + S) of seven diets, contained 42–59 % protein and 44–53 % carbohydrates (Esteban-Lustres et al., 2024). A microwave heated pressurized hot water treatment proved suitable for the partial solubilization of protein and carbohydrates. The starch fractions solubilized could be recovered after cooling and did not require the addition of plasticizers to obtain a biodegradable biopolymeric material (Esteban-Lustres et al., 2024). However, 30–60 % of the KW remained insoluble in the residual solids from the hydrothermal treatment. Therefore, in order to follow a biorefinery approach, these residual solids were evaluated for anaerobic digestion, which is the conventional final use of KW. Furthermore, anaerobic digestion from KW alone could be difficult due to the inhibition of methane formation due to excessive macronutrients and low carbon to nitrogen ratio (Ajay et al., 2021) and a previous removal could be beneficial. Since microwave assisted treatment is still immature on a larger scale (Gao et al., 2021), the potential of conventional heating operation is now being explored for a representative mixture of the high carbohydrate content sample, and the high protein content sample. In the present study, hydrothermal processing was proposed to sequentially extract a starch fraction and a soluble protein fraction, further valorized into biomaterials and biostimulants, and the impact on the anaerobic digestion of the residual solids was assessed.

2. Materials and methods

2.1. Kitchen waste samples

Samples from kitchen wastes, consisting on the pre- and post-consumption wastes, generated the first week of January 2021 in the kitchen of the Complexo Hospitalario Universitario (Ourense, Spain), were used. The segregation system eliminates non-organic elements and paper before dewatering and milling, and generates a mixed waste from dinner+breakfast (D + B) and lunch+snack (L + S) services. Two homogeneous batches were prepared corresponding to the combination of HKW from different menus with similar composition. Samples (500 g, moisture content, 79.3 ± 1.9 %) were stored in closed bags at −18 °C. Those defrosted were homogenized, freeze-dried and milled (MC300 Moulinex, 180 W) miller. Samples were further stored at −18 °C prior to use.

2.2. Hydrothermal extraction with pressurized hot water or autohydrolysis

Freeze-dried kitchen residues were ground and then distilled water was added at a solid:liquid ratio 1:30 (*w*/w). The suspensions were placed in the 3.75 L vessel of a pressurized Parr Instruments reactor (4842, USA) and operation was performed under non isothermal regime during heating up to the selected temperature. In the present study, an initial stage heating up 140 °C was applied to solubilize the carbohydrate fraction. Once the selected temperature was achieved, the reactor was cooled down, and the solid and liquid fractions were separated by filtration. The residual solids were again contacted at the same solid: liquid ratio during heating up to 160 °C to promote the solubilization of the protein fraction (Fig. 1).

The heating was conducted on a non-isothermal mode processing. The severity (log R_0) values applied were 2.06 and 2.59, being $R_0 = t{\cdot}exp\left[\frac{T-100}{14.75}\right]$, T the temperature (°C) and t the time of reaction (min). These values were similar to those previously studied in microwave assisted isothermal treatment, 1.95 and 2.48 (Esteban-Lustres et al., 2024).

2.3. Starch recovery

The liquid fractions obtained after hydrothermal treatment at 140 °C were cold stored overnight before separating the precipitated starch fraction (Esteban-Lustres et al., 2024). The corresponding biopolymer was dehydrated using a convective air oven (40 °C, 24 h), and stored in close dark plastic bottles prior to further analysis.

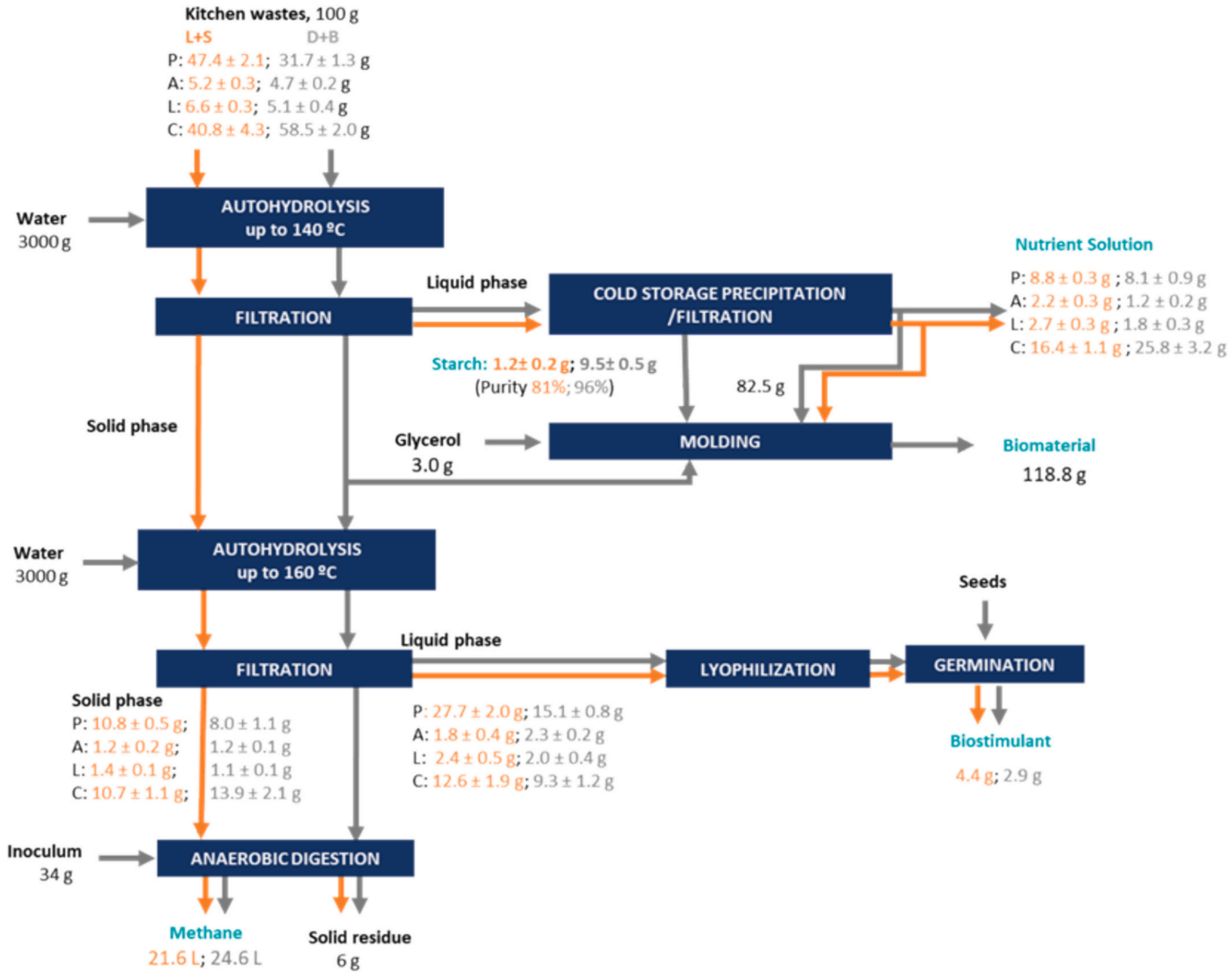

Fig. 1. Scheme of the KW samples processing following a biorefinery approach to obtain biomaterials, biostimulants and biomethane. P: protein, A: ash, L: lipids and C: carbohydrate content (by difference) (g/100 g kitchen waste).

The amylose ratio of the extracted starch and the total starch amount were estimated using two Megazyme enzymatic kits (Wicklow, Ireland) according to standard procedures (Moreira et al., 2012).

