GC-MS-Based Metabolomics Analysis of Prawn Shell Waste Co-Fermentation by *Lactobacillus plantarum* and *Bacillus subtilis*

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**Abstract:** GC-MS-based metabolomics were used to investigate metabolic changes in prawn shell waste during fermentation. Microbial strains *Lactobacillus plantarum* and *Bacillus subtilis* were co-fermented in a shake flask comprising of 5% (w/v) prawn shell waste and 20% (w/v) glucose as a carbon source. Analysis of the prawn shell waste fermentation showed a total of 376 metabolites detected in the culture supernatant, including 14 amino acids, 106 organic acids, and 90 antimicrobial molecules. Results show that the liquid fraction of the co-fermentation is promising for harvesting valuable metabolites for probiotics application.

**Keywords:** prawn shell waste; *Lactobacillus plantarum*; *Bacillus subtilis*; fermentation; metabolomics

1. Introduction

The industrial seafood processing industry generates more than 1 million metric tons of dry weight of shellfish waste annually [1]. As the heads and exoskeletons of shellfish that comprise about 50–60% of their total weight are not suitable for human consumption, these shellfish residues are discarded as seafood processing waste by ocean dumping, incineration, or disposal in landfills [2]. This has contributed to both land and sea pollution, hence sparking scientific and environmental interest to develop techniques to recover and utilize the biopolymers in shellfish waste [3].

Prawn shell waste is chemically composed of 20–30% chitin, 20–40% protein, 30–60% minerals, and 0–14% lipids [4]. Currently, crustacean waste serves as the largest source of chitin or its deacetylated derivative chitosan [5]. Chitin, a polysaccharide with a similar structure to cellulose, is an N-acetyl-glucosamine biopolymer with α-1,4 bonds between each monomeric unit [6]. The isolation of chitin involves deproteinization, demineralization, and bleaching [7]. Traditional chemical methods involve the use of highly concentrated sodium hydroxide to carry out deproteinization and highly corrosive hydrochloric acid to carry out demineralization [8]. Other than the formation of toxic waste, undesired by-products such as irregularly deacetylated polymers result [9]. In addition, the protein and carotenoid components of the prawn shell waste are rendered useless [10].

Research has focused on using environmentally friendly processes such as biological co-fermentation by lactic acid bacteria and protease producing bacteria [11]. The lactic acid produced during fermentation reacts with the calcium carbonate in the prawn shell waste, leading to the formation of calcium lactate, which can be separated from the chitin fraction [12]. Proteolytic enzymatic action also simultaneously hydrolyzes the protein fraction of prawn shells to recover chitin [13]. Much attention has been directed at optimizing the extracellular production of the chitinase enzyme by the selection of appropriate micro-organisms [14]. Various factors such as glucose concentrations, inoculum sizes, pH, temperature, and length of fermentation influence the fermentation process as well as deproteinization and demineralization efficiencies [15].
The remains of shellfish heads and exoskeletons are also rich in lipid soluble carotenoid pigments and the recovery of an astaxanthin-rich carotenoprotein concentrate for its antioxidant properties have been a focal point of scientific study [16]. The extraction of protein hydrolysates from prawn shell waste for use as food flavoring agents or for aquaculture diets has received considerable scientific attention [17]. However, the study of these bioactive compounds in the liquor fraction has posed great challenges due to their inherent instability upon analysis [18].

In this study, GC-MS-based metabolomics profiling was performed on the co-culture supernatant of both microbial strains, lactic acid bacteria *Lactobacillus plantarum* subsp. *plantarum* ATCC 14,917 and protease producing bacteria *Bacillus subtilis* subsp. *subtilis* ATCC 6051, using prawn shell waste as the nitrogen source and 20% glucose in deionized water as the carbon source [19]. *Lactobacillus plantarum* was selected as previous studies found it to be starch-hydrolyzing, heterofermentative, and proteolytic when tested in skim milk agar, which are important properties for the deproteinization and demineralization of prawn shells [20]. *Bacillus subtilis* was chosen as it was affirmed in previous studies to produce a high protease yield, which retained maximum protease activity even in the presence of salt, surfactants, metal ions, and solvents [21].

The composition of totals phenols, polysaccharides, reducing sugars, free amino acids, and organic acids in the culture supernatant were determined by GC-MS analysis after GC derivatization to understand the fermentation characteristics of microbial extraction of chitin from prawn shell waste [22]. The remnants of the prawn shell waste were filtered off from the fermented supernatant, washed with deionized water, and sterilized with 70% (v/v) ethanol [23]. After being dried in a vacuum oven at 60°C overnight, chemical analysis was performed and it was found to be chitin [24].

2. Materials and Methods

2.1. Fermentation Conditions and Harvesting of Samples

Single colonies of *Lactobacillus plantarum* on De Man, Rogosa, and Sharpe (MRS) agar plates were picked to 5 mL MRS broth and cultured at 37 °C, 200 rpm, overnight for 12 to 16 h. Similarly, single colonies of *Bacillus subtilis* on Luria-Bertani (LB) agar plates were picked to 5 mL LB broth and cultured at 30 °C, 200 rpm, overnight for 12 to 16 h. The *Lactobacillus plantarum* and *Bacillus subtilis* bacterial cells were collected by centrifuging at 14,500 × g, 25 °C, for 5 min and their respective supernatants were decanted, leaving the cell pellets behind.

A conical flask containing 5 g of prawn shell waste as well as 20 g of glucose dissolved in 100 mL of deionized water were autoclaved at 121 °C for sterilization [25]. The 100 mL 20% (w/v) glucose solution was poured into the sterile conical flask containing 5 g of prawn shell waste. *Lactobacillus plantarum* cells and *Bacillus subtilis* cells were picked up from the centrifuged bacterial cell pellets using inoculating loops and inoculated into the fermentation flask. The fermentation setup procedures were repeated twice and the triplicate flasks were incubated at 30 °C, 200 rpm, for 5 days.

2.2. Samples Preparation for Extracellular Metabolites Analysis

First, 1 mL culture supernatant was collected from each of the three fermentation setups after 5 days. Ten microliters of 2 g/L ribitol dissolved in water was added to 50 µL of each supernatant sample and mixed thoroughly in a fresh Eppendorf tube [26]. The addition of ribitol served as an internal standard to correct for metabolite loss during sample preparation [27]. The samples were lyophilized overnight using a Labconco freeze dryer set at −40 °C and 0.0002 mBar and GC-MS derivatization was performed the next day [28].

