Supporting Information

Sustainable biotransformation of microalgae *via* probiotic fermentation for enhanced functional, nutritional, and sensory properties

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Supporting Methods

Supporting Data

Supporting Tables

Supporting Figures

Figure S2. Extracted ion chromatograms (EICs) from LC-MS showing the bioconversion of precursor amino acids during *L. plantarum*-mediated fermentation of microalgae (MA) over 96 hours.

Figure S3. Olfactory evaluation of microalgae fermented with *L. plantarum.*

Appendix

Supporting Methods

Unless specified otherwise, chemicals and reagents are purchased from Sigma-Aldrich (St. Louis, MO, USA).

Bacterial strains cultivation

Non-lactic acid bacteria (non-LAB) strains—including *Bacillus* spp., *Cupriavidus necator*, *Microbacterium imperiale*, *Weizmannia coagulans*, and *Priestia megaterium*—were cultured in Luria-Bertani (LB) broth at 37 °C with agitation at 200 rpm until mid-logarithmic phase ($OD_{600} \approx 0.4$). Lactic acid bacteria (LAB) strains were cultivated in De Man, Rogosa, and Sharpe (MRS) broth under identical conditions (37 °C, 200 rpm) until $OD_{600} \approx 0.4$. *Streptococcus thermophilus* was cultured separately in M17 broth (Difco™, Becton, Dickinson and Company, Sparks, MD, USA) at 42 °C, 200 rpm till a similar growth phase.

Protease assay

The proteolytic activity of the bacterial strains was qualitatively evaluated using the skim milk agar assay method. Skim milk agar was prepared with the following composition: 28 g/L skim milk powder, 5 g/L casein, 2.5 g/L yeast extract, 1 g/L dextrose, and 15 g/L agar in 1 L of distilled water, adjusted to a final pH of 7.0 ± 0.2 at 25 °C. 10 µL aliquot of the bacteria culture

supernatant was aseptically spotted onto the surface of the agar and incubated at 37 °C. Proteolytic activity, as indicated by a zone of clearance around the inoculation site, was monitored across 96 hours.

Lipase assay

The lipolytic activity of the bacterial strains was qualitatively assessed using the tributyrin agar assay method. Tributyrin agar was prepared by dissolving 20 g of tributyrin agar powder in 1 L of distilled water, followed by adding 10 mL of glyceryl tributyrate upon cooling to 80 °C after autoclaving. 10 µL of the bacterial culture supernatant was spotted on the tributyrin agar and incubated at 37 °C. Lipolytic activity, as indicated by a zone of clearance around the inoculation site, was monitored across 96 hours.

β-glucosidase assay

β-glucosidase activity of the bacterial strains was assessed by quantifying the hydrolysis of *p*-nitrophenyl-β-D-glucopyranoside (pNPG). Bacterial culture supernatants were obtained by centrifugation at 4,000 × *g* for 20 minutes at 4 °C. For each sample, 0.5 mL of the culture supernatant was mixed with 2 mL of 1 mM pNPG solution and incubated at 45 °C for 30 minutes. The reaction was terminated by the addition of 2.5 mL of 1 M sodium carbonate. The release of *p*-nitrophenol was quantified by measuring absorbance at 400 nm using a spectrophotometer. β-glucosidase activity was calculated based on a standard calibration curve constructed using a commercial β-glucosidase enzyme, and all reactions were performed in triplicates.

Cellulase assay

Cellulolytic activity of the bacterial strains was qualitatively determined using the carboxymethyl cellulose (CMC) agar assay method. 0.2% CMC agar was prepared based on the following composition: CMC 2 g, sodium nitrate ($NaNO_3$) 20 mL, dipotassium hydrogen phosphate (K_2HPO_4) 1 g, potassium chloride (KCl) 1 g, magnesium sulfate ($MgSO_4$) 0.5 g, yeast extract 0.5 g, agar 15 g, 1 L distilled water. 10 µL of the culture supernatant was spotted on the 0.2% CMC agar and incubated at 37 °C. Cellulolytic activity, as indicated by a zone of clearance around the inoculation site, was monitored across 96 hours.

Submerged fermentation of microalgae

Lyophilized *C. vulgaris* powder was reconstituted in 50 mL of sterile deionized water to a final solids content of 5 % (w/v). The suspension was autoclaved at 121 °C for 15 min, cooled to room temperature, and inoculated with *Lactiplantibacillus plantarum* at an initial density of 10^6 CFU/g. Fermentation was carried out in 250 mL baffled Erlenmeyer flasks containing 50 mL working volume, leaving adequate headspace for gas exchange. Submerged fermentation was conducted at 37 °C in a thermostatically controlled shaker incubator at 200 rpm for 96 h under dark, aerobic conditions. No external aeration or gas flushing was applied. As the microalgae biomass was non-viable, illumination was omitted, and no photosynthetic activity was expected. Uninoculated *C. vulgaris* biomass flasks served as controls and were processed identically. Samples were collected at 0, 24, 48, 72 h and 96 h for subsequent biochemical and sensory analyses. Harvested samples were immediately frozen at -80 °C and freeze-dried for 7 days. The dried fermentates were then ground into a fine powder using a sterile blender and stored at −20 °C until further analysis.

Biomass yield and percentage change over time

To determine the percentage dry yield of the biomass (% weight/volume), 0.5 mL of each sample of unfermented and fermented microalgae suspensions were pipetted into pre-weighed 5 mL tubes for each sample. The samples were frozen overnight in -80 °C freezer, followed by freeze-drying until fully dried. After drying, the tubes were weighed again to obtain the weight of the dry biomass. Data were analysed using GraphPad Prism version 8.0, and the percentage dry yield of the biomass (% weight/volume) and the percentage change in biomass (%) were calculated using the following formulae:

Dry Yield (%w/v) = (Weight of dry biomass (g) / Volume of wet sample (mL)) x 100

Percentage Change in Biomass (%) = [(Fermented biomass - Unfermented biomass) / (Unfermented biomass)] x 100

In-house olfactory evaluations

An in-house, untrained olfactory panel (n = 10) was recruited to perform time-course olfactory evaluations on microalgae fermentates inoculated with selected bacterial strains. Panelists assessed samples at various fermentation timepoints under blinded conditions, with all samples coded to eliminate bias. Aroma profiling focused on four key sensory attributes: grassy, sour, fishy, and earthy. Perceived odour intensity was rated using a structured 3-point scale, where 1 = *very weak*, 2 = *moderate*, and 3 = *very strong*. All evaluations were conducted anonymously. Panellists also completed a demographic and lifestyle questionnaire, which captured data on age, gender, ethnicity, dietary habits, smoking status, and self-rated smell sensitivity (on a 5-point scale, where 1 = *very poor* and 5 = *very strong*) (**Table S7**). Prior to

participation, all individuals were briefed on the study objectives and procedures and provided written informed consent.

Electronic tongue (E-tongue) analysis

The taste and flavour evolution of the fermented microalgae samples was analysed using the ASTREE E-tongue system (Alpha MOS, Toulouse, France), a sensor-based technology designed to mimic human taste perception. The system employs seven potentiometric sensors (AHS, ANS, CPS, CTS, NMS, PKS, SCS) alongside an Ag/AgCl reference electrode, enabling the detection of key taste modalities such as bitterness, sweetness, umami, sourness, and saltiness, thereby generating a comprehensive taste fingerprint of each sample. E-tongue analysis was conducted following this protocol[1]. Briefly, 300 mg of freeze-dried fermentate was weighed into a 50 mL Falcon tube and reconstituted with 30 mL of sterile water. The mixture was vortexed and shaken on a rotary shaker for 30 minutes at room temperature, followed by centrifugation at 4000 × g for 30 minutes to obtain the supernatant. Between each sample run, the sensors and reference electrode were rinsed with water for 10 seconds to prevent cross-sample interference. Each sample was analysed for 120 seconds, with measurements repeated nine times to ensure system stability. The sensor signal at the 120th second was extracted from the last six measurements and averaged to generate the final raw data. Principal component analysis (PCA) was conducted using R software, and biplots were generated to visualize sample clustering and taste profile evolution during fermentation.

Headspace Solid Phase Micro Extraction (HS-SPME) GC-MS Analysis

Headspace solid-phase microextraction (HS-SPME) was conducted using a 23-gauge, 50/30 μm DVB/CAR/PDMS fibre (Supelco, USA). A volume of 500 μL of the wet sample was transferred into a 20 mL headspace vial and spiked with 100 μL of an internal standard solution (2,3-dimethoxytoluene at 10 ppm). The sample was incubated at 80 °C for 10 minutes, after which the SPME fibre was exposed to the headspace for 30 minutes while agitated at 250 rpm. Volatile compounds were then thermally desorbed from the fibre in the gas chromatograph (GC) injector at 250 °C for 600 seconds. Subsequent GC-MS analysis was performed using an Agilent 7890B GC system coupled with a 5977B mass spectrometer and equipped with a multimode inlet (Agilent Technologies, USA). Separation was achieved on a polar J&W DB-Wax Ultra Inert capillary column (30 m × 0.25 mm I.D., 0.25 μm film thickness; Agilent Technologies). The injection was operated in split/splitless mode, with split ratios of 1:10. The oven temperature was initially set to 35 °C, then ramped at 100 °C/min to 60 °C, followed by 8 °C/min to 190 °C, and finally increased at 20 °C/min to 250 °C, where it was held for 6.5 minutes. Helium was used as the carrier gas at a constant flow of 1.0 mL/min. The mass spectrometer operated in electron ionization mode at 70 eV, with source and transfer line temperatures of 230 °C and 250 °C, respectively, and data was collected in full scan mode over the m/z range 35–450.