2.4. *Liquid chromatography tandem mass spectrometry (LC-MS/MS) and downstream bioinformatic analysis*

Peptides and proteins obtained through hydrothermal treatments were identified by LC-MS/MS. Protein samples were loaded onto a standard Laemmli-type polyacrylamide gel, allowed to stack and enter the resolving gel, but not to separate. The gel pieces were then excised at the end of the run and subjected to in-gel digestion, as previously described (Domingo et al., 2023b).

The tryptic peptides were rebuilt in LC/MS grade water (formic acid: 0.1 % (*v*/v)) and analysed on a mass spectrometer (LTQ-Orbitrap Elite) coupled to a Proxeon Easy-nLC 1000 UHPLC system (Thermo Fisher Scientific, USA). Peptides were separated on a PepMap® RSLC C18 reverse-phase column (2 µm, 75 µm × 50 cm, 100 Å; Thermo Fisher Scientific, USA) using an acetonitrile gradient (5–30 % with 0.1 % formic acid) over 240 min. A positive mode was used for the mass scan, with top 15 at a dynamic exclusion time of 30 s and 35 % normalised collision energy. The resolution was adjusted at 30,000 with a minimum signal threshold at 1000, and the isolation width at 2.0 Da. A full MS scan was made from 390 to 1700 *m/z* (120,000 resolution). Data were then analysed employing the v.1.5.3.3 MaxQuant software (www.Coxdocs.org/doku.php?id=maxquant:start, 2023) versus the *Gallus gallus, Sus scrofa, Bos taurus,* Viridiplantae, Fungi, and Actinopterygii databases (www.uniprot.org, 2024). The search criteria included a maximum of two missed cleavages, fixed modification of cysteine (carbamidomethylation), variable modification of methionine (oxidation), and a minimum peptide length of seven amino acids. Precursor mass tolerance was set to 20 ppm for the initial search and 4.5 ppm for the main search. A false discovery rate (5 %) was admitted for protein and peptides identification. The obtained MaxQuant output files were processed as reported elsewhere (Domingo et al., 2023a).

2.5. *Anaerobic digestion*

Biochemical methane potential (BMP) assays were performed in duplicate for anaerobic digestion of each kitchen waste by a 3:1 mixture of anaerobic digester sludges, originating from a brewery and a sewage wastewater treatment plant, following the method of Rodríguez-Iglesias et al. (2024). In each 125 mL bottle 3 g total solids (TS)/L of substrate were added, except for blank and control assays. Blank assays were carried out without any substrate, meanwhile a volatile fatty acid mixture (1.01 g/L of acetic acid, 0.30 g/L of propionic acid and 0.24 g/L

of n-butyric acid) was added to control assays in order to assess the maximum yield of methane production for the inoculum.

Every bottle contained 2 g Na_2CO_3/L, 1 mL/L of micronutrients stock solution, 1 mL/L of macronutrients stock solution and 2 g volatile solids (VS)/L of inoculum. The inoculum contained 97.28 g TS/L and 77.45 g VS/L. The volume of work was adjusted to 50 mL with distilled water. Both stock solutions were prepared following Rodríguez-Iglesias et al. (2024).

The nutrients stock solutions were based on Ferreiro and Soto (2003). The composition of the macronutrients stock solution was: 170 g NH_4Cl/L, 37 g KH_2PO_4/L, 11.5 g $MgSO_4{\cdot}7\ H_2O$/L and 8 g $CaCl_2{\cdot}2\ H_2O$/L. The composition of the micronutrients stock solution was: 2 g $FeCl_2{\cdot}4\ H_2O$/L, 2 g $CoCl_2{\cdot}6\ H_2O$/L, 1 g/L of AEDT, 500 mg $MnCl_2{\cdot}4\ H_2O$/L, 200 mg resazurin/L, 108 mg Na_2SeO_3/L, 92 mg $NiCl_2{\cdot}6\ H_2O$/L, 90 mg $AlCl_3{\cdot}6\ H_2O$/L, 50 mg H_3BO_3/L, 50 mg $ZnCl_2$/L, 38 mg $CuCl_2{\cdot}2\ H_2O$ /L and 1 mL/L of 37 % HCl.

The volume of methane produced in each bottle was determined from the standardized volume obtained by manometric method (Strömberg et al., 2014) and the methane content of the head space gas analyzed by gas chromatography. An HP 6890 PLUS gas Chromatograph (GC, Agilent Technologies, Madrid, España) was used with a 15-m HP-PLOT Molecular Sieve 5 A column (0.53 mm ID, 50 μm film thickness). The injector and thermal conductivity detector (TCD) temperatures were both set at 150 °C. The oven started with a constant 50 °C temperature for 5 min, then, in 2 min it reached 90 °C.

$$V_S = \frac{P_V T_S V_T}{P_S T_E} \qquad \%CH_4 = \frac{A_M + 123.88}{8440}\cdot 100 \qquad V_M = V_S\cdot \%CH_4$$

Being V_s the gas volume at standard conditions, P_V the pressure inside the bottle, T_S the standard temperature (273 K), V_T the headspace volume, P_S the standard pressure (1 atm), T_E the temperature set for the assay, $\%CH_4$ the methane content in the headspace, A_M the peak area for methane and V_M the volume of methane in standard conditions.

The BMP was then calculated using the volume of methane produced (Strömberg et al., 2014) and the BMP yield was obtained from a theoretical BMP (Nielfa et al., 2015).

$$BMP = \frac{V_M - V_B}{m_{S,M}} \qquad BMP_t = \frac{COD_S\cdot R\cdot T_E}{P_S\cdot \%VS\cdot F}$$

Being V_B the blank methane production, $m_{S,M}$ the mass of substrate, COD_S the COD value of the substrate in g O_2/g of substrate, R the gas constant, %VS the volatile solids content of the substrate and F the conversion factor of 64 g O_2/mol CH_4.

2.6. Analytical methodology

The samples treated at different temperatures were characterized for moisture and ash content using until gravimetrical determinations after treating until constant weight at 105 °C and 575 °C, respectively. Mineral and metal amount were performed on a microwave (Marsxpress, USA) assisted acid digestion of the ashes (HNO_3 and H_2O_2 at 1600 W, 15 min and 200 °C, 10 min). The Cd and Pb amount were obtained by Inductively Coupled Plasma Mass Spectrometry (Thermo Scientific, USA). The rest of analytes were determined with the ICP-OES device (Varian, USA), using indium as internal standard. Hg was determined by CVAAS. Protein amount was obtained from the total nitrogen content using the Kjeldahl method with the factor of 6.25 usually employed for foodstuff. The content of the soluble protein was determined by the incubation of the samples with the reagent of Bradford (Sigma, Spain) for 5 min at room temperature. The absorbance measurements were run at 595 nm versus a standard curve of bovine serum albumin (Sigma, Spain). The total lipid amount was measured following the indications of the Folch method (Folch et al., 1957). The mixtures were homogenized using 20 parts of chloroform:methanol (2:1) and one part of the sample prior centrifugation (10 min, 3000 rpm, 15 °C). The lipid amount was gravimetrically obtained after the chloroform removal (40 °C, 320 mbar).

The total phenolic content was spectrophotometrically determined as gallic acid equivalents using the Folin-Ciocalteau reagent (1 N) in the presence of sodium carbonate (20 %) (Singleton and Rossi, 1965). The mixtures containing the tested samples were incubated for 45 min at room temperature in darkness. The absorbance measurements were run at 765 nm.

The carbohydrate content was obtained after an acid digestion with sulfuric acid at 72 % (30 °C, 60 min). The liquid fraction was filtered (0.45 μm) and analysed by HPLC (Agilent 1100, Germany) using an Aminex column (HPX—87H, 300 × 7.8 mm, BioRad, USA) (0.003 M H_2SO_4 at 0.6 mL/min as mobile phase, 60 °C).