2.3. GC-MS Analysis of Extracellular Metabolites

GC derivatization was performed for metabolic profiling on the GC-MS [29]. The lyophilized samples were re-dissolved in 100 µL of 20 mg/mL methoxyamine hydrochloride in pyridine and incubated at 37 °C for 1 h for carbonyls protection [30]. One hundred microliters of *N*-methyl-*N*-(trimethylsilyl)-trifluoroacetamide
(MSTFA) with 1% trimethyl-chlorosilane (TMCS) was added to each sample and silylation was carried out at 70 °C for 30 min [31]. The samples were centrifuged at 14,500× g for 15 min and the supernatant was used for GC-MS analysis [32]. Samples of 1 µL were injected into the HP-5MS capillary column (Agilent Technologies, Singapore) by splitless mode using an auto-injector [33]. Helium was used as a carrier gas at 1.1 mL/min [34]. The injector temperature and ion source temperature were set at 250 °C and 230 °C, respectively, on the GC-MS (Agilent Technologies, Singapore) [35]. The oven temperature was kept at 75 °C for 5 min, raised at 4 °C per minute to a final temperature of 280 °C, and held for 2 min [36]. Data were recorded from m/z 50 to 500 with a scan time of 0.1 s [37]. Metabolites were identified using the NIST08 mass spectral library and normalized using the internal standard ribitol before comparison [38].

2.4. Statistical Analysis of Metabolites

The peak area for ribitol from the GC-MS run was recorded and equated to 20 µg/200 µL. The peak areas for detected metabolites were tabulated and their concentrations calculated via multiplying by ribitol concentration 20 µg/200 µL and dividing over peak area for ribitol. Metabolite measurement results from the triplicate fermentation flasks were expressed as mean ± standard deviation.

2.5. Determination of Chitin Yield and Purity

The mass of the crude chitin obtained was weighed after being dried in the vacuum oven overnight to determine its yield. The Lowry’s test for residual protein was carried out to ascertain the purity of the recovered chitin. Firstly, 5, 10, 15, 20, 25, and 30 µL of 2 mg/mL bovine serum albumin (BSA) was added to 195, 190, 185, 180, 175, and 170 µL of deionized water respectively to form a range of 200 µL protein standards for the construction of a protein calibration curve. Then, 1 mL of Lowry’s solution was added to the protein standards and left to react for 15 min, after which 100 µL of 1 N Folin’s Phenol reagent was added and the protein standards were left to react for another 30 min. Absorbance was measured at 750 nm and the values were plotted into a graph of absorbance versus µg protein. Fifty milligrams of the extracted crude chitin was then treated with 10 mL of 1 M aqueous sodium hydroxide solution for 24 h at 70 °C. 1 mL of Lowry’s solution and 100 µL of 1 N Folin’s Phenol reagent was similarly added to the boiled NaOH supernatant to determine the residual protein content of the recovered chitin [39].

3. Results

3.1. Metabolomics Analysis by GC-MS

A total of 376 metabolites were detected by GC-MS. Fourteen amino acids were detected in the fermentation, with the highest quantity being alanine (4642.67 mg/L), followed by proline (91.76 mg/L), threonine (91.73 mg/L), leucine (63.91 mg/L), norleucine (53.57 mg/L), alanylthreonine (26.39 mg/L), glycine (25.56 mg/L), sarcosine (16.19 mg/L), isoleucine (13.96 mg/L), alloisoleucine (13.86 mg/L), glutamic acid (5.68 mg/L), valine (3.13 mg/L), 1,4-dihydrophenylalanine (2.92 mg/L), and lysine (0.44 mg/L). Ketoisocaproic acid, which is a metabolic intermediate in the metabolic pathway for the amino acid leucine, was detected at 44.06 mg/L; while ketoisovaleric acid, which is a metabolite of the amino acid valine, was detected at 1.2 mg/L.

One hundred and six organic acids were found in the culture supernatant, with the highest quantities being butanoic acid (4399.87 mg/L), mannonic acid (2567.14 mg/L), 2,3-dimethylbutanoic acid (2129.98 mg/L), carboxylic acid (1432.07 mg/L), glucopyranuronic acid (1239.42 mg/L), D-glycerol-L-manno-heptonic acid (1192.77 mg/L), 3-o xoocatanoic acid (1185.00 mg/L), propanoic acid (1184.32 mg/L), and lactic acid (1055.38 mg/L). There were also significant quantities of mandelic acid (443.5 mg/L), gluconic acid (307.05 mg/L), 2-ketobutyric acid (222.57 mg/L), hexanedioic acid (200.31 mg/L), 2-hydroxyisocaproic acid (173.95 mg/L), xylonic acid (156.31 mg/L), butyric acid (153.36 mg/L), hexadecenoic acid (147.85 mg/L), octadecanoic acid (147.83 mg/L), dipropylacetic acid (120.83 mg/L), and 3-deoxy-D-arabino-hexonic acid (112.61 mg/L) detected.
Ninety metabolites were reported in the literature to possess antimicrobial properties, of which 37 metabolites were fatty or organic acids. The remaining 53 reportedly antimicrobial metabolites, which were non-acids, include acetamide (2999.12 mg/L), uridine (1277.01 mg/L), 2-hydroxybenzaldehyde (940.97 mg/L), acetylhydrazide (366.71 mg/L), 2-propanamide (338.39 mg/L), glycerol (336.23 mg/L), 2-quinolinone (284.36 mg/L), benzenesulfonamide (167.36 mg/L), thymol (68.98 mg/L), quinazoline (66.92 mg/L), sedoheptulose (64.36 mg/L), kaurene (58.27 mg/L), 1,2-benzoisothiazole (56.13 mg/L), phenanthroline (49.88 mg/L), benzoic acid (44.86 mg/L), pyrazine (33.19 mg/L), ethanol (31.01 mg/L), 1,4-benzoquinone (28.12 mg/L), benzocate (24.82 mg/L), benzothiazolinone (23.64 mg/L), indole (22.32 mg/L), and 2-aminothiadiazole (20.98 mg/L).

Full detailed results for the detected metabolites are shown in Tables 1–4 below.