Untargeted metabolite analysis by LC-MS

Freeze-dried biomass (100 mg) was extracted with 20 mL of 50% aqueous MeOH. The mixture was vortexed briefly and sonicated for 10 min at room temperature. After sonication, the samples were centrifuged at 14,000 rpm for 5 min to separate the supernatant and solid biomass. The supernatant was transferred into LCMS glass vial for LCMS analysis (injection

volume: 5 uL). Supernatant which exhibited turbidity were further filtered using 0.45 µm Claristep hydrophilic filter (Sartorius, Goettingen, Germany) prior to LCMS analysis.

HPLC-MS analyses were conducted using Agilent UHPLC 1290 Infinity coupled to Agilent 6540 accurate-mass quadrupole time-of-flight (QTOF) mass spectrometer and an ESI source. Gradient elution that starts from 98% water with 0.1% formic acid to 100% acetonitrile in 0.1% formic acid over 8.6 min along with an Acquity UPLC BEH C18 (2.1 × 50 mm, 1.7 µm) column at a flow rate of 0.5 mL/min was used. The operating parameters for QTOF were the same as previously reported [2].

The HRMS data were processed and analyzed using Agilent MassHunter Qualitative Analysis version 10.0 software; The untargeted metabolites analysis and annotation was performed using MZmine 3.9.0 [3]; Compounds annotation in MZmine was performed by matching experimental MS/MS spectra against library MS/MS spectra. The actual identity of indole lactic acid, phenyl lactic acid, and hydroxyphenyl lactic acid was validated by comparing MS/MS spectra and retention time with analytical standards. Metaboanalyst 6.0 was used for heatmap data visualization [4].

Statistical analysis

Olfactory evaluation data were analysed using GraphPad Prism version 8.0. For each aroma attribute, mean intensity scores were subjected to two-way repeated measures ANOVA, with treatment (unfermented vs. *Lactiplantibacillus plantarum*-fermented) and fermentation time-point (0, 24, 48, 72 and 96 hours) specified as within-subject factors. Panellist variation was included as a blocking factor to account for individual differences. The assumption of

sphericity was not made, and Geisser-Greenhouse correction was applied where necessary. Statistical significance was determined at an alpha level of 0.05.

Figures preparation

BioRender (BioRender.com) was used to generate schematic figures for visualising experimental workflows and processes.

Supporting Data

Supporting Tables

Table S1. Enzymatic Activity Profiles of 22 Selected Bacterial Strains

Strains	Protease Activity	Lipase Activity	Cellulase Activity	β-Glucosidase Activity (mU/mL)
Cupriavidus necator	-	+	+	0.05
Microbacterium imperiale	-	-	+	0
Bacillus pumilus	+++	++	-	0
Bacillus subtilis	++	++	+++	0.07
Bacillus amyloliquefaciens	++	+++	++	0.73
Bacillus licheniformis	+	++	++	0.14
Weizmannia coagulans	-	+++	-	0.14
Priestia megaterium	+++	++	+	0

Lacticaseibacillus paracasei	+++	-	-	0.40
Lacticaseibacillus paracasei ATCC 11578	++	-	-	0
Lactiplantibacillus plantarum	-	-	-	0
Lactiplantibacillus plantarum	-	+	+	0.48
Lactiplantibacillus plantarum ATCC 14917	+++	-	-	0
Lacticaseibacillus rhamnosus	++	-	-	0.54
Limosilacobacillus fermentum	++	-	-	0
Streptococcus thermophilus	++	-	-	0
Liquorilactobacillus nagelii	++	-	-	0
Ligilactobacillus salivarius	++	-	-	0
Pediococcus pentosaceus	++	-	-	0.22
Pediococcus pentosaceus	++	-	-	0
Leuconostoc mesenteroides	++	-	-	0
Leuconostoc citreum	++	-	-	0

Agar assays were used to assess protease, lipase, and cellulase activity and are scored qualitatively. Symbols represent relative activity levels: – (no activity), + (low), ++ (moderate), +++ (high). β-glucosidase activity was quantified from culture supernatants and expressed in

236 milliunits per milliliter (mU/mL). Strains exhibiting **≥ 0.20mU/mL** of β-glucosidase activity
237 are classified as positive (values highlighted in red).

238 **Table S2: Dry biomass yield (%w/v) and percentage change (%) of unfermented and fermented microalgae biomass over 72 hours**

Sample	Dry Yield (% w/v)			Mean (n =3)	Standard deviation	Percentage change in fermented biomass (relative to unfermented controls)			Mean (n=3)	Standard deviation
	Replicate 1	Replicate 2	Replicate 3			Replicate 1	Replicate 2	Replicate 3		
Microalgae_0h (unfermented)	9.18	9.22	8.7	9.03	0.29	-	-	-	-	-
Microalgae_24h (unfermented)	8.92	9.16	9.24	9.11	0.17	-	-	-	-	-
Microalgae_48h (unfermented)	9.14	8.94	9.26	9.11	0.16	-	-	-	-	-
Microalgae_72h (unfermented)	9.4	9.1	9.08	9.19	0.18	-	-	-	-	-
*B. amyloliquefaciens*_MA_0h	9.2	9.26	8.72	9.06	0.30	0.22	0.43	0.23	0.29	0.12
*B. amyloliquefaciens*_MA_24h	7.94	8.16	8.16	8.09	0.13	-10.99	-10.92	-11.69	-11.20	0.43
*B. amyloliquefaciens*_MA_48h	8.38	7.72	8.26	8.12	0.35	-8.32	-13.65	-10.80	-10.92	2.67
*B. amyloliquefaciens*_MA_72h	6.22	5.46	6.04	5.91	0.40	-33.83	-40.00	-33.48	-35.77	3.67
*B. subtilis*_MA_0h	9.2	9.24	8.7	9.05	0.30	0.22	0.22	0.00	0.14	0.13
*B. subtilis*_MA_24h	8.18	8.32	8.14	8.21	0.09	-8.30	-9.17	-11.90	-9.79	1.88
*B. subtilis*_MA_48h	7.94	7.68	7.76	7.79	0.13	-13.13	-14.09	-16.20	-14.47	1.57
*B. subtilis*_MA_72h	7.7	7.42	7.14	7.42	0.28	-18.09	-18.46	-21.37	-19.30	1.80
*L. plantarum*_MA_0h	9.18	9.26	8.8	9.08	0.25	0.00	0.43	1.15	0.53	0.58

*L. plantarum*_MA_24h	9.2	9.46	8.98	9.21	0.24	3.14	3.28	3.22	3.21	0.07
*L. plantarum*_MA_48h	9.46	9.28	9.6	9.45	0.16	3.50	3.80	3.90	3.73	0.21
*L. plantarum*_MA_72h	9.82	9.5	9.68	9.67	0.16	4.47	4.40	4.54	4.47	0.07

Dry biomass yield (% w/v) and percentage change in microalgae biomass (%) during 72-hour fermentation with selected microbial strains. *B. amyloliquefaciens*, *B, subtilis, L. plantarum* are labelled as "*B. amyloliquefaciens*_MA", "*B. subtilis*_MA" and "*L. plantarum*_MA" respectively; unfermented samples are labelled as Microalgae. Fermentation timepoints are expressed as 0h, 24h, 48h, and 72h, corresponding to 0, 24, 48, and 72 hours of fermentation, respectively. Dry biomass yield was quantified as dry weight (% w/v) and percentage change was calculated relative to unfermented controls at corresponding time points. Data represent mean ± standard deviation (n = 3 biological replicates). Notably, biomass decreased progressively during *Bacillus spp.* fermentations, with *B. amyloliquefaciens* showing the highest reduction (~36% at 72 h), while *L. plantarum* showed a modest increase in biomass over time (~+5%).

Table S3: List of volatiles detected in unfermented microalgae and *L. plantarum*-fermented microalgae throughout fermentation

								Microalgae only (unfermented)					*L. plantarum*-fermented microalgae				
No	**Name**	**CAS No**	**Formula**	**Retention Time (min)**	**Retention Index (RI)**	**Compound class**	**Odour Description**	**0h**	**24h**	**48h**	**72h**	**96h**	**0h**	**24h**	**48h**	**72h**	**96h**
1	Acetic acid	64-19-7	C2H4O2	11.2	1462	Acid	Sharp, sour, vinegar	0.000373829	5.59499E-05	0.000102105	7.71635E-05	0.000117517	8.44834E-05	0.00023027	2.85498E-05	1.42339E-05	0
2	Butanoic acid	107-92-6	C4H8O2	13.9	1640	Acid	Sharp, acetic, cheese, dairy	0.000224656	7.06529E-05	8.0395E-05	0.000100432	9.52012E-05	7.0737E-05	0.00022923	0	0	0
3	Hexanoic acid	142-62-1	C6H12O2	17.0	1860	Acid	Sour, fatty, sweaty, cheesy	1.729911E-05	1.32659E-05	2.2313E-05	1.95154E-05	2.3045E-05	2.02186E-05	2.65836E-05	4.02418E-06	5.36998E-06	0
4	Octanoic acid	124-07-2	C8H16O2	19.5	2077	Acid	Fatty, waxy, rancid, cheesy	1.731004E-05	4.65514E-05	3.47141E-05	2.71749E-05	5.11016E-05	4.19597E-05	2.47645E-05	0	0	0
5	Propanoic acid	79-09-4	C3H6O2	12.6	1549	Acid	Pungent, acidic, cheesy, vinegar	0	0	0	1.44669E-05	1.71544E-05	0	1.33469E-	0	0	0