Standard analytic methods (APHA, 2017) were applied for total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and ammonium concentration analysis. VFAs content was analysed by HPLC (Hewlett Packard, Agilent, 1100). Head space's methane content was obtained by analyzing 1 mL samples by gas chromatography on an HP 6890 PLUS chromatograph (GC, Agilent, Spain). Headspace volume was determined by manometric method.

2.7. Rheological behavior of the biomaterials

Aqueous solutions containing 8 % starch, 20 % residual solids from hydrothermal processing and 2.5 % glycerol were stirred in a hot plate with temperature control (87 °C) for 15 min. In addition, the formulation, can be supplemented with a portion of the liquid stream from the precipitation stage. Preliminary tests at different concentrations of each of the fractions were performed based on previous studies by the authors (Torres et al., 2020; Esteban-Lustres et al., 2024). Note here that the hot solutions were immediately placed on the selected molds, and were dried in a convective air oven (30 °C) until constant weight.

The gelled matrices were rheologically tested at 25 °C employing a MCR302 controlled stress rheometer (Anton Par, Austria). A sand blasted plate-plate geometry (25 mm) was employed. Samples were place on the lower plate (gap 1 mm), covered with light parafine oil, and rested 5 min prior to the rheology testing. Small amplitude oscillatory shear (SAOS) measurements were made at 15 Pa within the linear viscoelastic region (< 30 Pa). In all cases, tests were conducted at least in triplicate. Note here that the water syneresis of the biomaterials was weekly assessed at room temperature for 3 months.

2.8. Microbiologial testing

Microbiological testing of the extracted starch was made at least in triplicate using the plate count method for *Salmonella* spp., *Escherichia coli, Clostridium perfringens,* coliforms, molds, yeasts, total aerobic microorganisms grown at 30 °C and *Enterobacteriaceae* at 37 °C.

The films were also tested for the presence of pathogenic strains. Samples were aseptically inoculated in liquid medium based microbiology, LBM Thiol Broth Copan and further incubated under aerobic conditions at 37 °C and at 30 °C during 48 h. Additional cultivation in solid medium onto Polyvitex (PVX, agar-chocolate) (bioMérieux, Spain); Columbia blood agar (bioMérieux, Spain) and Columbia Nalidixic Acid agar (CAN, bioMérieux, Spain): 37 °C, in all cases at 37 °C under CO_2 atmosphere. Other solid media used were Schaedler agar (SCS, bioMérieux, Spain), at 37 °C under anaerobiosis, MacConckey agar (bioMérieux, Spain), at 37 °C under aerobiosis, Sabouraud Glucosado Agar (SGC2, bioMérieux, Spain) at 30 °C under aerobiosis. The incubation of the subcultures was carried out for 48–72 h for bacterial culture and for 10 days for fungal culture.

2.9. Plant biostimulant

Sunflower (*Helianthus annuus*) seeds were brought from the Local market (Ourense, Spain). The seeds were sterilized by immersing them in a diluted sodium hypochlorite (NaOCl, 4 %) solution for 5 min,

followed by thorough rinsing with distilled water five times (Teacă et al., 2008). Three solutions with 2 %, 6 %, and 10 % (*w/v*) concentrations were prepared from the original extract. These solutions were then centrifuged to separate the starch fraction (pellet) from the protein-rich fraction (supernatant). The starch fractions were collected, oven-dried at 50 °C, and weighed to quantify their yield. The protein-rich fractions were recovered and subsequently analysed for their effects on sunflower seed germination. The concentrations of the protein-rich fractions (C1, C2, C3) were determined gravimetrically. The seeds were then immersed in protein-rich fractions (C1, C2, C3) and kept for 8 h in the dark at 22 °C. Treated seeds were placed in Petri dishes containing filter paper and moistened (3 mL) of different concentrations of KW extract. The dishes were then kept under a 12 h light/12 h dark cycle at a constant temperature of 22 °C. Control seeds were treated with distilled water under the same conditions. Every four days, 3 mL of the extract was administered to each sample. Each experiment was performed in triplicate. Germination parameters and seedling length were daily measured for 10 days. Seedlings length (cm) were measured daily until day 9 of germination, and the fresh weight of the seedlings (g FW) was recorded on the final day. The following variables germination index (GI), germination percentage (G%), and germination rate index (GRI), were determined as described by Kader (2005):

$$G\% = (\text{Number of germinated seeds}/\text{Total number of seeds}) \times 100$$

$$GI = \sum (T_i \times N_i)$$

where t_i is the time (in days) after seed sowing and N_i is the number of seeds germinated on the day i.

$$GRI = G_1/1 + G_2/2 + \cdots + G_x/x$$

where G1, G2, …, Gx: The number of seeds that germinated on day 1, 2, …, x, respectively.

2.10. Statistical analysis

The statistical treatment of the data was made using the ANOVA model, one-factor analysis of variance using the PASW Statistics v.22 software (IBM SPSS Statistics, USA). Whenever the variance analysis presented differences, a post-hoc Scheffé test was used to differentiate between average values (95 % confidence, $p < 0.05$).

3. Results and discussion

3.1. Composition of kitchen waste

Outcomes from a previous characterization study on the selected model hospital kitchen, confirmed that regardless the different menus prepared along a week the wastes resulting from dinner and breakfast (D + B) contained mostly carbohydrates and those from lunch and snack (L + S) contained mainly protein (Esteban-Lustres et al., 2024). Two different and relatively homogeneous waste streams were used along the present study, each consisting on the mixture of analogous wastes from different diets. Data in Table 1 summarizes the proximal composition of both the mixture of wastes from D + B, a high carbohydrate content sample, and from L + S, a high protein content sample. The organic content of the KW studied is higher than in the wastes from other restaurant services, because of the selective removal of non-organic materials, like papers or packing materials.

The ash content was in the range of those reported for household and restaurant food wastes (Prasoulas et al., 2020; Esteban-Lustres et al., 2022). Both samples exhibited higher protein content than from a grill restaurant (Carmona-Cabello et al., 2020), which was among the protein richest food wastes (Carmona-Cabello et al., 2018COGSC; Esteban-Lustres et al., 2022). The carbohydrate content of the D + B sample was higher than in wastes from cafeteria and different types of restaurants

Table 1
Average composition (g/100 g KW) of the two types of wastes from the hospital kitchen and postconsumption wastes, corresponding to dinner+breakfast (D + B) and to lunch+snack (L + S) and their solid residue after hydrothermal pretreatment (160 °C).

	D + B		L + S	
	Before pretreatment	Solid residue	Before pretreatment	Solid residue
Ash (%, d.b.)	4.8 ± 0.2	1.2 ± 0.1	5.5 ± 0.3	1.3 ± 0.2
Protein (%, d.b.)	32.6 ± 1.3	8.2 ± 1.1	49.8 ± 2.1	11.3 ± 0.5
Carbohydrates (%, d.b.)	60.3 ± 1.9	14.3 ± 2.1	42.9 ± 4.3	11.2 ± 1.1
Lipids (%, d.b.)	5.3 ± 0.4	1.1 ± 0.1	6.9 ± 0.3	1.5 ± 0.1
C/N ratio	11.4 ± 0.8	10.9 ± 0.3	5.9 ± 0.3	6.2 ± 0.3
Total solids (%, d.b.)	93.8	98.6	94.4	98.6
Volatile solids (%, d.b.)	87.1	88.4	87.8	82.3

whereas the content in the L + S sample was comparable to those from cafeteria and grill restaurant (Vavouraki et al., 2013; Carmona-Cabello et al., 2020). The low lipid content, in the range 5.3 % for D + B samples and 6.9 % in L + S, are significantly lower than the range 17–33 % of values reported for households or other restaurants, cafeterias and canteens (Carmona-Cabello et al., 2020; Prasoulas et al., 2020; Xie et al., 2022; Esteban-Lustres et al., 2024). In the present study, the cooking oil was not found in the samples, because it had been previously and automatically segregated for recycling. Except for protein, the amount of the major components was in the range reported in literature, with 55–67 % carbohydrates, 11–27 % protein, 14–33 % oil and grease, 17–55 % starch and 2–7 % ash (Vavouraki et al., 2013; Carmona-Cabello et al., 2018; Xie et al., 2022). Therefore, the C/N ratio was statistically lower than the amount reported for other food wastes.