Table 1. Amino acids detected in culture supernatant of dual *Lactobacillus plantarum* and *Bacillus subtilis* fermentation in prawn shell waste and 20% glucose in deionized water.

| Metabolite         | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|--------------------|-------------------|-----------------|--------------------------|
| Alanine            | C₃H₇NO₂           | 4642.67 ± 3.90  | Amino acid               |
| Alanylthreonine    | C₇H₁₄N₂O₄         | 26.39 ± 0.01    | Amino acid               |
| Alloisoleucine     | C₆H₁₃N₂O₂         | 13.86 ± 0.01    | Amino acid               |
| 1,4-Dihydrophenylalanine | C₆H₁₃NO₂        | 2.92 ± 0.01     | Amino acid               |
| Glutamic acid      | C₅H₇NO₄           | 5.68 ± 0.01     | Amino acid               |
| Glycine            | C₅H₇NO₂           | 25.56 ± 0.02    | Amino acid               |
| Isoleucine         | C₆H₁₃N₂O₂         | 13.96 ± 0.06    | Amino acid               |
| KETOisocaproic acid| C₆H₁₀O₃           | 44.06 ± 0.13    | Leucine ketoacid         |
| KETOisovaleric acid| C₆H₅O₃           | 1.20 ± 0.01     | Valine ketoacid          |
| Leucine            | C₆H₁₃NO₂           | 63.91 ± 0.01    | Amino acid               |
| Lysine             | C₆H₁₄N₂O₂         | 0.44 ± 0.01     | Amino acid               |
| Proline            | C₆H₁₂NO₂          | 91.76 ± 1.28    | Amino acid               |
| Threonine          | C₅H₇NO₃           | 91.73 ± 0.05    | Amino acid               |
| Valine             | C₅H₁₁NO₂           | 3.13 ± 0.01     | Amino acid               |

Table 2. Antimicrobial Compounds detected in culture supernatant of dual *Lactobacillus plantarum* and *Bacillus subtilis* fermentation in prawn shell waste and 20% glucose in deionized water.

| Metabolite              | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|-------------------------|-------------------|-----------------|--------------------------|
| Acetamide               | C₄H₄NO            | 2999.12 ± 4.06  | Antimicrobial [40]       |
| Acetylhydrazide         | C₆H₄N₂O           | 366.71 ± 0.01   | Antimicrobial [41]       |
| Acetic acid             | C₂H₄O₂            | 71.94 ± 0.17    | Antimicrobial [42]       |
| Acridinedione           | C₁₃H₁₈N₂O₂        | 4.31 ± 0.01     | Antimicrobial [43]       |
| Acrylic acid            | C₃H₇O₂            | 0.72 ± 0.01     | Antimicrobial [44]       |
| Allonic acid            | C₄H₁₂O₇            | 18.89 ± 0.08    | Anti-tumor               |
| 4-Aminobenzoic acid     | C₅H₉NO₂           | 7.00 ± 0.01     | Antimicrobial [45]       |
| 2-Aminothiadiazole      | C₃H₄N₂S           | 20.98 ± 0.01    | Antimicrobial [46]       |
| Arachidonic acid        | C₂₀H₃₂O₂           | 5.92 ± 0.01     | Antimicrobial [47]       |
| Azelaic acid            | C₇H₁₄O₄           | 0.50 ± 0.01     | Antimicrobial [48]       |
| Benzamide               | C₇H₇NO             | 11.18 ± 0.12    | Antimicrobial [49]       |
| 1,2-Benzenediic acid    | C₄H₈O₂             | 1.31 ± 0.01     | Antimicrobial [50]       |
| Benzeneacetic acid      | C₄H₈O₂             | 9.04 ± 0.01     | Antimicrobial [51]       |
| Benzenepropanoic acid   | C₆H₁₀O₂            | 0.84 ± 0.01     | Antimicrobial [52]       |
| Benzenesulphonamide     | C₆H₁₀NO₂S          | 167.36 ± 1.56   | Antimicrobial [53]       |
| Benzenethiol            | C₆H₄S             | 1.47 ± 0.01     | Antimicrobial [54]       |
| Metabolite | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|------------|-------------------|-----------------|--------------------------|
| 1,2-Benzisothiazole | C7H5NS | 56.13 ± 0.59 | Antimicrobial [55] |
| Benzisothiazolinone | C7H5NOS | 23.64 ± 0.01 | Antimicrobial [56] |
| 1,2-Benzisoxazole | C7H5NO | 1.75 ± 0.01 | Antimicrobial [57] |
| Benzoxazole | C7H5O2^- | 24.82 ± 0.01 | Antimicrobial [58] |
| 1,3-Benzodioxole | C7H6O2 | 6.97 ± 0.01 | Antimicrobial [59] |
| Benzoic acid | C7H6O2 | 27.37 ± 0.38 | Antimicrobial [60] |
| 1,4-Benzoquinone | C6H4O2 | 28.12 ± 0.37 | Antimicrobial [61] |
| Benzoic acid | C7H6O2 | 1.26 ± 0.01 | Antimicrobial [62] |
| 1-Benzylindole | C15H13N | 7.92 ± 0.04 | Antimicrobial [63] |
| Butanol | C4H10O | 1.81 ± 0.01 | Antimicrobial [64] |
| Butyric acid | C4H8O2 | 153.36 ± 0.26 | Antimicrobial [65] |
| Carboxylate | CH2NO2^- | 9.02 ± 0.01 | Antimicrobial [66] |
| Carboxylic acid | CH3NO2 | 1432.07 ± 4.62 | Antimicrobial [67] |
| Cephaloridine | C19H27N3O4S2 | 6.53 ± 0.01 | Antibiotic |
| Colchicine | C22H35NO6 | 15.06 ± 0.01 | Anti-inflammatory |
| Decanoic acid | C10H20O2 | 70.50 ± 0.01 | Antimicrobial [68] |
| Dihydroisosteviol | C20H32O3 | 5.44 ± 0.01 | Antimicrobial [69] |
| Docosahexaenoic acid | C22H32O2 | 5.79 ± 0.01 | Antimicrobial [70] |
| Docosanol | C22H44O | 6.41 ± 0.01 | Antimicrobial [71] |
| Dodecanamide | C12H25NO | 5.28 ± 0.01 | Antimicrobial [72] |
| Ethanol | C2H5O2 | 31.01 ± 0.30 | Antimicrobial [73] |
| Ethyl acetate | C4H8O2 | 44.86 ± 0.48 | Antimicrobial [74] |
| Galacturonic acid | C6H10O7 | 5.03 ± 0.05 | Antimicrobial [75] |
| D-glucal | C4H10O6 | 3.52 ± 0.01 | Anticancer |
| Gluconic acid | C6H12O7 | 307.05 ± 0.60 | Antimicrobial [76] |
| Glycol | C4H8O3 | 336.23 ± 1.94 | Antimicrobial [77] |
| Glyoxylic acid | C2H2O3 | 4.68 ± 0.01 | Antimicrobial [78] |
| Griseofulvin | C22H27N3O7S | 3.14 ± 0.01 | Antibiotic |
| Guaiacol | C7H8O2 | 8.43 ± 0.01 | Antimicrobial [79] |
| Hexadecanoic acid | C16H32O2 | 147.85 ± 1.49 | Antimicrobial [80] |
| 2,4-Hexadienoic acid | C4H8O2 | 0.87 ± 0.01 | Antimicrobial [81] |
| Hexanedioic acid | C6H10O4 | 200.31 ± 0.01 | Antimicrobial [82] |
| Hexanoic acid | C6H12O2 | 20.24 ± 0.01 | Antimicrobial [83] |
| 2-Hydroxybenzaldehyde | C7H6O2 | 940.97 ± 1.64 | Antimicrobial [84] |
| 3-Hydroxybutyric acid | C3H5NO | 18.19 ± 0.24 | Antimicrobial [85] |
| 4-Hydroxyphenylamine | C7H5NO | 1.77 ± 0.01 | Antimicrobial [86] |
| 2-Hydroxyisocaproic acid | C7H12O3 | 173.95 ± 2.09 | Antimicrobial [87] |
| 3-(4-Hydroxyphenyl)propionic acid | C9H10O3 | 1.71 ± 0.01 | Anti-inflammatory |
| Indole | C9H8N | 22.32 ± 0.27 | Antimicrobial [88] |
| Indole-3-carboxylic acid | C9H7NO2 | 8.27 ± 0.01 | Antimicrobial [89] |
| Isocteric acid | C4H8O2 | 1.30 ± 0.01 | Antimicrobial [90] |
| 3-Isovaleric acid | C7H12O2 | 3.31 ± 0.01 | Antimicrobial [91] |
| Kauene | C30H32 | 58.27 ± 0.10 | Antimicrobial [92] |
| 2-Keto-D-glucose | C4H10O5 | 2.11 ± 0.01 | Antibiotic |
| Lactic acid | C3H6O3 | 1055.38 ± 7.90 | Antimicrobial [93] |
| Linolenic acid | C18H32O3 | 8.00 ± 0.01 | Antimicrobial [94] |
| Lycopodine | C14H25NO | 4.13 ± 0.01 | Antimicrobial [95] |
| Malic acid | C4H6O5 | 21.02 ± 0.29 | Antimicrobial [96] |
| Mandelic acid | C6H4O3 | 443.50 ± 6.14 | Antimicrobial [97] |
| Meldrum’s acid | C4H4O4 | 1.49 ± 0.01 | Antimicrobial [98] |
| Methanol | CH3OH | 10.15 ± 0.01 | Antimicrobial [99] |
| Methylene cyclopropane | C5H8 | 0.18 ± 0.01 | Antiviral [100] |
| Nonadecanoic acid | C19H38O2 | 2.48 ± 0.01 | Anticancer [101] |
| Nonanoic acid | C9H18O2 | 16.07 ± 0.01 | Antimicrobial [102] |
| Octadecanoic acid | C18H36O2 | 147.83 ± 1.66 | Antimicrobial [103] |
Table 2. Cont.