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6	1-Hexanol	111-27-3	C6H14O	9.6	1358	Alcohol	Green, fruity, sweet	1.11306E-05	7.48597E-06	6.23502E-06	6.79656E-06	5.62038E-06	7.58196E-06	8.14862E-05	0	0	0
7	1-Octanol	111-87-5	C8H18O	12.6	1548	Alcohol	Mushroom, green, waxy	0	0	0	0	0	0	0	0	0	4.31749E-06
8	1-Octen-3-ol	3391-86-4	C8H16O	11.1	1453	Alcohol	Mushroom	0.000108602	7.89387E-05	0.00011246	0.000122192	0.000126945	0.00011717102	0.00011291286	5.94533E-05	4.57677E-05	4.48933E-05
9	1-Pentanol	71-41-0	C5H12O	8.0	1256	Alcohol	Fresh, bready, winey	3.40815E-05	0.000108101	0.00011004	0.000106372	0.000110896	6.81737E-05	0.000162888	5.75653E-06	9.02769E-06	9.83897E-06
10	1-Penten-3-ol	616-25-1	C5H10O	6.6	1163	Alcohol	Pungent, green, horseradish, green vegetable, tropical, fruity	0.000130451	0.000133269	8.80199E-05	0.000114489	0.000130628	9.5083E-05	7.84661E-05	0	0	0
11	Isobutanol	78-83-1	C4H10O	5.7	1098	Alcohol	Ethereal, winey	0	0	0	0	0	0	0	6.8378E-	0	0

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12	Isopentyl alcohol	123-51-3	C5H12O	7.4	1215	Alcohol	Fusel, alcoholic, fruity, banana	3.87013E-06	1.64211E-05	3.58926E-06	4.64628E-06	5.24433E-07	2.8019E-06	1.3368E-05	6.88474E-05	7.67948E-05	4.84116E-05
13	Isophytol	505-32-8	C20H40O	21.1	2290	Alcohol	Floral, herbal, green	0.000283568	0.000247227	0.00030138	0.000257763	0.000218515	0.000252264	0.000298784	0.000306844	0.000292597	0.000368416
14	2-Heptenal, (Z)-	57266-86-	C7H12O	9.2	1334	Aldehyde	Green, fatty, sweet	3.57133E-05	4.22325E-05	2.06006E-05	3.77043E-05	3.64459E-05	6.31658E-05	3.86303E-05	5.35539E-06	1.19544E-05	1.84186E-05
15	2-Hexenal, (E)-	6728-26-3	C6H10O	7.6	1229	Aldehyde	Green, banana, aldehydic, fresh, herbal	4.15399E-05	2.95631E-05	4.40041E-05	3.84183E-05	4.39E-05	4.75577E-05	3.4967E-05	1.3438E-05	1.36717E-05	7.35864E-06
16	2-Nonenal, (E)-	18829-56-6	C9H16O	12.6	1550	Aldehyde	Cucumber, fatty, green	1.3641E-05	1.93503E-05	6.58394E-06	1.08327E-05	1.23925E-05	7.66058E-06	4.31469E-06	5.83761E-06	2.55098E-06	0
17	Heptanal	111-71-7	C7H14O	7.0	1191	Aldehyde	Fatty, green	8.14218E-06	5.3004E-06	1.77838E-05	1.34867E-05	1.59664E-05	1.34607E-05	0	0	0	3.1134E-06

18	Hexanal	66-25-1	C6H12O	5.6	1085	Aldehyde	Green, grassy	2.95069E-05	4.9805E-05	7.3148E-05	3.17118E-06	4.81524E-05	8.81279E-05	2.97348E-06	2.18273E-05	2.39616E-05	1.65279E-05
19	Nonanal	124-19-6	C9H18O	10.3	1400	Aldehyde	Green, cucumber	3.67461E-05	3.55442E-05	3.17581E-05	3.06157E-05	2.04399E-05	2.30536E-05	9.41831E-06	8.65151E-06	1.49292E-05	1.39231E-05
20	2-Octenal, (E)-	2548-87-0	C8H14O	10.9	1441	Aldehyde	Fresh, cucumber, fatty, green, citrus	3.04781E-05	3.47488E-05	2.22665E-05	3.24509E-05	3.86952E-05	2.44124E-05	0	9.47891E-06	1.05135E-05	9.66193E-06
21	2-Pentenal, (E)-	1576-87-0	C5H8O	6.3	1138	Aldehyde	Pungent, green, fruity, apple orange, tomato	1.51164E-05	4.7341E-05	4.86063E-05	4.22268E-05	4.86639E-05	4.97087E-05	2.66813E-05	6.98378E-06	9.204E-06	2.39077E-05
22	3-methylbutanal	590-86-3	C5H10O	3.9	921	Aldehyde	Ethereal, aldehydic, chocolate, peach, fatty	2.55363E-05	1.69893E-05	1.53889E-05	9.52913E-06	1.05045E-05	2.14092E-05	5.1961E-06	0	0	0
23	4-Heptenal, (Z)-	6728-31-0	C7H12O	7.9	1247	Aldehyde	Green, oily, fatty, dairy	3.67575E-06	5.52971E-06	4.70133E-06	5.25069E-06	5.82723E-06	5.47214E-06	3.67406E-06	4.42002E-06	0	2.93683E-06
24	beta-	432-	C10H16	14.0	1643	Aldehyde	Tropical, saffron,	9.1109	7.51192	3.68818	9.54359	6.1081	3.993	0.000	9.155	2.874	4.798

	Cyclocitral	25-7	O				herbal, clean, rose, sweet, tobacco, green, fruity	8E-05	E-05	E-05	E-05	E-05	24E-05	107971	99E-05	44E-05	27E-05
25	cis-2-Butenal	590-18-1	C4H6O	5.1	1047	Aldehyde	Pungent, suffocating, irritating	4.05156E-05	4.18626E-05	4.11305E-05	4.13284E-05	4.00872E-05	3.88505E-05	2.45241E-05	4.86375E-06	4.81032E-06	1.94214E-06
26	Dodecanal	112-54-9	C12H24O	15.3	1732	Aldehyde	Soapy, waxy, aldehydic, citrus, green, floral	0.000104569	4.85737E-06	1.72808E-05	0	1.15631E-05	5.45698E-06	4.29987E-06	4.93151E-06	0	2.65449E-06
27	Octanal	124-13-0	C8H16O	8.6	1296	Aldehyde	Orange peel, green	0	3.71881E-06	3.18694E-06	6.57751E-06	3.00568E-06	3.68664E-06	0	0	0	0
28	Pentanal	110-62-3	C5H10O	4.5	984	Aldehyde	Fermented, bready, cocoa	0.000164836	0.000127786	0.000128118	0.000111268	0.000125985	0.00013758383	3.51212E-05	0	1.45685E-05	3.46825E-05
29	Undecanal	112-44-7	C11H22O	13.6	1614	Aldehyde	Waxy, soapy, floral, aldehydic, citrus, green, fatty, laundered cloth	0	3.1398E-06	2.86654E-06	0	0	0	0	0	0	0

30	4-ethylbenzaldehyde	4748-78-1	C9H10O	15.2	1729	Aromatic	Almond, bitter, sweet, anise cherry	1.90247E-05	6.79073E-05	8.25158E-05	8.93263E-05	0.000107134	3.87547E-05	0	0	0	0
31	Benzaldehyde	100-52-7	C7H6O	12.4	1540	Aromatic	Almond, cherry, sharp, sweet	0.000686077	0.000670456	0.000738445	0.000639122	0.000723182	0.00066759 1	0.00017475 3	0.00028728 5	0.00026435 8	0.00024576 1
32	Benzaldehyde, 2,4-dimethyl-	613-45-6	C9H10O	15.5	1751	Aromatic	Naphthyl, cherry, almond, spicy, vanilla	0.00014304	0.00020615	0.00019 1227	0.00017273	0.000183541	0.00018536 6	6.22234E-05	3.82608E-05	1.39722E-05	3.62033E-05
33	Benzaldehyde, 3-methyl-	620-23-5	C8H8O	13.9	1641	Aromatic	Sweet, fruity, cherry, almond	3.63298E-05	0	0	0	0	0	0	0	0	0
34	Benzene, 1,3-bis(1,1-dimethylethyl)-	1014-60-4	C14H22	10.8	1433	Aromatic	-	4.89165E-05	5.79204E-05	6.22572E-05	5.59074E-05	4.92305E-05	7.00738E-05	0	3.06168E-05	4.80208E-05	3.11789E-05
35	Benzyl alcohol	100-51-6	C7H8O	17.5	1892	Aromatic	Floral, rose, phenolic, balsamic	0	0	0	0	0	0	3.24128E-05	2.45013E-05	0	0
36	Naphthalene,	447-	C13H16	15.8	1768	Aromatic	Licorice	0.0001	8.07668	0.00019	0.000154	0.00016	8.171	0.000	0.000	0.000	0.000

	1,2-dihydro-1,1,6-trimethyl-	53-0						71255	E-05	4913	746	5185	33E-05	179282	128624	209427	213828
37	Phenylacetaldehyde	122-78-1	C8H8O	14.2	1659	Aromatic	Rose, sweet, floral	0	1.34409E-05	2.36096E-05	0	7.33735E-06	2.18227E-05	0	0	0	0
38	Phenylethyl alcohol	60-12-8	C8H10O	17.9	1933	Aromatic	Floral, rose, sweet	0.000291961	0.00025571	0.000275207	0.000254718	0.00027 4726	0.000177831	0.000301547	0.001545977	0.002388 09	0.002478273
39	p-Xylene	106-42-3	C8H10	6.4	1147	Aromatic	Sweet	1.11668E-05	0	0	0	0	8.23851E-06	0	0	0	0
40	2,4-Decadienal, (E,E)-	25152-84-5	C10H16O	16.6	1827	Enal	Satty, chicken	0	0	0	0	1.28238E-05	0	0	0	0	0
41	2,4-Heptadienal, (E,E)-	4313-03-5	C7H10O	11.9	1507	Enal	Fatty, green, oily, aldehydic, vegetable, cinnamon	0.000576431	0.00070 9327	0.00077 8931	0.000728 95	0.00092 8734	0.000724294	0.000373158	0	5.45677E-05	0.000106013