3.2. Hydrothermal treatment

The composition of the solid residues remaining after hydrothermal processing is also presented in Table 1. Carbohydrate content was reduced by 76.3 and 73.8 %, proteins by 74.8 and 77.3 % and lipids by 79.2 and 78.3 %, for D + B and L + S samples, respectively. The ash content reduction was similar, 75.0 % and 76.4 %, for D + B and L + S samples, respectively, leading to comparable values for the volatile solids content.

The hydrothermal pretreatment has been reported to enhance the deoiling facilitating the separation of oil, which could be used for biodiesel production and avoid biological inhibitory reactions (Xie et al., 2022). However, the oil content in the KW used in the present study was lower than in wastes coming from other restaurant services.

Temperature and time were jointly considered as key variables of the hydrothermal process, and were selected based on severity calculations, to maintain similar conditions as those from a previous study (Esteban-Lustres et al., 2024). Also the solid to liquid ratio could be influencing (Xie et al., 2022), but in the present study was fixed at a value non limiting the suspension mixing. The hydrothermal processing enables solubilization of valuable fractions and also sterilization.

A cascade multiproduct process was proposed for the transformation of this waste into biomaterials, biostimulants and bioenergy, because valorization following a biorefinery scheme is recommended (Carmona-Cabello et al., 2018; Mahjoub and Domscheit, 2020). Whereas abundant studies on the biorefineries from preconsumption wastes is available, postconsumption wastes require further work to develop separate valorization of components or alternative bioconversion routes (Esteban-Lustres et al., 2022). According to the mass balance in Fig. 1, 9.5 % starch was recovered, with 96 % purity. After starch separation a nutrient rich liquid phase was obtained, further evaluation as a carbon

and nitrogen source in bioconversion processes is needed. Another fraction can be destined to be incorporated in starch based formulations.

3.3. Starch based biomaterials

Restaurant wastes contain an average of 28 % starch, allowing this fraction to be proposed for large scale uses (Carmona-Cabello et al., 2018). Commonly, the valorization trough biodegradation pathways has been proposed, and can be illustrated with two examples. The starch separated after acidic pretreatment of garden and kitchen waste mixture in a ratio of 1:3 was enzymatically hydrolyzed to serve for ethanol bioconversion and the solids were destined to biogas production (Karimi and Karimi, 2018). A washing pretreatment with water of KW was proposed to remove more salt and cooked oil in an integrated multi-product biorefinery process to produce biodiesel, biogas, biofertilizer and bacterial cellulose (Wu et al., 2021).

Synthetic polymers represent an environmental problem and alternative biodegradable and renewable materials are needed. Therefore, in this study the valorization of the starch fraction to biomaterials was preferred to the energetic use. Starch can be used to prepare inexpensive biodegradable biomimetic films for biomedical applications (Das et al., 2020), as efficient wound dressings (Raina et al., 2022), or as an acceptable matrix for animal feed (Sancho et al., 2004). However, in comparison to other natural polymers, such as chitosan, collagen, gelatin or alginate, starch offers deficient operation and shape stability in liquids. The addition of crosslinkers is usually required to enhance its

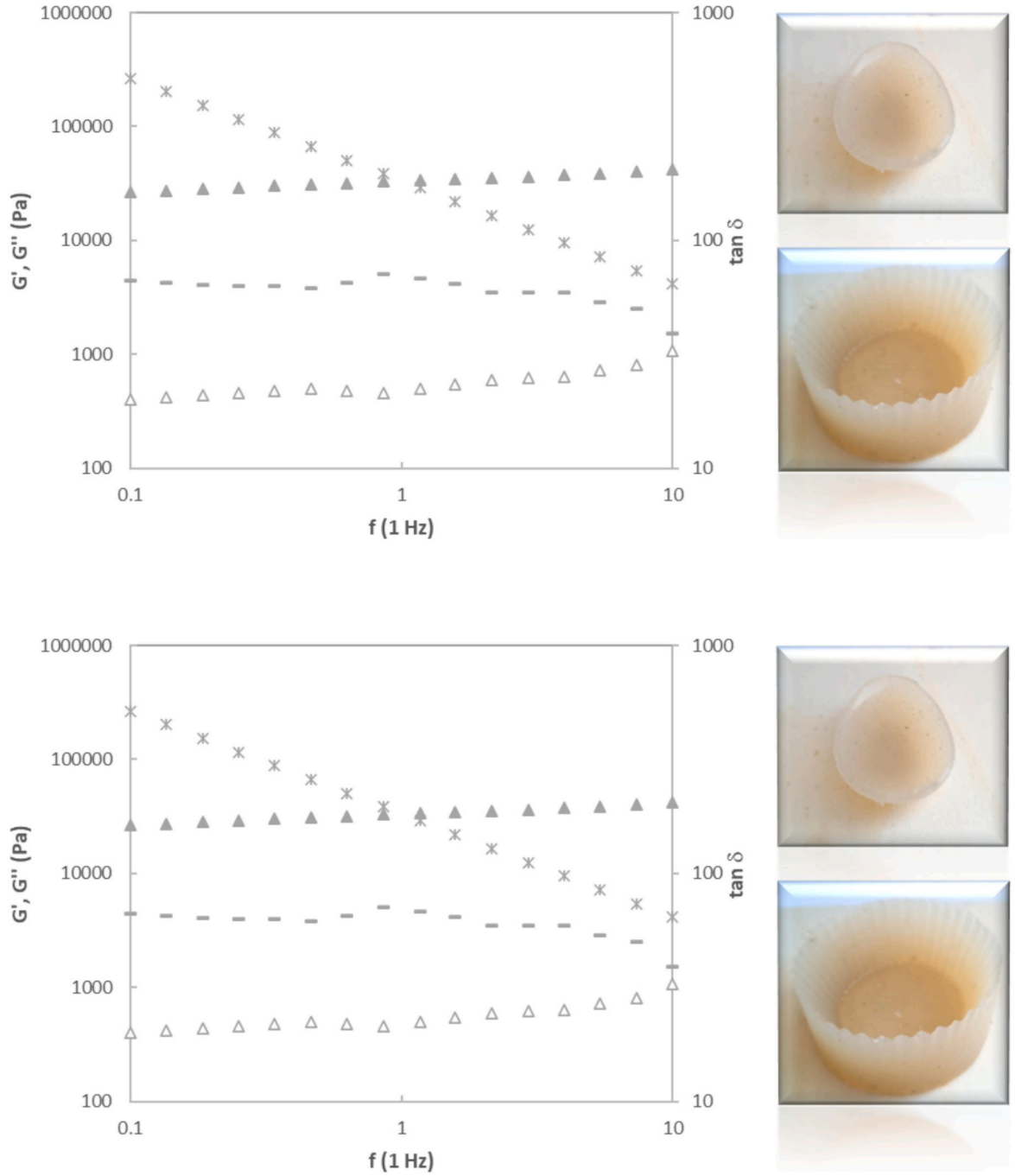

Fig. 2. Rheological features of the representative developed gelled matrices (left) for different molds (right). Symbols: G' (closed triangles), G" (open triangles), complex viscosity (crosses) and phase tan δ (dashed lines).

mechanical features.