| Metabolite                  | Molecular Formula | Quantity (mg/L)     | Biological Characteristic          |
|-----------------------------|-------------------|---------------------|------------------------------------|
| Octanoic acid               | C₈H₁₆O₂            | 1.38 ± 0.01         | Antimicrobial [104]                |
| Octenidine                  | C₃₆H₆₂N₄          | 1.03 ± 0.01         | Antimicrobial [105]                |
| Pentanedioic acid           | C₅H₈O₄            | 50.59 ± 0.64        | Antimicrobial [106]                |
| Phenanthroline              | C₁₂H₈N₂            | 49.88 ± 0.39        | Antimicrobial [107]                |
| 3-Phenyl-5-isoxazolone     | C₆H₅NO₂            | 2.14 ± 0.01         | Antimicrobial [108]                |
| Phosphoric acid             | H₃PO₄             | 0.68 ± 0.01         | Antimicrobial [109]                |
| Propanamide                 | C₃H₇NO             | 6.08 ± 0.01         | Antimicrobial [110]                |
| Propanenitrile              | C₃H₅N             | 8.05 ± 0.01         | Antimicrobial [111]                |
| Pyruvic acid                | C₃H₄O₂            | 1184.32 ± 9.56      | Antimicrobial [112]                |
| Propionamide                | C₃H₇NO            | 10.84 ± 0.01        | Antimicrobial [113]                |
| Pteridine                   | C₆H₄N₄            | 3.82 ± 0.03         | Antimicrobial [114]                |
| Pyranone                    | C₅H₄O₂            | 7.89 ± 0.07         | Antimicrobial [115]                |
| Pyrazine                    | C₅H₄N₂            | 33.19 ± 0.01        | Antimicrobial [116]                |
| Pyridazine                  | C₅H₅N₂            | 3.29 ± 0.01         | Antimicrobial [117]                |
| Pyrrole                     | C₄H₅N             | 3.04 ± 0.02         | Antimicrobial [118]                |
| Pyrrolopyrimidine           | C₆H₅N₃            | 3.33 ± 0.01         | Antiviral [119]                    |
| Pyruvic acid                | C₃H₄O₃            | 56.20 ± 0.02        | Antimicrobial [120]                |
| Quinazoline                 | C₅H₆N₂            | 66.92 ± 0.01        | Antimicrobial [121]                |
| Quinoline                   | C₅H₅N             | 1.87 ± 0.01         | Antimicrobial [122]                |
| 2-Quinolinone               | C₅H₇NO            | 284.36 ± 0.01       | Antimicrobial [123]                |
| Sedoheptulose               | C₇H₁₄O₇           | 64.36 ± 0.01        | Antimicrobial [124]                |
| Sesamol                     | C₇H₆O₃            | 9.33 ± 0.07         | Antimicrobial [125]                |
| Tartaric acid               | C₅H₄O₆            | 7.94 ± 0.01         | Antimicrobial [126]                |
| Thiophene                   | C₄H₄S             | 0.93 ± 0.01         | Antimicrobial [127]                |
| Thiourea                    | CH₄N₂S            | 2.16 ± 0.01         | Antimicrobial [128]                |
| Thymol                      | C₁₀H₁₄O           | 68.98 ± 0.01        | Antimicrobial [129]                |
| 1,2,4-Triazole-3-carboxylic acid | C₃H₃N₃O₂        | 56.93 ± 0.01        | Antimicrobial [130]                |
| Undecanoic acid             | C₁₁H₂₂O₂          | 2.09 ± 0.01         | Antimicrobial [131]                |
| Urea                        | CH₃N₂O            | 0.65 ± 0.01         | Antimicrobial [132]                |
| Uridine                     | C₄H₁₂N₂O₆         | 1277.01 ± 3.34      | Antimicrobial [133]                |