42	2,4-Hexadienal, (E,E)-	142-83-6	C6H8O	10.5	1415	Enal	Sweet, green, spicy, floral, citrus	2.61753E-05	4.4413E-05	3.19583E-05	1.63111E-05	1.95492E-05	5.34876E-05	0	4.86428E-06	3.27238E-06	8.94491E-06
43	2,4-Nonadienal, (E,E)-	5910-87-2	C9H14O	15.0	1717	Enal	Fatty, melon, cucumber, chicken fat	1.71847E-05	7.44766E-05	7.43974E-05	5.47693E-05	9.9412E-05	8.66124E-05	1.7384E-05	0	0	9.03327E-06
44	2,6-Nonadienal, (E,Z)-	557-48-2	C9H14O	13.3	1599	Enal	Green, fatty, dry, cucumber, violet leaf	4.21532E-05	2.43174E-05	2.53043E-05	3.00407E-05	2.21378E-05	1.305E-05	2.79858E-05	1.36566E-05	1.38285E-05	4.88694E-06
45	Methyl palmitate	112-39-0	C17H34O2	20.7	2228	Ester	Fatty, waxy	6.4327E-05	1.85663E-05	3.67519E-05	5.34491E-05	2.14683E-05	3.95351E-05	2.32069E-05	4.1457E-05	4.10557E-05	1.84766E-05
46	Methyl salicylate	119-36-8	C8H8O3	16.2	1799	Ester	Wintergreen, minty	0.000748143	0.000647308	0.000582888	0.000574573	0.000528463	0.000589075	0.000615054	0.000173008	0.000535453	0.000540567
47	2-Acetyl-5-methylfuran	1193-79-9	C7H8O2	13.4	1607	Furan	Sweet, musty, nutty, caramellic	0	0	0	0	0	0	0	0	8.27736E-05	0
48	2-ethylfuran	3208-	C6H8O	4.2	955	Furan	Chemical, beany,	2.9886	2.66821	2.75321	2.68418	3.24093	3.115	2.309	2.124	1.554	2.426

		16-0					ethereal, cocoa, bready, malty, coffee, nutty	7E-05	E-05	E-05	E-05	E-05	1E-05	77E-05	33E-05	44E-05	48E-05
49	2-Pentylfuran	3777-69-3	C9H14O	7.6	1234	Furan	Fruity, beany, vegetable	0.000262495	0.00017 0152	0.00015 3915	0.000109 902	8.60189 E-05	0.000 304494	8.220 13E-05	7.560 5E-05	6.408 52E-05	0.000 113595
50	3-Furanmethanol	4412-91-3	C5H6O2	14.3	1669	Furan	Sweet, nutty, herbal	0	0	0	0	0	0	1.665 61E-05	0	0	0
51	5-methyl furfural	620-02-0	C6H6O2	12.9	1568	Furan	Sweet, caramel, maple	1.6415 3E-05	1.40762 E-05	1.45381 E-05	1.31659 E-05	1.43611 E-05	1.524 32E-05	0	0	0	0
52	Furan, 2-methyl-	534-22-5	C5H6O2	3.6	874	Furan	Chocolate, ethereal, acetone	3.3788 5E-06	1.99509 E-06	1.92152 E-06	1.74903 E-06	0	3.190 82E-06	5.881 3E-07	1.144 47E-06	0	1.371 79E-06
53	Furfural	98-01-1	C5H4O2	11.4	1473	Furan	Sweet, woody, almond, bread, baked	0.0001 92257	0.00017 6687	0.00023 4249	0.000142 119	9.04195 E-05	0.000 169261	2.001 06E-05	2.411 57E-06	0	0
54	trans-2-(2-	70424	C9H12O	8.8	1306	Furan	Bean, grassy	5.5219	1.06584	1.05849	9.12875	1.08564	9.220	0	1.834	3.566	0

	Pentenyl)furan	-14-5						5E-06	E-05	E-05	E-06	E-05	86E-06		51E-06	62E-07	
55	1,3,5,7-Cyclooctatetraene	629-20-9	C8H8	8.1	1265	Hydrocarbon	-	0	0	0	0	0	0	0	0	0	1.98204E-06
56	3-Heptadecene, (Z)-	68155-00-0	C9H10O	15.1	1723	Hydrocarbon	-	0.000283823	0.000362702	0.00058726	0.000529519	0.00050902	0.00017116	0.00018336	0.00048412	0.00040323	0.00048442
57	Heptadecane	629-78-7	C17H36	14.8	1698	Hydrocarbon	Waxy	0.000700864	0.000731208	0.00121 5075	0.001006742	0.00117 0633	0	0.00044254 6	0.00047186	0.00049341 4	0.00095068 4
58	Pentadecane	629-62-9	C15H32	11.8	1498	Hydrocarbon	-	4.04429E-05	9.63707E-05	0.00013 0275	9.38504E-05	0.00012 3106	6.7386E-05	6.13493E-05	4.87533E-05	5.03987E-05	5.40487E-05
59	Undecane	1120-21-4	C10H22	4.6	999	Hydrocarbon	-	0	4.80151E-06	5.10924E-06	4.5991E-06	0	3.23377E-06	0	2.66008E-06	0	6.42428E-06
60	(E,E)-3,5-Octadien-2-	30086-02-3	C8H12O	13.1	1584	Ketone	Fruity, green, grassy	0.001027837	0.000853237	0.00081 154	0.00071048	0.00075 2466	0.00097705	0.00085 68	0.00021 18	0.00010 63	7.81424E-

	one												66	94	37	35	05
61	1-Octen-3-one	4312-99-6	C8H14O	8.8	1309	Ketone	Herbal, mushroom, earthy, must,y dirty	1.3969E-05	1.60312E-05	1.79359E-05	0	1.32361E-05	1.37119E-05	1.8517E-05	1.60293E-05	5.74918E-06	1.69357E-05
62	1-Penten-3-one	1629-58-9	C5H8O	4.9	1026	Ketone	Spicy, pungent, peppery, mustard, garlic, onion	0	0	1.80323E-05	0	0	0	1.4325E-05	0	0	0
63	1-Propanone, 1-(2-furanyl)-	3194-15-8	C7H8O2	13.2	1590	Ketone	Fruity	0	0	0	0	0	0	0	0	3.11861E-06	4.629E-06
64	2,3-Butanedione	431-03-8	C4H6O2	4.4	976	Ketone	Buttery, sweet, creamy, pungent, caramellic	0	0	0	1.55107E-05	0	0	0	2.16852E-05	0	0
65	2,3-Pentanedione	600-14-6	C5H8O2	5.2	1056	Ketone	Sweet, buttery, creamy	7.004E-06	2.19717E-05	2.35508E-05	2.08714E-05	2.55922E-05	2.23478E-05	1.63437E-05	1.83899E-05	1.67855E-05	5.24942E-06
66	2-Butanone	78-93-3	C4H8O	3.8	908	Ketone	Acetone, ethereal, fruity, camphoraceous	0.00024514	0.000221226	0.000348183	0.000155413	0.000153143	0.000223449	0.000126828	0.000274341	0.000202228	0.000144416

67	2-Heptanone	110-43-0	C7H14O	7.0	1187	Ketone	Cheesy, fruity, ketogenic, green, banana, creamy	3.44669E-05	1.6017E-05	1.51541E-05	0	0	0	0	0	0	0
68	2-Nonanone	821-55-6	C9H18O	10.2	1397	Ketone	Fruity, sweet, waxy, soapy, cheesy, green, herbal, coconut	1.36669E-05	2.43512E-05	3.91895E-05	0	0	4.48629E-05	1.56326E-05	0	0	0
69	2-Pentadecanone, 6,10,14-trimethyl-	502-69-2	C18H36O	20.0	2137	Ketone	Oily, herbal, jasmine, celery, woody	0.000321032	0.000296771	0.000322788	0.000317161	0.000394462	0.00029919 4	0.00020713 4	0.00018791 7	0.00023420 6	0.00021228 4
70	2-Tridecanone	593-08-8	C13H26O	16.5	1820	Ketone	Fatty, waxy, dairy, milky	2.19476E-05	2.93369E-05	1.91158E-05	2.79608E-05	3.16983E-05	2.98741E-05	2.02939E-05	0	0	0
71	3,5-Octadien-2-one	38284-27-4	C8H12O	12.3	1532	Ketone	Fruity, fatty, mushroom	0.000141213	0.00015384	0.000166226	9.56053E-05	0.00012918	0.00010881 9	9.72888E-05	0	0	0
72	3-Nonen-2-one	14309-57-0	C9H16O	12.2	1524	Ketone	Fruity, berry, fatty, oily	0	1.54487E-05	1.45496E-05	2.19196E-05	2.7222E-05	2.13097E-05	1.19724E-05	5.08251E-06	0	0