In this framework, Fig. 2 shows the mechanical features at 25 °C of a representative gelled matrix made with fractions (8 % starch, 20 % residual solids) from the hydrothermal treatment of the KW samples and incorporated with 2.5 % glycerol. The viscous and elastic profiles [viscous (G") and elastic (G') moduli] exhibited a typical gel character (G' > G", both moduli almost invariant with the frequency) (Torres et al., 2014). The presence of the residuals solids from hydrothermal treatment involved a relevant strengthening of the gelled matrix, when compared with those previously reported for this starch (Esteban-Lustres et al., 2024). Although, the incorporation of a plasticizer as glycerol was required here for the gel network reinforcement that allows adequate moldability without breakage when cooling.

Hydrogels with modified starch and polyacrylic acid hydrogel systems (Zhou et al., 2022), with polyvinylalcohol, citric acid and glycerol for wound dressing film (Das et al., 2020) were reported, where higher plasticizers content (around 35 %) was required for matrices prepared with similar starch content. Simionescu et al. (2013) found that the addition of other natural biopolymers as gelatin to starch-based gelled matrices increased the network flexibility and shape stability. Other authors (Pang et al., 2014) indicated that the presence of some proteins can have a negative impact on the rheological features of gelatin hydrogels, contrarily to those developed with starch. Improved rheological characteristics was identified for hydrogels made with alginate and carrageenan for extrusion based bioprinting (Raus et al., 2021). It should be highlighted that the proposed HKW starch-based can preserve suitable gel mechanical performance after one month storage at room temperature. The ability to hold water of the proposed biomaterials in the environment was reduced at 10 % after the tested storage period, whereas those previously made with the same starch in the absence of the solids and glycerol exhibited a decrease in the water content of the 25 % after 1 week of storage (Esteban-Lustres et al., 2024).

3.4. Proteins

The escalating global demand for protein, a cornerstone of a balanced diet, presents significant environmental and food security challenges (Sranacharoenpong et al., 2015). Mitigating protein waste is thus not merely an economic consideration but a critical imperative for sustainable resource management and alleviating food insecurity. A promising avenue for addressing these issues lies in the valorization of food waste through sustainable conversion technologies, which can unlock substantial protein reserves. These innovative approaches hold considerable potential to contribute to global hunger alleviation. Beyond their nutritional significance, these recovered proteins also possess substantial industrial value, finding diverse applications ranging from nutraceuticals to advanced materials. Recent advancements highlight their utility in creating innovative biomaterials such as bioplastics, organic solar cells, and light-emitting devices (Zhou et al., 2023). Our investigation into hospital food waste supports this model, revealing it as a rich and readily available source of high-quality proteins that can be effectively extracted using sustainable hydrothermal treatments involving subcritical water. A total of 52 proteins were consistently identified across all samples via LC-MS/MS analysis (Table S1). Overall, the results revealed a pronounced prevalence of animal-derived proteins. Specifically, a significant portion of the identified proteins originated from common livestock and aquatic sources: chicken constituted 23 %, followed closely by pig and bovine proteins, each contributing 21 %, and fish proteins accounting for 19 % of the total identified proteins (Fig. 3.a). Smaller percentages were represented by proteins of plant (10 %) and fungal origin (6 %). Given that the protein supplementation market is a robust and rapidly expanding sector (Patel et al., 2023), the recovery of high-quality animal proteins from a waste stream represents a significant opportunity for sustainable product development. Moreover, essential amino acids comprised a considerable percentage (43 %) of the total amino acid content across all identified proteins. These results are particularly noteworthy, as animal proteins typically possess a complete amino acid profile, including all essential amino acids vital for human health.

Protein type analysis, based on the sum of the intensities of each protein within its category, revealed that collagen proteins constituted the majority (65 %) of all identified proteins across samples, followed by 27 % of proteins from various muscle tissues (Fig. 3.b). Egg proteins and enzymes, primarily involved in carbohydrate metabolism, constituted 3 %. Less represented categories included seed and nuclear proteins, ion transporters, defense response proteins, and other structural proteins (Fig. 3.b). The most abundant proteins identified were bovine and chicken collagens, followed by bovine and fish myosins (Table 2). Furthermore, significant quantities of egg proteins, including albumin, ovalbumin, and apovitellenin, as well as seed proteins, notably glutelin, were detected.

Collagen is a highly valued ingredient, capable of enhancing the nutritional profile, improving texture, and extending the shelf life of various food products (Ahmad et al., 2024). Beyond food, collagen boasts established applications in diverse fields such, as medicine and cosmetics (Shenoy et al., 2022). Furthermore, collagen supplements are widely recognized for their benefits in maintaining the health and vitality of key bodily structures, including skin, hair, nails, and joints (Shenoy et al., 2022). Consequently, the high yield of collagen recovered from hospital food waste presents a clear and compelling pathway for its repurposing into high-value products, thereby significantly contributing to a circular economy model.

Our LC-MS/MS analysis also provided clear insights into the distribution and content of identified proteins across the various conditions (Fig. 3.c). The quantity and nature of the extracted proteins were significantly dependent on both the types of wastes and the processing temperature. Specifically, the most substantial protein recovery, in terms of the number of unique proteins identified, was observed in the D + B 160 and L + S 160 samples, which accounted for the 92 % and 83 % of all identified proteins, respectively (Fig. 3.c). These results suggest that the highest temperature tested was highly effective in facilitating the release of the greatest number of proteins from the raw material. However, by summing the intensities of all identified proteins in each condition (a direct measure of protein concentration), we found that the richest samples originated from lunch and snack wastes (L + S), regardless of the temperature used (Fig. 3.d).

The distribution of main protein types across the tested conditions (Fig. S1) clearly indicates that structural proteins were most prevalent in lunch and snack waste (L + S) samples compared to dinner and breakfast waste (D + B) samples. Furthermore, higher temperatures generally improved the extraction of muscle proteins, while egg proteins were more abundant in samples from dinner and breakfast wastes treated at 160 °C.

At the elevated temperatures used and under subcritical water conditions, proteins are known to undergo hydrolysis, breaking down into smaller peptides and amino acids (Álvarez-Viñas et al., 2022; Hou et al., 2017). The formation of protein hydrolysates is particularly significant due to their wide-ranging applications. In fact, the generated peptides are extensively utilized as highly digestible and bioavailable food and feed additives, especially valued in animal nutrition where they can improve growth and feed efficiency (Hou et al., 2017). Furthermore, recent research highlights their potential as biostimulants in sustainable agriculture, promoting plant growth and resilience (Malécange et al., 2023). This application has already been successfully demonstrated with peptides-rich algae extracts produced via similar green extraction technologies involving hydrothermal processing with subcritical water (Domingo et al., 2023b).