Table 3. Other organic compounds detected in culture supernatant of dual Lactobacillus plantarum and Bacillus subtilis fermentation in prawn shell waste and 20% glucose in deionized water.

| Metabolite                  | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|-----------------------------|-------------------|-----------------|--------------------------|
| Altronic acid               | C₄H₁₂O₇           | 0.22 ± 0.01     | Organic acid              |
| Amphetamine                 | C₆H₁₃N            | 1.35 ± 0.01     | Stimulant                 |
| Aromadendrene               | C₁₅H₂₄            | 4.54 ± 0.01     | Essential oil             |
| Benzene                     | C₆H₆              | 16.07 ± 0.01    | Aromatic                  |
| Benzylocyclobutene          | C₅H₈              | 7.98 ± 0.01     | Aromatic                  |
| Benzonitrile                | C₇H₇N             | 91.31 ± 0.01    | Aromatic                  |
| Butanal                     | C₅H₄O             | 29.38 ± 0.19    | Aldehyde                  |
| Butane                      | C₅H₁₀             | 543.18 ± 5.86   | Alkane                    |
| Butanedioic acid            | C₄H₆O₄            | 31.11 ± 0.03    | Organic acid              |
| Butanediol                  | C₄H₈O₂            | 139.50 ± 0.03   | Alcohol                   |
| 1,2,2,3,4-Butanepentacarbonitrile | C₆H₅N₅        | 0.55 ± 0.01     | Aromatic                  |
| Butanoic acid               | C₄H₈O₂            | 4399.87 ± 6.20  | Organic acid              |
| 1-Butene                    | C₅H₈              | 379.99 ± 5.33   | Alkene                    |
| 1,4-Butenediol              | C₄H₈O₂            | 46.28 ± 0.01    | Alcohol                   |
| 2-Butenoic acid             | C₄H₈O₂            | 52.41 ± 0.11    | Organic acid              |
| 3-Buten-1-ol                | C₅H₈O             | 2.31 ± 0.01     | Alcohol                   |
| Metabolite                          | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|------------------------------------|-------------------|----------------|--------------------------|
| Butyamine                          | C₄H₁₁N           | 84.67 ± 0.01   | Amine                    |
| Butyne                             | C₄H₈             | 7.46 ± 0.01    | Alkene                   |
| Butynol                            | C₄H₁₀O           | 0.43 ± 0.01    | Alcohol                  |
| Butyrate                           | C₄H₉O₂⁻           | 0.72 ± 0.01    | Flavoring                |
| Camphoric acid                     | C₁₀H₁₆O₄         | 0.81 ± 0.01    | Organic acid             |
| Carbophenoxon sulfone              | C₁₁H₁₆ClO₅PS₂     | 11.46 ± 0.01   | Organosulfone            |
| Cholestan                          | C₂₇H₄₈           | 3.63 ± 0.01    | Cholesterol              |
| 1-Cholestenol                      | C₂₇H₄₆           | 31.64 ± 0.01   | Cholesterol              |
| Cholestenone                       | C₂₇H₄₄O         | 7.61 ± 0.09    | Cholesterol              |
| Cholesterol                        | C₂₇H₄₆O         | 75.80 ± 0.66   | Cholesterol              |
| Chromium                           | Cr               | 2.53 ± 0.01    | Mineral                  |
| Cortisone                          | C₂₁H₂₆O₅         | 2.09 ± 0.01    | Steroid                  |
| Cyclobutanemethanol                | C₅H₁₀O           | 25.00 ± 0.01   | Aromatic                 |
| Cyclohexane                        | C₆H₁₂            | 4.64 ± 0.03    | Aromatic                 |
| Cyclohexene                        | C₆H₁₀            | 1.31 ± 0.01    | Aromatic                 |
| 3-Cyclohexene-1-methanol           | C₇H₁₂O           | 2.78 ± 0.01    | Essential oil            |
| 1-Cyclohexyl-tetradecane           | C₂₀H₄₀           | 5.00 ± 0.01    | Aromatic                 |
| Cyclopenta[de]naphthalene          | C₁₂H₁₈         | 8.26 ± 0.01    | Aromatic                 |
| Cyclopentane                       | C₅H₁₀            | 4.84 ± 0.01    | Aromatic                 |
| 1,2,4-Cyclopentanetriene           | C₅H₄O₃          | 7.93 ± 0.01    | Aromatic                 |
| Cyclopentene                       | C₅H₈            | 0.61 ± 0.01    | Aromatic                 |
| Cyclopropanecarboxylic acid        | C₄H₈O₂          | 3.04 ± 0.01    | Organic acid             |
| Decane                             | C₁₀H₂₂          | 1.98 ± 0.01    | Alkane                   |
| 1-Decanol                          | C₁₀H₂₂O         | 1.75 ± 0.01    | Fatty alcohol            |
| 2,6-Diamino-4-hexyenoic acid       | C₆H₁₀N₂O₂        | 2.10 ± 0.01    | Organic acid             |
| 1,3-Diazepane-2,4,6-trione         | C₅H₈N₂O₃        | 1.09 ± 0.01    | Aromatic                 |
| 3-Dibenzocturaminene               | C₁₂H₈NO        | 19.35 ± 0.18   | Aromatic                 |
| Diethylene glycol                  | C₄H₁₀O₃         | 67.89 ± 0.68   | Solvent                  |
| 2,3-Dihydroxybutanoic acid         | C₅H₈O₄          | 13.75 ± 0.07   | Organic acid             |
| 1,1-Diisobutyloxybutane            | C₁₂H₂₀O₂        | 1.72 ± 0.01    | Aldehyde                 |
| Diisopropyl malonate               | C₄H₁₆O₄         | 1.30 ± 0.01    | Acid ester               |
| Dimethylbutanedioate               | C₄H₁₀O₄         | 0.77 ± 0.01    | Flavoring                |
| 2,3-Dimethylbutanoic acid          | C₅H₁₀O₂         | 2129.98 ± 3.01 | Fatty acid               |
| 3,3-Dimethyl-1-butanol             | C₅H₁₀O           | 18.60 ± 0.01   | Alcohol                  |
| Dimethylcyclohexanone              | C₅H₈O           | 89.00 ± 0.01   | Aromatic                 |
| Dimethyldecahydroxynaphthalene     | C₁₈H₃₂         | 56.95 ± 0.01   | Aromatic                 |
| Dimethyl malonate                  | C₅H₈O₃          | 8.30 ± 0.01    | Acid ester               |
| Dipropylacetic acid                | C₆H₁₂O₂         | 120.83 ± 0.01  | Organic acid             |
| 13,16-Docosadienoic acid           | C₂₂H₄₂O₂        | 51.71 ± 0.35   | Fatty acid               |
| Docosanoic acid                    | C₂₂H₄₂O₂        | 2.40 ± 0.01    | Fatty acid               |
| 13-Docosanamide                    | C₂₂H₄₂NO        | 64.20 ± 0.78   | Fatty amide              |
| Dodecane                           | C₁₂H₂₆         | 1462.61 ± 0.01 | Alkane                   |
| Dodecanedioic acid                 | C₁₂H₂₆O₄        | 4.84 ± 0.01    | Organic acid             |
| 5,8,11-Eicosatrienoic acid         | C₂₀H₃₂O₂        | 0.97 ± 0.01    | Fatty acid               |
| Estratetraenol                     | C₁₈H₃₂O          | 15.35 ± 0.01   | Steroid                  |
| Ethane                             | C₂H₆           | 37.25 ± 0.01   | Alkane                   |
| Ethanedioic acid                   | C₂H₃O₄         | 16.61 ± 0.19   | Organic acid             |
| Ethanesulfonic acid                | C₂H₃O₂S         | 3.13 ± 0.02    | Sulfonic acid            |
| Ethanimidic acid                   | C₂H₃NO         | 0.63 ± 0.01    | Organic acid             |
| Ethyl butyrate                     | C₄H₁₂O₂         | 7.25 ± 0.02    | Flavoring                |
| Ethylene                           | C₂H₄            | 1.99 ± 0.01    | Alkene                   |
| Ethylene glycol                    | C₅H₁₀O₂         | 141.94 ± 0.01  | Solvent                  |
| 3-Furanacetaldehyde               | C₄H₆O₂         | 0.75 ± 0.01    | Aldehyde                 |