73	3-Octanone	106-68-3	C8H16O	8.1	1260	Ketone	Lavender, mushroom, sweet	1.00294E-05	7.74798E-06	3.31775E-06	0	0	9.17242E-06	2.68099E-05	0	0	1.46366E-06
74	3-Octanone, 2-methyl-	923-28-4	C9H18O	9.0	1323	Ketone	-	0.00010475	7.37462E-05	0.00010 4964	0	3.45306E-05	0.000 123455	1.749 83E-05	0	0	0
75	5-Hepten-2-one, 6-methyl-	110-93-0	C8H14O	9.4	1345	Ketone	Citrus, green, musty, lemongrass, apple	2.80764E-05	2.42381E-05	2.37667E-05	2.75072E-05	3.0203E-05	2.55302E-05	1.943 99E-05	0	0	0
76	6-Methyl-3,5-heptadiene-2-one	1604-28-0	C8H12O	13.5	1608	Ketone	Spicy, cinnamon, coconut, spicy, woody, sweet, weedy	0.00018724	0.00024 5117	0.00024 3097	0.000150 534	0.00023 5556	0.000 263096	0.000 179241	0	0	0
77	Acetoin	513-86-0	C4H8O2	8.7	1299	Ketone	Buttery, creamy, dairy, milky, fatty	0	0	0	0	1.11621E-05	0	0	0	0	0
78	Acetone	67-64-1	C3H6O	3.2	818	Ketone	Solvent, ethereal, apple, pear	0	0	0	0	1.89788E-05	0	1.275 31E-05	1.878 63E-05	9.595 86E-05	9.938 38E-05
79	Acetophenone	98-86-	C8H8O	14.4	1670	Ketone	Sweet, hawthorn	1.4756	0	0	0	0	0	1.450	0	0	0

		2						9E-05						63E-05			
80	Cyclohexanone, 2,2,6-trimethyl-	2408-37-9	C9H16O	9.2	1335	Ketone	Thujonic, pungent, labdanum, honey	2.48519E-05	5.27998E-05	4.69297E-05	2.01988E-05	3.13161E-05	4.28309E-05	2.55285E-05	2.17541E-05	0	5.135E-06
81	Isophorone	78-59-1	C9H14O	13.6	1621	Ketone	Cooling, woody, sweet, green, camphoraceous, fruity, musty	8.98165E-05	0.000126727	4.45773E-05	0	4.33334E-05	3.9674E-05	8.85449E-05	4.15323E-05	7.95499E-05	0.000117045
82	m-Methylacetophenone	585-74-0	C9H10O	16.2	1795	Ketone	Hawthorn, sweet, mimosa, coumarinic, cherry, acacia	0.000203678	0.000213941	0.000214632	0.00019917	0.00020 2363	0.000236624	0.000175738	0.000164306	0.000187912	0.000184644
83	alpha-Ionone	127-41-3	C13H20O	17.2	1874	Terpene	Sweet, woody, floral, violet, orris, tropical, fruity	0.002100297	0.001270786	0.001921168	0.001877712	0.00126 9374	0.002012284	0.001886774	0.001812874	0.001802384	0.001933268
84	beta-Ionone epoxide	23267-57-4	C13H20O2	18.9	2019	Terpene	Fruity, sweet, berry, woody, violet, orris, powdery	0.001456673	0.001330894	0.001314103	0.001370537	0.00149 5476	0.001394885	0.001381675	0.001193137	0.001325855	0.001481914

85	Neophytadiene	504-96-1	C20H38	17.9	1929	Terpene	-	0.000179889	0.000251886	0.000341725	0.000260144	0.000364417	0.00027305	0.00032496	0.00032797	0.00032256	0.00043768
86	trans-beta-Ionone	79-77-6	C13H20O	18.3	1966	Terpene	dry powdery floral woody orris berry seedy	0.001467838	0	0.004007879	0.001349576	0	0.00400017	0.00383805	0.00355101	0.00369138	0.00388032
87	trans-Geranylacetone	3796-70-1	C13H22O	17.1	1865	Terpene	Floral, fresh, green, rose	0.000366719	0.000322123	0.000318789	0.000209751	0.000342013	0.00033779	0.00033265	0	0	0
88	2-Acetylthiazole	24295-03-2	C5H5NOS	14.3	1665	Others	Pandan, popcorn, hazelnut, peanut	4.19906E-05	5.78992E-05	6.20847E-05	3.29585E-05	7.25037E-05	6.0368E-05	1.98643E-05	1.23594E-06	0	0
89	2,3,5-Trimethylpyrazine	14667-55-1	C7H10N2	10.6	1421	Pyrazine	Nutty	5.561466E-06	6.45521E-06	1.25676E-05	0	0	0	4.92684E-06	1.19941E-05	1.312E-05	1.35664E-05
90	2,5-Dimethylpyrazine	123-32-0	C6H8N2	9.3	1340	Pyrazine	Cocoa, roasted, beefy, nutty	2.833199E-05	0	0	2.30964E-05	1.68021E-05	0	1.85597E-05	0	4.28933E-05	1.95621E-05
91	2,6-	108-	C6H8N2	9.3	1338	Pyrazine	Cocoa, roasted,	0	0	0	0	0	0	0	1.703	0	1.017

	dimethylpyrazine	50-9					nutty, meaty								75E-05		84E-05
92	2-ethyl-3,6-dimethylpyrazine	13360-65-1	C8H12N2	11.2	1460	Pyrazine	Roasted, potato	2.4717E-05	2.25479E-05	2.13461E-05	1.89756E-05	2.06317E-05	2.2107E-05	5.59949E-06	2.93993E-05	1.99367E-05	1.892E-05
93	2-Ethyl-5-methylpyrazine	13360-64-0	C7H10N2	10.4	1408	Pyrazine	Coffee, nut	8.4125E-06	1.40265E-05	1.44929E-05	1.0381E-05	1.704E-05	1.73075E-05	1.08178E-05	8.73359E-06	1.25065E-05	1.31454E-05
94	2-Ethylpyrazine	13925-00-3	C6H8N2	9.5	1350	Pyrazine	Nutty, fermented coffee, meaty	0	1.4925E-06	0	0	0	0	0	0	0	0
95	2-Methylpyrazine	109-08-0	C5H6N2	8.4	1281	Pyrazine	Nutty, cocoa, chocolate	5.64735E-06	1.56795E-05	1.67164E-05	1.50864E-05	1.66667E-05	1.35332E-05	0	1.45025E-05	1.58873E-05	1.60826E-05
96	2,4,6-trimethylpyridine	108-75-8	C8H11N	10.0	1388	Pyridine	-	5.35797E-06	6.96537E-06	8.23105E-06	6.81916E-06	7.76736E-06	8.21101E-06	4.28681E-06	7.05771E-06	4.94132E-06	5.82558E-06
97	3-methylpyridine	108-99-6	C6H7N	8.9	1316	Pyridine	Green, earthy, hazelnut, nutty	4.72888E-06	3.89947E-06	0	7.09646E-06	0	3.85177E-06	0	0	8.36633E-06	4.07514E-06

98	Pyridine	110-86-1	C5H5N	7.2	1204	Pyridine	Sour, fishy	1.01316E-05	9.70381E-06	1.02752E-05	7.86009E-06	6.04669E-06	1.05357E-05	1.15231E-05	1.07348E-05	9.52469E-06	9.12224E-06
99	1H-Pyrrole-2,5-dione, 3-ethyl-4-methyl-	21494-57-5	C7H9NO	21.2	2298	Pyrrole	-	0.000192216	0.000163596	0.000182589	0.000195079	0.000218631	0.000170895	0.000188666	0.000168249	0.000178433	0.000196725
101	Dimethyl trisulfide	3658-80-8	C2H6S3	10.2	1399	Sulphurous	Sulphurous, onion, meaty, rotten eggs	0	0	0	2.53319E-06	0	0	0	0	0	0

Summary of all the volatile compounds detected by GC-MS in unfermented microalgae samples and *L. plantarum*-fermented microalgae samples across different time points (0h, 24h, 48h, 72h, and 96h). Each compound entry includes its chemical name, CAS number, molecular formula, retention time (min), retention index (RI), compound class, and odour description and abundances at different time points.

Table S4: ASTREE E-tongue sensor summary with food applications

	Sensor	Taste Modality	Sensitivity and typical detected compounds	Common applications
1	AHS	Sour	Organic acids, H^+ ions	· Fermented foods (e.g., yogurt, kimchi, sauerkraut). · Vinegar/acidity profiling in sauces. · Spoilage detection (e.g., acid build-up).
2	CTS	Salty	Na^+, K^+, Cl^-, mineral salts	· Salt reduction in soups and snacks. · Mineral water profiling. · Electrolyte beverage development.
3	NMS	Umami	Glutamate, IMP, GMP, amino acids	· Umami enhancement in broth/stock. · Fermented soy (miso, soy sauce). · Meat analogues or plant-based meat optimization.
4	ANS	Sweet	Glucose, fructose, sucrose, and artificial sweeteners	· Sweetener formulation in beverages · Sugar content consistency in fruit juices · Sugar-free product comparisons
5	SCS	Bitter	Caffeine, polyphenols, quinine, alkaloids	· Coffee and tea bitterness profiling. · Cocoa/chocolate evaluation. · Bitterness masking in functional foods/supplements.
6	PKS	General/Reference	Detects overall ionic strength or changes in general chemical environment	· Acts as a reference to help differentiate complex mixtures and stabilize the signal
7	CPS	General/Reference		

Description of electronic tongue (E-tongue) sensors used for taste modality detection in food samples. The table summarizes the target analytes for each sensor and their common applications in food quality evaluation, flavour profiling, and product development [5-13].