Lastly, the generation of free amino acids from protein hydrolysis opens up additional avenues for valorization. Amino acids are fundamental building blocks with diverse industrial applications, including their use in food and beverage fortification, specialized animal feed formulations, pharmaceutical manufacturing, cosmetic products, and

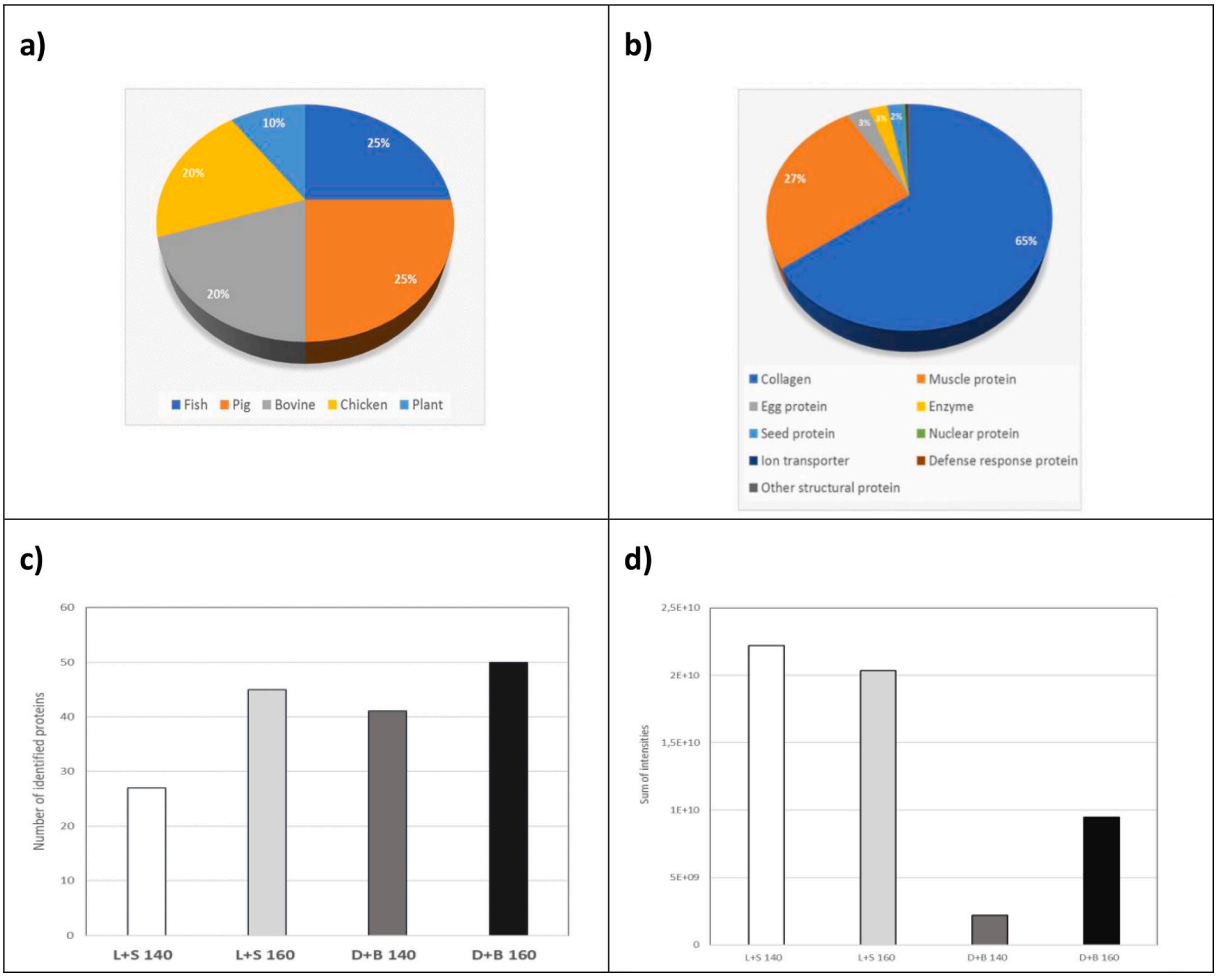

Fig. 3. Pie chart of **a)** the types of sources and **b)** the type and function of the proteins identified in all samples analysed. Distribution of the number **c)** and the sum of intensities **d)** of proteins identified in the 4 extraction conditions tested.

Table 2
List of the 20 most abundant proteins identified in all samples.

Protein ID	Protein name	Source	Total intensity	Type
A0AAA9TY75	Collagen type I alpha 1 chain	Bovine	11,789,000,000	Extracellular matrix structural constituent
A0A8V0XK94	Collagen type I alpha 2 chain	Chicken	5,871,600,000	Extracellular matrix structural constituent
F1MRC2	Myosin-2	Bovine	2,877,100,000	Muscle protein
A0A3B4BHT1	Myosin	Fish	991,030,000	Muscle protein
A0AA47MLM9	Myosin heavy chain	Fish	505,190,000	Muscle protein
A0AA47NRF1	Myosin heavy chain	Fish	492,340,000	Muscle protein
A0A3Q1LYQ9	Myosin heavy chain 1	Bovine	463,260,000	Muscle protein
A0A2H4Y814	Ovalbumin	Chicken	365,370,000	Egg protein
A0A8V1ADM3	Myosin heavy chain	Chicken	350,900,000	Muscle protein
A1XQT6	Myosin light chain 1/3	Pig	340,980,000	Muscle protein
A0A8V0XGW5	Apovitellenin-1	Chicken	270,430,000	Egg protein
A1YQH2	Glutelin	Plant	213,010,000	Seed protein
A0A8D1GE67	Myosin-7	Pig	212,600,000	Muscle protein
T1T4Y4	Glutelin	Plant	195,010,000	Seed protein
A0A287AD38	Beta-tropomyosin	Pig	194,340,000	Muscle protein
A0A8D1Y0H3	Titin	Pig	189,580,000	Muscle protein
A0A286ZYX8	Fructose-bisphosphate aldolase	Pig	177,030,000	Carbohydrate metabolism protein
P02769	Albumin	Bovine	155,080,000	Egg protein
A0A672L5W6	Phosphopyruvate hydratase	Fish	112,490,000	Carbohydrate metabolism protein
A0AAD3NJG7	Actin	Fish	111,720,000	Muscle protein

agrochemical production (Zhao et al., 2022).

3.5. Biostimulant effect of protein-rich fraction on sunflower seed germination

The protein-rich fraction clearly demonstrated a positive effect on the germination of sunflower seeds, as illustrated in Fig. 4. The