Table 3. Cont.
| Metabolite                        | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|----------------------------------|-------------------|----------------|--------------------------|
| 2-Furancarboxylic acid           | C₅H₄O₃           | 1.98 ± 0.01    | Organic acid             |
| 2-Furanone                       | C₄H₄O₂           | 3.41 ± 0.02    | Flavoring                |
| Glucuronolactone                 | C₆H₁₀O₆          | 3.95 ± 0.04    | Lactone                  |
| Glyceraldehyde acetone           | C₆H₁₀O₃          | 247.79 ± 0.01  | Carboxaldehyde           |
| L-gulono-1,4-lactone             | C₆H₁₀O₆          | 21.25 ± 0.23   | Lactone                  |
| Heptadecane                      | C₁₇H₃₆           | 7.06 ± 0.01    | Alkane                   |
| Heptadecane-1,2-diol             | C₁₇H₃₈O₂         | 54.71 ± 0.01   | Fatty alcohol            |
| 3-Heptyn-1-ol                   | C₇H₁₄O          | 10.73 ± 0.01   | Fatty alcohol            |
| Heptanamide                      | C₇H₁₅NO          | 14.97 ± 0.01   | Fatty amide              |
| Hexadecanamide                   | C₁₆H₃₃NO        | 5.81 ± 0.01    | Fatty amide              |
| Hexadecane                       | C₁₆H₃₄           | 97.90 ± 0.01   | Alkane                   |
| 1-Hexene                         | C₆H₁₂            | 10.50 ± 0.01   | Alkene                   |
| 3-Hexenedioic acid              | C₆H₁₂O₄          | 11.76 ± 0.01   | Fatty acid               |
| 3-Hexen-1-ol                    | C₆H₁₂O           | 3.00 ± 0.01    | Fatty alcohol            |
| 4-Hexen-1-yne                    | C₆H₈             | 2.27 ± 0.01    | Alkynine                 |
| 3-Hydroxy-2-butanone             | C₄H₈O₂           | 72.50 ± 0.01   | Methyl ketone            |
| 2-Hydroxyglutamic acid           | C₅H₁₀O₃          | 2.30 ± 0.01    | Organic acid             |
| 3-Hydroxypropionic acid          | C₃H₄O₃           | 1.32 ± 0.01    | Organic acid             |
| 3-Hydroxysebacic acid            | C₁₀H₁₈O₅         | 4.09 ± 0.03    | Organic acid             |
| Inabenfide                       | C₁₅H₂₅ClN₂O₂     | 3.19 ± 0.01    | Herbicide                |
| Iron                             | Fe               | 3.25 ± 0.01    | Mineral                  |
| 2-Ketobutyric acid               | C₄H₈O₃           | 222.57 ± 0.02  | Organic acid             |
| 2-Ketohexanoic acid              | C₆H₁₀O₃          | 1.03 ± 0.01    | Fatty acid               |
| Ketovaleric acid                 | C₅H₁₀O₃          | 17.59 ± 0.01   | Ketoacid                 |
| Malonic acid                     | C₅H₁₀O₂          | 0.25 ± 0.01    | Organic acid             |
| Methanaminium                    | CH₄N             | 5.93 ± 0.05    | Conjugate acid           |
| Methyl butyrate                  | C₃H₁₀O₂          | 9.83 ± 0.01    | Flavoring                |
| Methyl cyclopentadiene           | C₅H₈             | 465.49 ± 0.01  | Aromatic                 |
| 6-Methyl-3,5-heptadien-2-one     | C₆H₁₂O₂          | 106.73 ± 0.48  | Flavoring                |
| Methyl phenyl sulfide            | C₇H₈OS           | 2.38 ± 0.01    | Aromatic                 |
| 2-Methylpropanoic acid           | C₄H₈O₂           | 8.21 ± 0.01    | Organic acid             |
| 2-Methylpropene                  | C₅H₁₀           | 69.91 ± 0.31   | Alkene                   |
| 2-Methyl-4-propyl-1,3-oxathiane  | C₅H₁₀OS          | 53.44 ± 0.01   | Flavoring                |
| Methyl tetradecanoate            | C₁₅H₂₄O₂         | 3.53 ± 0.01    | Flavoring                |
| 4-Methyl-5-thiazolethanol        | C₆H₈NOS         | 120.92 ± 0.01  | Flavoring                |
| Methyl valerate                  | C₆H₁₂O₂          | 445.57 ± 0.01  | Flavoring                |
| 3-Methylvaleric acid             | C₆H₁₂O₂          | 5.55 ± 0.01    | Fatty acid               |
| Monoethyl malonic acid           | C₅H₁₀O₂          | 13.41 ± 0.16   | Organic acid             |
| Monostearin                      | C₂₁H₄₂O₄        | 35.76 ± 0.31   | Emulsifier               |
| Morphine                         | C₁₇H₃₉NO₃       | 7.05 ± 0.01    | Painkiller               |
| N-acetyl-glucosamine             | C₈H₁₅NO₆        | 24.93 ± 0.33   | Chitosan                 |
| Nickel                           | Ni               | 6.56 ± 0.01    | Mineral                  |
| Nonane                           | C₄H₂₀           | 2.28 ± 0.01    | Alkane                   |
| 5-Norbornene-2-carboxylic acid   | C₈H₁₀O₂          | 0.93 ± 0.01    | Organic acid             |
| Octadecanamide                   | C₁₅H₃₂NO        | 47.22 ± 0.01   | Fatty amide              |
| Octadecane                       | C₁₈H₃₈          | 137.50 ± 0.01  | Alkane                   |
| Octadecanamide                   | C₁₈H₃₂NO        | 67.10 ± 0.77   | Fatty amide              |
| 17-Octadecynoic acid             | C₁₈H₃₂O₂        | 18.04 ± 0.01   | Fatty acid               |
| Octahydranaphthalene             | C₁₀H₁₆          | 3.48 ± 0.01    | Aromatic                 |
| Octahydranaphthalene-1,4-diol    | C₁₀H₁₂O₂        | 57.23 ± 0.01   | Alcohol                  |
| γ-Octalactone                    | C₆H₁₄O₂         | 238.91 ± 0.37  | Flavoring                |