Table S5. Metabolite profile of umami-related compounds detected during *L. plantarum*-mediated biotransformation of microalgae

Compound name	Mass to charge ratio (m/z)	Peak Area				
		***L. plantarum*_MA_0h**	***L. plantarum*_MA_24h**	***L. plantarum*_MA_48h**	***L. plantarum*_MA_72h**	***L. plantarum*_MA_96h**
Glutamic acid	148.0605	26077.91	25747.33	7396.46	6104.25	4747.83

3'-AMP	346.0547	15341.44	15621.17	64523.82	71823.88	56305.31
Adenosine 2',3'-cyclic monophosphate (cAMP)	330.059	10029.51	8643.28	14599.89	8634.29	4084.71
Adenosine 5'-monophosphate (AMP)	348.07	1293.7	13687.83	57535.56	68646.83	57002.32
Cyclic GMP (cGMP)	344.0396	4024.884766	4647.526367	7276.584961	3959.945313	774.7654419
Guanosine 5'-monophosphate	362.0501	40930.2	48802.02	61079.58	32945.93	15488.41

Umami-related compounds were detected using LC-MS and identified based on their mass-to-charge ratio (m/z) Peak area values represent relative abundances at each fermentation time point (0h, 24h, 48h, 72h, 96h).

Table S6. Metabolite profile of amino acids and their bioconversion products during *L. plantarum*-mediated biotransformation of microalgae

Compound name	**Mass to charge ratio (m/z)**	**Peak Area**				
		***L. plantarum*_MA_0h**	***L. plantarum*_MA_24h**	***L. plantarum*_MA_48h**	***L. plantarum*_MA_72h**	***L. plantarum*_MA_96h**
L-Tyrosine	182.0787	37898	34893	7181	0	0
Phenylalanine	166.0866	89252	89795	8013	6714	4542
4-Hydroxyphenyllactic acid	181.0503	7257	5588	87693	127266	145663
D-Tryptophan	205.0973	58778	57684	8754	16172	13113
D-3-phenyllactic acid	165.0557	28351	20197	136790	327943	389709
DL-Indole-3-lactic acid	204.0666	0	0	24333.55	53092.48	60450.36

Amino acids and their relevant metabolites were detected using LC-MS and identified based on their mass-to-charge ratio (m/z). Peak area values represent relative abundances at each fermentation time point (0h, 24h, 48h, 72h, 96h).

Table S7. Demographic and lifestyle information of the sniff test panellists (n = 10).

Participant (n=10)	Gender	Age range	Race	Diet	Smoker?	Self-rated smell sensitivity
1	Male	31-40	Chinese	Omnivore	No	5
2	Male	41-50	Chinese	Omnivore	No	2
3	Male	31-40	Chinese	Omnivore	No	3
4	Male	21-30	Chinese	Omnivore	No	3
5	Male	31-40	Chinese	Omnivore	No	3
6	Female	31-40	Chinese	Omnivore	No	5
7	Female	41-50	Indian	Omnivore	No	3
8	Female	31-40	Malay	Omnivore	No	5
9	Female	21-30	Chinese	Omnivore	No	3
10	Female	31-40	Chinese	Omnivore	No	3

Demographic details and lifestyle factors of the untrained olfactory evaluation panel (n = 10). All panellists were non-smokers and followed an omnivorous diet. Self-rated olfactory sensitivity was collected using a 5-point scale (1 = very poor, 5 = very strong).

Table S8. Two-way ANOVA statistics for grassy odour intensity.

ANOVA table	SS	DF	MS	F (DFn, DFd)	P value	Significance and Interpretation
Interaction (Time × Treatment)	3.400	4	0.8500	F (4, 72) = 3.161	P=0.0188	The change in grassy odour over time depends on treatment.
Time (Row Factor)	2.440	4	0.6100	F (3.282, 59.07) = 2.269	P=0.0845	No significant change in grassy odour intensity over time alone.
Treatment (Column Factor)	0.2500	1	0.2500	F (1, 18) = 0.2089	P=0.6531	No overall difference between fermented and unfermented samples.
Subject (Panellist variation)	21.54	18	1.197	F (18, 72) = 4.450	P<0.0001	Panellists varied significantly in how they rated the grassy odour.

A two-way repeated measures ANOVA was used to assess the effects of fermentation treatment, time, and their interaction on grassy odour intensity. A significant interaction between time and treatment ($p = 0.0188$) indicates that the change in grassy odour perception over time differed depending on fermentation condition. A significant subject effect indicates variability among panellist ratings ($P<0.0001$). No significant main effects of time or treatment were observed. Geisser-Greenhouse correction was applied to the time effect ($\varepsilon = 0.8204$). Note: *F* = F-ratio; DF = degrees of freedom; SS = sum of squares; MS = mean square.

Table S9. Statistical summary of pairwise comparison for grassy odour intensity between unfermented and *L. plantarum*-fermented microalgae.

Difference between column means	
Mean of Microalgae only	2.060
Mean of *L. plantarum*_MA	1.960
Difference between means	0.1000
SE of difference	0.2188
95% CI of difference	-0.3596 to 0.5596

Reported values include mean difference, standard error (SE), and 95% confidence interval (CI).

Table S10. Two-way ANOVA statistics for sour odour intensity.

ANOVA table	**SS**	**DF**	**MS**	**F (DFn, DFd)**	**P value**	**Significance and Interpretation**
Interaction (Time × Treatment)	1.840	4	0.4600	F (4, 72) = 2.875	P=0.0287	The change in sour odour over time depends on treatment.
Time (Row Factor)	1.840	4	0.4600	F (2.301, 41.41) = 2.875	P=0.0607	No significant change in sour odour intensity over time alone.
Treatment (Column Factor)	0.8100	1	0.8100	F (1, 18) = 0.9480	P=0.3431	No overall difference in sour odour between the fermented and unfermented groups.
Subject (Panellist variation)	15.38	18	0.8544	F (18, 72) = 5.340	P<0.0001	Panellists varied significantly in how they rated sour odour.

A two-way repeated measures ANOVA was used to assess the effects of fermentation treatment, time, and their interaction on sour odour intensity. A significant interaction between time and treatment ($p = 0.0287$) indicates that the change in grassy odour perception over time differed depending on fermentation condition. A significant subject effect indicates variability among panellist ratings ($P<0.0001$). No significant main effects of time or treatment were observed. Geisser-Greenhouse correction was applied to the time effect ($\varepsilon = 0.5751$). Note: *F* = F-ratio; DF = degrees of freedom; SS = sum of squares; MS = mean square.

Table S11. Statistical summary of pairwise comparison for sour odour intensity between unfermented and *L. plantarum*-fermented microalgae.

Difference between column means	
Mean of Microalgae only	1.220
Mean of *L. plantarum*_MA	1.400
Difference between means	-0.1800
SE of difference	0.1849
95% CI of difference	-0.5684 to 0.2084

Reported values include mean difference, standard error (SE), and 95% confidence interval (CI).

Table S12. Two-way ANOVA statistics for fishy odour intensity.

ANOVA table	**SS**	**DF**	**MS**	**F (DFn, DFd)**	**P value**	**Significance and Interpretation**
Interaction (Time × Treatment)	0.1000	4	0.02500	F (4, 72) = 0.06329	P=0.9925	No difference in changes between fermented and unfermented samples over time.
Time (Row	1.460	4	0.3650	F (2.627, 47.29) = 0.9241	P=0.4262	No significant change in fishy odour intensity

Factor)						over time alone.
Treatment (Column Factor)	0.000	1	0.000	F (1, 18) = 0.000	P>0.9999	No overall difference in fishy odour between the fermented and unfermented groups.
Subject (Panelist variation)	24.96	18	1.387	F (18, 72) = 3.511	P<0.0001	Panellists varied significantly in how they rated fishy odour.

A two-way repeated measures ANOVA was used to assess the effects of fermentation treatment, time, and their interaction on fishy odour intensity. A significant subject effect indicates variability among panellist ratings (P<0.0001). No significant main effects of interaction, time or treatment were observed. Geisser-Greenhouse correction was applied to the time effect (ε = 0.6569). Note: *F* = F-ratio; DF = degrees of freedom; SS = sum of squares; MS = mean square.

Table S13. Statistical summary of pairwise comparison for fishy odour intensity between unfermented and *L. plantarum*-fermented microalgae.

Difference between column means	
Mean of Microalgae only	1.520
Mean of *L. plantarum*_MA	1.520
Difference between means	0.000
SE of difference	0.2355
95% CI of difference	1.520

Reported values include mean difference, standard error (SE), and 95% confidence interval (CI).

Table S14. Two-way ANOVA statistics for earthy odour intensity.

ANOVA table	SS	DF	MS	F (DFn, DFd)	P value	Significance and Interpretation
Interaction (Time × Treatment)	0.9400	4	0.2350	F (4, 72) = 0.7719	0.9400	No difference in changes between fermented and unfermented samples over time.
Time (Row Factor)	1.140	4	0.2850	F (3.299, 59.38) = 0.9361	1.140	No significant change in earthy odour intensity over time alone.
Treatment (Column Factor)	0.3600	1	0.3600	F (1, 18) = 0.1617	0.3600	No overall difference in earthy odour between the fermented and unfermented groups.
Subject (Panellist variation)	40.08	18	2.227	F (18, 72) = 7.314	40.08	Panellists varied significantly in how they rated earthy odour.

A two-way repeated measures ANOVA was used to assess the effects of fermentation treatment, time, and their interaction on earthy odour intensity. A significant subject effect indicates variability among panellist ratings ($P<0.0001$). No significant main effects of interaction, time or treatment were observed. Geisser-Greenhouse correction was applied to the time effect ($\varepsilon = 0.5470$). Note: F = F-ratio; DF = degrees of freedom; SS = sum of squares; MS = mean square.