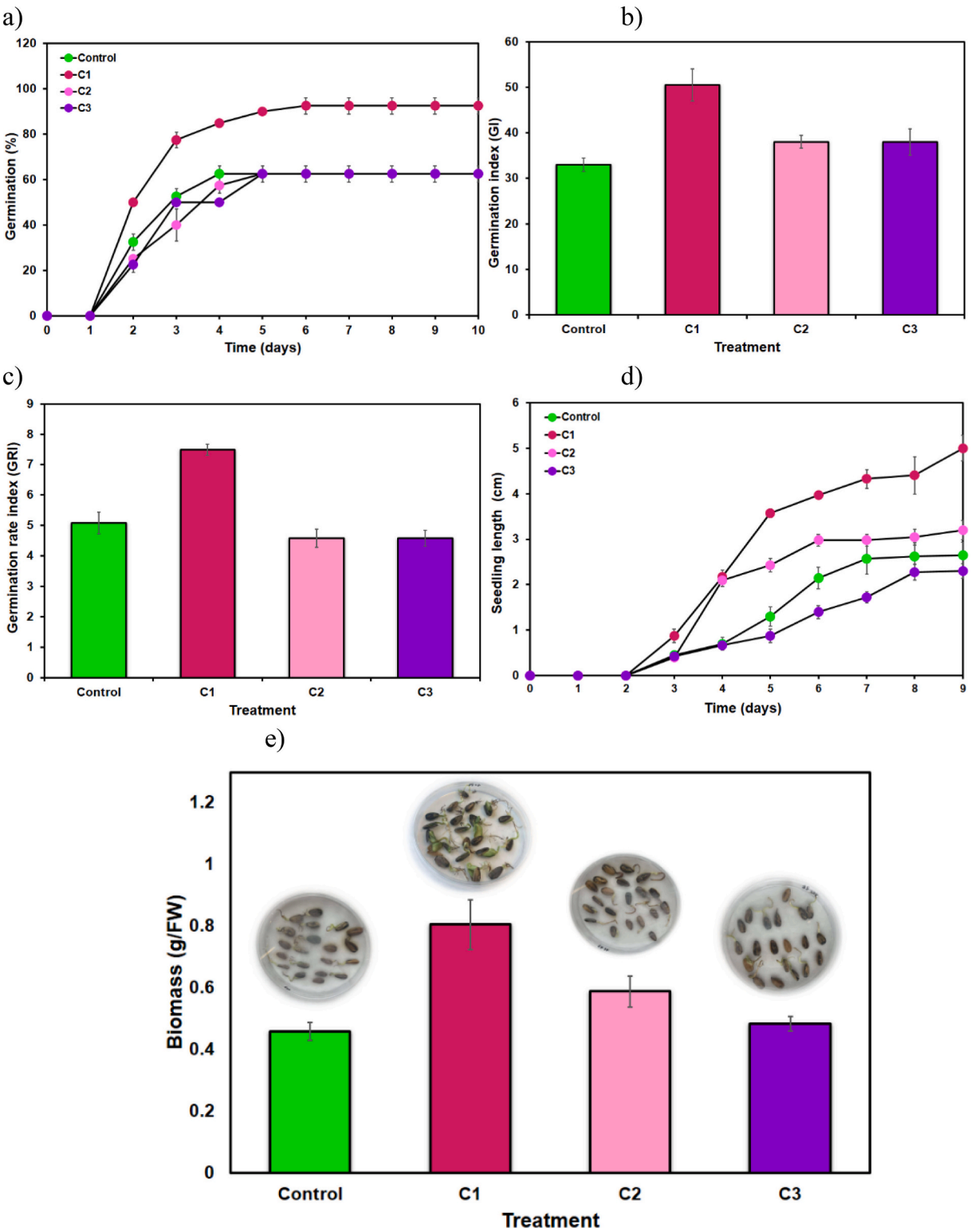

Fig. 4. Effect of protein rich fraction on the percentage of germination (a), index of germination (b), rate index of germination (c), seedling length (d) and fresh biomass (e) of *Helianthus annuus* seeds. Untreated seeds (Control); treated seeds: C1 (0.01), C2 (0.03), C3 (0.06) g/mL.

Germination Percentage (GP%, Fig. 4.a) of seeds treated with the lowest concentration (C1: 0.01 g/mL) reached 90 % by day 5 and stabilized at 93 % by day 6, indicating a significant enhancement compared to the untreated control. In contrast, the control seeds (untreated) exhibited a lower GP%, reaching approximately 63 % by day 4. Seeds treated with higher concentrations, C2 (0.03 g/mL) and C3 (0.06 g/mL), showed a lower GP% than the control during the initial germination period (days 2–4). However, by day 5, the GP% of these treatments leveled off to rates comparable to the control. Fig. 4b demonstrates that seeds treated with the lowest concentration (C1, 0.01 g/mL) of the protein-rich fraction achieved the highest Germination Index (GI), surpassing both the control and higher concentrations (C2 and C3). Fig. 4c highlights that C1 also resulted in the fastest Germination Rate Index (GRI), improving both the efficiency and speed of germination. In contrast, higher

concentrations (C2 and C3) showed slower rates, potentially indicating an inhibitory effect. This dose-dependent response identifies C1 as the most effective treatment for enhancing sunflower seed germination. Fig. 4d depicts the positive impact of the protein-rich fraction on seedling length. Treatment with the lowest concentration (C1) consistently resulted in the highest increase in seedling growth over 9 days, reaching a maximum length of 5 cm and exceeding the control and other treatments. The control seedlings show limited growth, with a final length of 2.65 cm, indicating a lack of external stimulation. C2 exhibits moderate improvement, reaching 3.2 cm by day 9, while C3 shows the least improvement among the treatments, with a final length of 2.3 cm. This shows that, while C1 supports optimum germination, greater amounts may impede it. Fig. 4e illustrates the fresh weight of sunflower seedlings on the final day of germination across treatments. The C1 treatment (0.8 g) achieved the highest biomass, significantly outperforming the control (0.45 g). C2 improved fresh weight moderately (0.58 g), whereas C3 (0.48 g) showed minimal improvement. These findings highlight the dose-dependent effect of the protein-rich fraction, with C1 being the most effective in promoting seedling growth. The findings highlight the biostimulant effect of the protein-rich extract on sunflower seed germination, indicating its ability to promote both germination and early seedling growth. This improvement is attributed to the existence of bioactive compounds, primarily amino acids and peptides that play crucial roles in metabolic processes and enzymatic functions (Atilio and Causin, 1996; Rai, 2002). Furthermore, the extract contains essential nutrients, such as nitrogen, that promote seedling growth, and minor amounts of phenolic compounds, which may offer antioxidant benefits. These components improve the physiological processes (Sierras et al., 2016) essential for germination and vigorous seedling growth, with the clearest impacts observed at a concentration of C1 (0.01 g/mL). Hussain et al. (2024) demonstrated the beneficial effects of the amino acid tryptophan on sunflower (*Helianthus annuus* L.) growth and stress tolerance. Their findings revealed that tryptophan enhances plant growth by improving germination rates and supporting stress tolerance. Sun et al. (2024) reviewed the influence of amino acids, phenols, several sources of protein hydrolysates (comprising free amino acids and polypeptides), and phenolic biostimulants on the growth of different species of plants.

Our findings emphasize the potential of the obtained protein-rich fraction at concentration C1 as a sustainable and effective biostimulant to enhance crop growth. Furthermore, this approach might be a potential choice for use with different plant species, offering a versatile solution for improving agricultural productivity.

Protein hydrolysates are a category of plant biostimulants known for their phytohormone-like effects on plant development. They consist of a complex mixture of polypeptides and free amino acids, and may also include macro- and micronutrients, as well as polysaccharides and lipids derived from the original raw materials (Kim et al., 2019a, 2019b; Pasupuleti et al., 2010). Sorrentino et al. (2021) showed that protein hydrolysates enhanced *Arabidopsis thaliana* seed germination, growth, and salt tolerance. PHs contain bioactive peptides with phytohormone-like activities that modulate growth and stress responses by influencing hormone signaling pathways. The authors observed that protein hydrolysates impact key metabolic processes, particularly altering hormonal balance, suggesting a regulatory role in plant development under stress. Wang et al. (2022) examined the effects of seed priming with protein hydrolysates on tomato germination and found that it promoted the activity and gene expression of crucial enzymes, including amylase and sucrose synthase. This treatment also elevated the concentrations of soluble sugars, proteins, and free amino acids, thereby facilitating more efficient mobilization of stored reserves during germination.

Since working with these complex mixtures makes it harder to attribute effects to particular molecules, it would be useful to test isolated or purified compounds in order to better understand and compare their specific biostimulant effects. Also, the concept of biostimulant is quite broad and not very precise, since it can refer to different effects, from improving seed germination to modifying carbon metabolism or increasing stress tolerance. These effects are not always correlated, an extract may produce multiple biostimulant responses, some beneficial and others potentially negative.

3.6. Microbiological testing

In the starch fraction no *Salmonella* spp. were detected and after plate counting the CFU/g was under 10 for Coliforms, *Clostridium perfringens*, *Escherichia coli* β-glucuronidase positive, mould and yeast, total aerobes and Enterobacteria at 37 °C. In the films different *Bacillus* spp. could grow, but *Salmonella* spp., coliforms (including *Escherichia coli*, *Clostridium perfringens*), yeast and filamentous molds were not detected. The conditions of the present study using short treatment times but high temperature could be suitable for the inactivation of model microorganisms in both the starch recovered from the liquid fraction and in the formulated films. This preliminary testing confirms the potential safe utilization of the biodegradable material alternative to plastics and suitable for manufacture of different recipients and objects of quotidian use.