Table 3. Cont.
| Metabolite                        | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|----------------------------------|-------------------|-----------------|---------------------------|
| Octane                           | C₈H₁₈             | 25.30 ± 0.01    | Alkane                    |
| 1-Octene                         | C₉H₁₆             | 10.56 ± 0.01    | Alkane                    |
| Oleic acid                       | C₁₈H₃₄O₂          | 17.59 ± 0.01    | Fatty acid                |
| 3-Oxooctanoic acid               | C₈H₁₄O₃           | 1185.00 ± 0.01  | Fatty acid                |
| 2-Oxovaleric acid                | C₅H₈O₂            | 4.12 ± 0.01     | Ketoacid                  |
| Para-methoxy-N-methylamphetamine| C₁₁H₁₂NO          | 145.28 ± 0.01   | Stimulant                 |
| Pentadecanoic acid               | C₁₅H₃₀O₂          | 11.42 ± 0.01    | Fatty acid                |
| Pentaethylene glycol             | C₂₂H₄₆O₆          | 6.10 ± 0.01     | Solvent                   |
| Pentadecane                      | C₁₅H₁₃₂           | 2.32 ± 0.01     | Alkane                    |
| Pentanamide                      | C₅H₁₁NO           | 1.41 ± 0.01     | Acid amide                |
| Pentane                          | C₅H₁₂             | 7.22 ± 0.09     | Alkane                    |
| Pentanoic acid                   | C₅H₁₀O₂           | 26.12 ± 0.20    | Flavoring                 |
| Pentaoxacyclopentadecane         | C₁₀H₂₀O₅          | 1.60 ± 0.01     | Crown ether               |
| Pentenedioate                    | C₅H₈O₄⁺           | 2.88 ± 0.01     | Organic acid              |
| Pentenedioic acid                | C₅H₈O₄            | 7.41 ± 0.07     | Organic acid              |
| 2-Pentenoic acid                 | C₅H₈O₂            | 70.15 ± 0.95    | Organic acid              |
| 9-O-pivaloyl-N-acetylcolchinol   | C₂₅H₃₁NO₆         | 24.44 ± 0.17    | Aromatic                  |
| Pregnenolone                     | C₂₁H₃₂O₂          | 3.80 ± 0.01     | Steroid                   |
| Propanal                         | C₃H₆O             | 2.77 ± 0.02     | Aldehyde                  |
| Propane                          | C₃H₈              | 6.39 ± 0.02     | Alkane                    |
| Propanedioic acid                | C₃H₄O₄            | 10.46 ± 0.01    | Organic acid              |
| 1,3-Propanediol                  | C₃H₆O₂            | 3.03 ± 0.01     | Alcohol                   |
| 1,2,3-Propanetriol               | C₃H₆O₃            | 1595.72 ± 0.02  | Polyl                     |
| Propanone                        | C₃H₆O₂            | 114.26 ± 1.34   | Ketone                    |
| 2-Propanamide                    | C₃H₅NO            | 338.39 ± 4.16   | Fatty amide               |
| 2-Propanoic acid                 | C₃H₅O₂            | 15.90 ± 0.01    | Organic acid              |
| Propylamine                      | C₃H₇N             | 3.25 ± 0.01     | Fatty amine               |
| Propylene glycol                 | C₃H₆O₂            | 2458.09 ± 1.26  | Solvent                   |
| Pseudoephedrine                  | C₁₀H₁₈NO          | 24.34 ± 0.01    | Decongestant              |
| Pseudouridine                    | C₆H₁₂N₂O₆         | 2.99 ± 0.01     | Nucleoside                |
| Pyranordiol                      | C₂H₄O₃            | 40.72 ± 0.01    | Alcohol                   |
| Pyruvate oxime                   | C₃H₅NO₃           | 14.13 ± 0.09    | Acid amine                |
| Scopolin                         | C₁₈H₂₆O₉          | 179.76 ± 2.08   | Phytochemical              |
| Sebacic acid                     | C₁₀H₁₈O₄          | 3.53 ± 0.01     | Fatty acid                |
| Succinate                        | C₄H₇O₂⁺           | 0.78 ± 0.01     | Flavoring                 |
| Succinonitrile                   | C₄H₇N₂            | 0.16 ± 0.01     | Nitrile                   |
| Talonic acid                     | C₄H₇O₇            | 5.55 ± 0.01     | Organic acid              |
| Tetradeacane                     | C₁₅H₳₈O₂          | 14.12 ± 0.01    | Alkane                    |
| Tetradecanoic acid               | C₁₄H₂₅O₂          | 7.86 ± 0.03     | Fatty acid                |
| 1-Tetradeacol                    | C₁₄H₂₅O₂          | 1.24 ± 0.01     | Fatty alcohol             |
| Tetraethylene glycol             | C₈H₁₈O₃           | 0.53 ± 0.01     | Solvent                   |
| 1,2,4,5-Tetramethylbenzene       | C₁₀H₁₄            | 650.91 ± 0.01   | Aromatic                  |
| Thiodiglycol                     | C₁₀H₁₀O₂S         | 12.39 ± 0.14    | Alcohol                   |
| Tricyclodecyl propionate         | C₁₂H₂₄O₂          | 2.31 ± 0.01     | Fragrance                 |
| Tridecane                        | C₁₃H₂₈            | 207.98 ± 0.01   | Alkane                    |
| Tridecanoic acid                 | C₁₃H₂₅O₂          | 15.33 ± 0.01    | Fatty acid                |
| Triethylene glycol               | C₆H₁₄O₄           | 120.91 ± 0.04   | Solvent                   |
| 2,3,4-Trihydroxybutanoic acid    | C₄H₄O₂            | 41.02 ± 0.31    | Organic acid              |
| 2,4,5-Trihydroxypentanoic acid   | C₅H₁₀O₅           | 18.61 ± 0.01    | Organic acid              |
| 1,2,4-Trimethylbenzene           | C₉H₁₄             | 16.28 ± 0.01    | Aromatic                  |
| 1-Undecene                       | C₁₁H₂₂            | 7.66 ± 0.03     | Alkene                    |