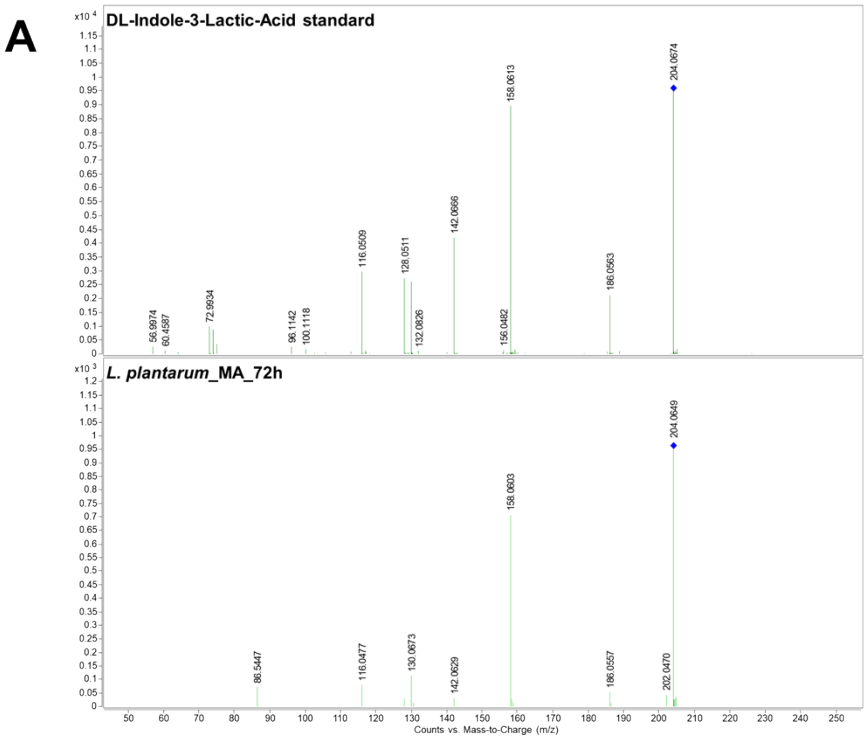
Table S15. Statistical summary of pairwise comparison for earthy odour intensity between unfermented and *L. plantarum*-fermented microalgae.

Difference between column means	
Mean of Microalgae only	1.720

Mean of *L. plantarum*_MA	1.600
Difference between means	0.1200
SE of difference	0.2984
95% CI of difference	-0.5070 to 0.7470

Reported values include mean difference, standard error (SE), and 95% confidence interval (CI).

Supporting Figures



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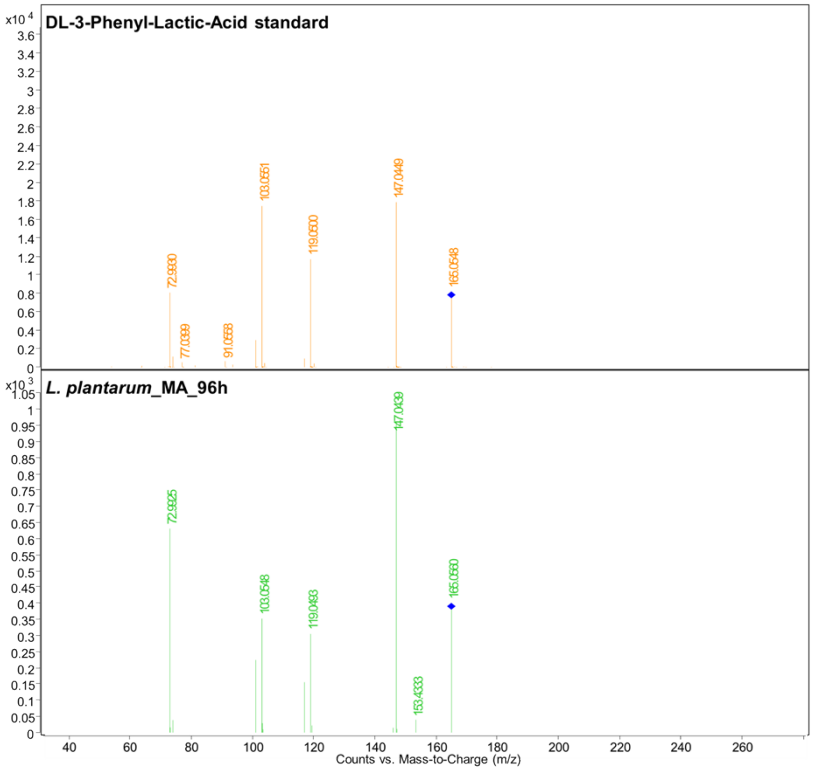

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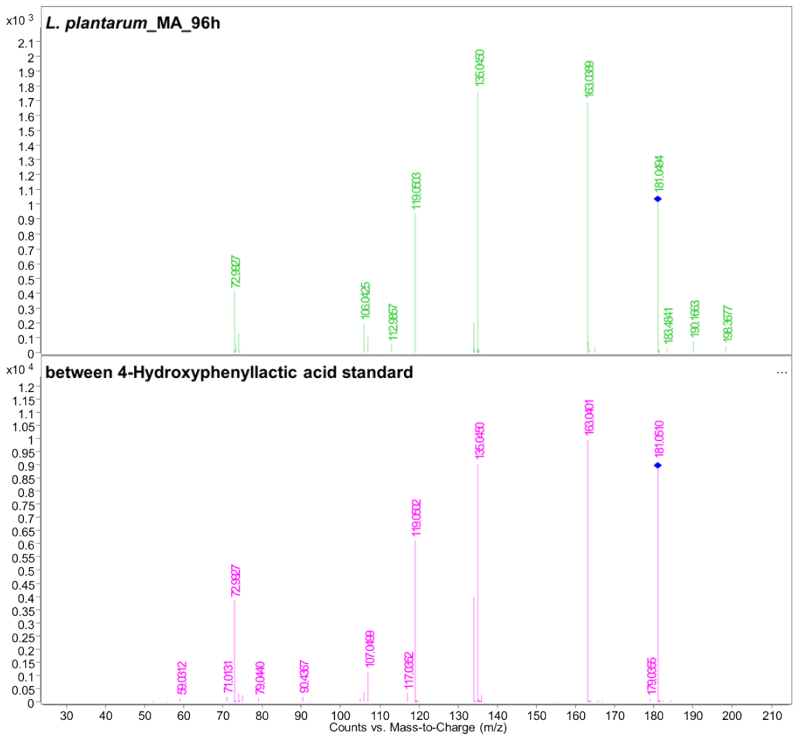

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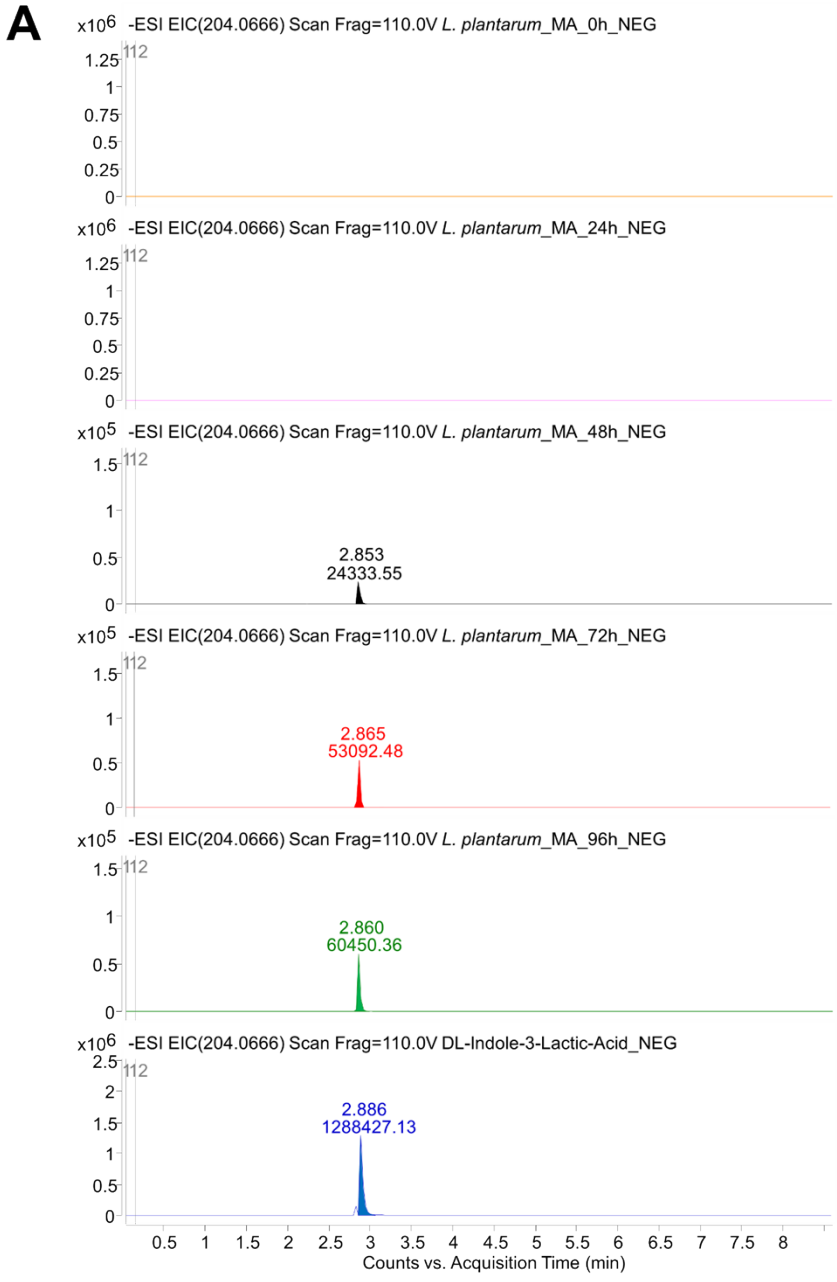
Figure S1. LC-MS/MS fragmentation spectra at collision-induced dissociation (CID)10V of aromatic lactic acid derivatives in *L. plantarum*-fermented microalgae. (A) MS/MS spectra of key fragment ions matched between DL-Indole-3-lactic acid reference standard and *L. plantarum*-fermented microalgae at 72h of fermentation. **(B)** MS/MS spectra of key fragment ions matched between DL-3-phenyllactic acid reference standard and *L. plantarum*-fermented microalgae at 96 h of fermentation. **(C)** MS/MS spectra of key fragment ions matched between 4-Hydroxyphenyllactic acid reference standard and *L. plantarum*-fermented microalgae at 96h of fermentation.