The thermal treatment was suitable for these microorganisms selected for their wide distribution in the environment, as indicators of pollution or as common pathogens. Hydrothermal processes represent a chemical free method using only water and can destroy pathogens. This treatment is widely employed for the medical wastes, feed and human food sterilization. Pressure sterilization can eliminate most microorganisms from medical wastes and pressure steam is also used as sterilization technology for different materials generated as medical waste (121 °C for 20 min under 100 kPa). Georganas et al. (2022) reviewed the potential of hydrothermal processing, for the minimization of biological hazards in food residues from food services of hospitality sector, restaurants, households and education institutions. Chen et al. (2012) confirmed that the hydrothermal processing (120 °C, at least 40 min, 0.3 MPa) can reduce or eliminate indigenous microorganisms, yeasts and molds, total aerobic counts, total coliforms, and *Staphylococcus aureus*, in raw food residues from student canteens. Biodegradable fractions present in food wastes, collected from fishmonger and greengrocer sections, and treated at least at 65 °C for 20 min lowered the total count of *Enterobacteria*, *Staphylococcus aureus* and *Clostridia* to convert them into acceptable raw materials for animal feed (Sancho et al., 2004).

3.7. Biochemical methane potential

The biochemical methane potential of the hospital kitchen wastes was studied for 66 days. Both the carbohydrate rich sample (D + B) and the protein-rich sample (L + S) and their respective autohydrolysis solid waste (R_D + B and R_L + S) were evaluated. Their performance is shown in Fig. 5.

The two raw samples (D + B and L + S) show similar methane potential of 283.86 ± 45.02 and 279.34 ± 50.94 mL CH_4/g VS, after the autohydrolysis (R_D + B and R_L + S) they show slight variation, 244.48 and 295.78 mL CH_4/g VS, respectively. The VFAs control reached a maximum yield of 54.4 %, similar to the kitchen waste. The standard deviation is remarkable, most likely, a result of the heterogeneous nature of the kitchen wastes, which presented easily noticeable differences among particles.

The BMP of these kitchen wastes are lower than the usual potential for mesophilic anaerobic digestion of kitchen waste, ranging from 350 to 450 mL CH_4/g VS (Gallipoli et al., 2020; Khanthong et al., 2023; Kim et al., 2019a, 2019b; Ye et al., 2015). Inhibition by VFAs and low pH can be dismissed, as there was no assay in which VFAs were detected, meaning all the VFAs were converted to methane, and pH decreased a maximum of 0.09.

The main difference between the present samples and those from literature is the lower C/N ratio, caused by the high protein amount of the kitchen waste (Table 1). These C/N ratios must be suboptimal for

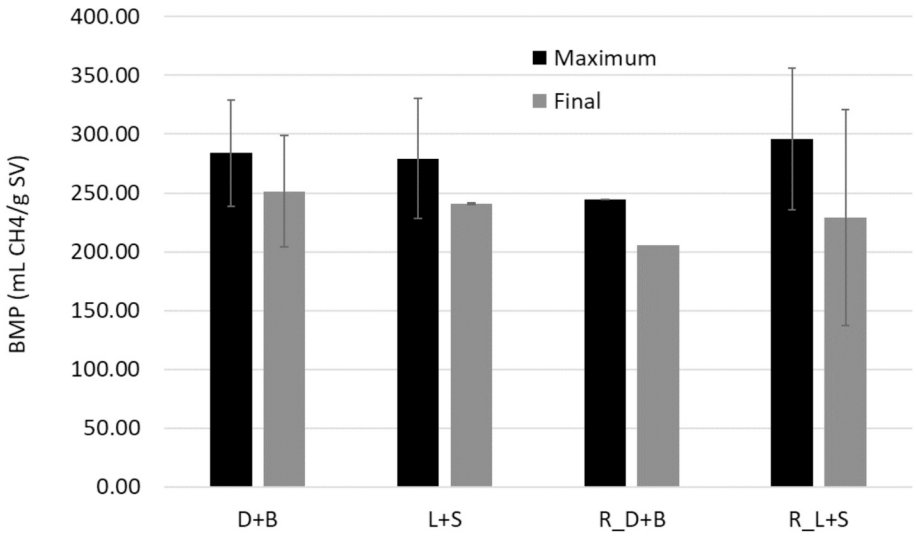

Fig. 5. Maximum values of the biochemical methane potential (mL CH_4/g VS) reached by each kitchen waste (D + B, L + S, R_D + B and R_L + S). Final values of the biochemical methane potential (mL CH_4/g VS) were evaluated after 66 days.

anaerobic digestion of kitchen waste, although the final ammonium concentration reached is low: a maximum of 161.6 ± 60.1 mg/L in a L + S sample and minimum of 99.2 ± 4.38 mg/L in a R-D + B sample.

The effect of the thermal treatment is not the same in the two samples, as Pagliaccia et al. (2019) and Gallipoli et al. (2020) also experienced. Thermal processing can enhance de anaerobic digestion by degradation of organic polymers, at the same time, complex refractory organic compounds could be formed and reduce biodegradability (Pagliaccia et al., 2019). Moreover, the kitchen wastes were already exposed to high temperatures during the cooking process, so the effect of autohydrolysis and other thermal treatments has less of an impact on kitchen waste than on other substrates like seaweed (Mhatre et al., 2019; Flórez-Fernández et al., 2021; Rodríguez-Iglesias et al., 2024).

The production of methane from pre-treated animal wastes is not always larger than the production when untreated samples are used, and could even decrease, due to the inhibitory impact of long chain fatty acids and ammonia, released during the hydrolysis of lipids and proteins. Other authors have proposed an optimal treatment temperature in the range 160 to 190 °C, during 20–30 min. Higher temperature promotes the formation recalcitrant compounds (Carrere et al., 2016).

The global cascade treatment proposed in this study allowed the production of a nutrient rich liquid phase and starch-based biomaterial, from the first autohydrolysis stage, as well as a biostimulant from the second stage and biomethane from the solids (Fig. 1). The advantages compared to the direct digestion of this waste could be in relation to the higher value added products, and the fact that the biomethane potential is not significantly lowered, although only a third fraction of the solids is destined to this use. The hydrothermal treatment proposed is a scalable technology and is also established at commercial scale for sludge treatment, to improve dewaterability and digestibility. In order to compensate the cost of this highly energy demanding stage, alternatives such as the assistance of microwave heating or the development of higher added value biodegradable biomaterials could be explored.

4. Conclusions

This study is a complementary approach to the management and valorization of the kitchen residues. The studied pre- and post-consumption wastes are a model system useful to analyse value added solutions. The waste streams from dinner+breakfast and lunch+snack were grouped and the composition of these mixtures were relatively constant, despite the different diets simultaneously used in the hospital. The kitchen residues exhibited lower lipid content and higher protein amount than other kitchen residues. The protein amount was larger in the samples corresponding with the lunch-snack.

Hydrothermal extraction with water under subcritical conditions in two sequential stages solubilized more than 75 % of the samples. The soluble fraction from the initial treatment stage contained a starch rich and that from the second contained a nutrient rich fraction. Both could be combined for the development of biopolymers that could replace other packaging materials and the nutrient containing liquid could be further evaluated for bioconversion. The solubles from the second stage, enriched in protein hydrolysates was also useful as a plant growth biostimulant. The final solid residue was destined to anaerobic digestion. The autohydrolysis treatment did not take a toll on the methane potential of the kitchen waste, but higher valuable fractions could be removed in initial stages.

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CRediT authorship contribution statement

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editing, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Herminia Domínguez reports financial support was provided by Government of Galicia Department of Education Science Universities and Professional Training. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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