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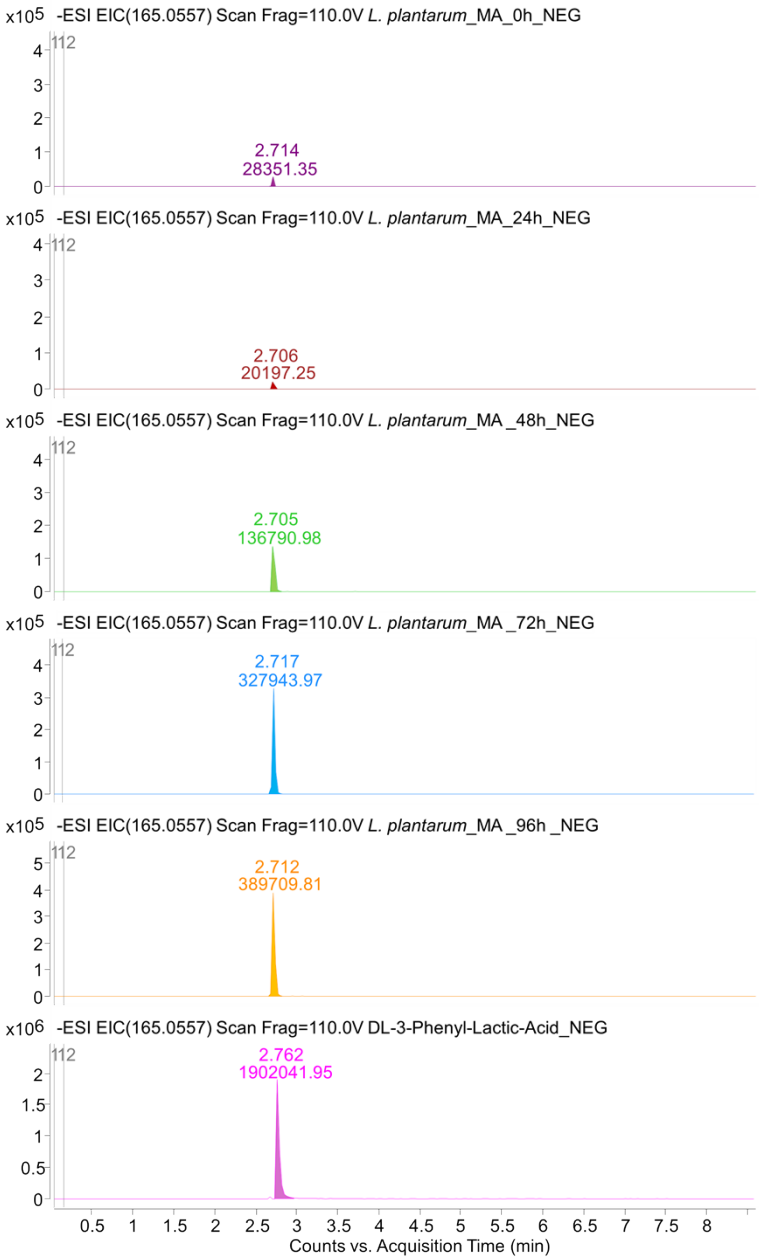
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28351.35
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Counts vs. Acquisition Time (min)

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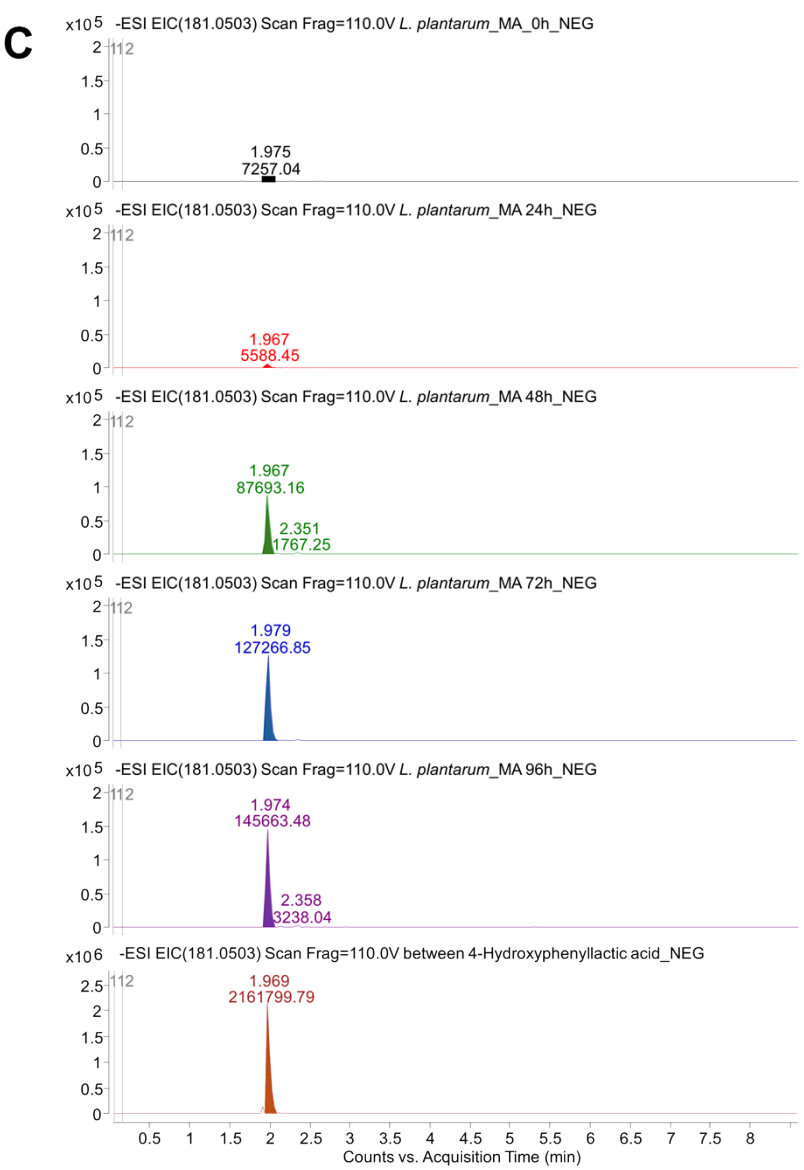
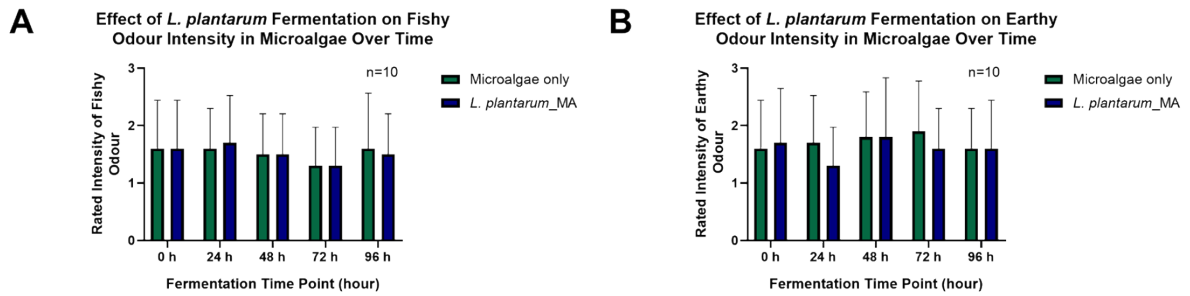


Figure S2. Extracted ion chromatograms (EICs) from LC-MS showing the bioconversion of precursor amino acids during *L. plantarum*-mediated fermentation of microalgae (MA) over 96 hours. (A–C) LC-MS EICs showing the time-dependent increase in signal intensity of **(A)** DL-indole-3-lactic acid (m/z 204.0666), **(B)** D-3-phenyllactic acid (m/z 165.0557), and **(C)** 4-Hydroxyphenyllactic acid (m/z 181.0503), across fermentation time points (0h, 24h, 48h, 72h, 96h) compared to reference standards.



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354 **Figure S3. Olfactory evaluation of microalgae fermented with *L. plantarum.* (A-B)**
355 Sensory intensities of **(A)** fishy and **(B)** earthy odour attributes in unfermented microalgae
356 (Microalgae only) and *L. plantarum*-fermented microalgae (*L. plantarum*_MA) over 96 hours.
357 Olfactory evaluation was performed by an untrained in-house olfactory panel (n = 10), with
358 intensities ranked on a structured 3-point scale (1 = weak, 2 = moderate, 3 = strong). Bars
359 represent mean ± standard deviation.

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