| Vitamin C                        | C₆H₈O₆            | 9.22 ± 0.01     | Ascorbic acid             |
| Metabolite                                      | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|------------------------------------------------|-------------------|-----------------|--------------------------|
| Altrio-heptulose                                | C₇H₁₂O₇          | 6.79 ± 0.01     | Sugar substitute         |
| Arabinitol                                      | C₅H₁₀O₅          | 115.06 ± 0.03   | Sugar alcohol            |
| Arabinofuranose                                 | C₅H₁₀O₅          | 1714.08 ± 2.23  | Sugar substitute         |
| Arabinofuranoside                              | C₅H₄O₅           | 592.25 ± 0.06   | Sugar substitute         |
| D-arabino-3-hexulose                           | C₆H₁₂O₆          | 17.21 ± 0.01    | Sugar substitute         |
| Arabinonic acid                                | C₅H₁₀O₆          | 81.43 ± 1.14    | Sugar acid               |
| Arabinopyranose                                | C₅H₁₀O₅          | 2350.31 ± 1.98  | Sugar substitute         |
| Arabinose                                      | C₅H₁₀O₅          | 912.65 ± 2.11   | Sugar substitute         |
| Arabitol                                       | C₅H₁₀O₅          | 1456.58 ± 0.56  | Sugar alcohol            |
| 3-Deoxy-D-arabino-hexonic acid                 | C₆H₁₂O₆          | 112.61 ± 0.11   | Sugar acid               |
| 2-Deoxy-erythro-pentofuranose                  | C₅H₁₀O₄          | 596.47 ± 8.29   | Sugar substitute         |
| 3-Deoxy-erythro-pentonic acid                  | C₅H₁₀O₅          | 43.20 ± 0.03    | Sugar acid               |
| 2-Deoxy-erythro-pentopyranose                  | C₅H₁₀O₄          | 2.50 ± 0.01     | Sugar substitute         |
| 2-Deoxy-D-galactopyranose                      | C₆H₁₂O₅          | 381.36 ± 2.07   | Sugar substitute         |
| 2-Deoxy-D-glucose                              | C₆H₁₂O₅          | 677.13 ± 0.01   | Sugar substitute         |
| Deoxy-ribose                                   | C₅H₁₀O₄          | 19.08 ± 0.01    | Sugar substitute         |
| 3-Deoxy-D-ribohexonic acid                     | C₆H₁₂O₅          | 20.71 ± 0.01    | Sugar acid               |
| Dihydroxyacetone                               | C₅H₄O₃           | 21.99 ± 0.01    | Sugar substitute         |
| Dulcitol                                       | C₆H₁₂O₆          | 3323.48 ± 4.53  | Sugar alcohol            |
| Erythritol                                     | C₅H₁₀O₄          | 0.26 ± 0.01     | Sugar alcohol            |
| Erythro-pentitol                               | C₅H₁₂O₃          | 29.50 ± 0.03    | Sugar alcohol            |
| Erythrose                                      | C₅H₁₀O₄          | 522.45 ± 5.06   | Sugar substitute         |
| Erythro-tetrofuranose                          | C₅H₁₀O₅          | 22.65 ± 0.01    | Sugar substitute         |
| Fructopyranose                                 | C₅H₁₂O₆          | 6.94 ± 0.01     | Sugar substitute         |
| Fructose                                       | C₅H₁₂O₆          | 2462.43 ± 1.42  | Sugar substitute         |
| Fructose oxide                                 | C₆H₁₃NO₆         | 2421.99 ± 0.01  | Sugar substitute         |
| Galactofuranose                                | C₆H₁₂O₆          | 1076.99 ± 0.78  | Sugar substitute         |
| Galactohexulose                                | C₆H₁₂O₇          | 2.20 ± 0.01     | Sugar substitute         |
| Galactopyranose                                | C₆H₁₂O₆          | 943.28 ± 2.36   | Sugar substitute         |
| Galactose                                      | C₆H₁₂O₆          | 8909.55 ± 1.18  | Sugar substitute         |
| Galactose oxime                                | C₆H₁₃NO₆         | 369.21 ± 0.39   | Sugar substitute         |
| Glucaric acid                                  | C₆H₁₀O₈          | 0.08 ± 0.01     | Sugar acid               |
| Glucitol                                       | C₅H₁₀O₄          | 601.89 ± 7.85   | Sugar alcohol            |
| Glucofuranic acid                              | C₆H₁₂O₆          | 2035.95 ± 1.10  | Sugar substitute         |
| Glucopyranose                                  | C₆H₁₂O₆          | 7024.77 ± 8.40  | Sugar substitute         |
| Glucopyranuronic acid                          | C₆H₁₀O₇          | 1239.42 ± 0.13  | Sugar acid               |
| Glucose                                        | C₅H₁₀O₆          | 2010.62 ± 1.31  | Sugar substitute         |
| Glucose oxide                                  | C₆H₁₃NO₆         | 610.91 ± 0.23   | Sugar substitute         |
| Glucuronic acid                                | C₆H₁₀O₇          | 7.58 ± 0.07     | Sugar acid               |
| Gluconic acid                                  | C₅H₆O₄           | 0.77 ± 0.01     | Sugar acid               |
| Glyceraldehyde                                 | C₅H₆O₃           | 422.51 ± 1.30   | Sugar substitute         |
| D-glycero-D-galacto-heptose                    | C₇H₁₂O₇          | 91.04 ± 0.01    | Sugar substitute         |
| D-glycero-D-gluco-heptose                      | C₇H₁₂O₇          | 129.78 ± 1.66   | Sugar substitute         |
| D-glycero-D-gulo-heptonic acid                 | C₇H₁₂O₈          | 40.26 ± 0.14    | Sugar acid               |
| D-glycero-L-manno-heptonic acid                | C₇H₁₂O₈          | 1192.77 ± 2.99  | Sugar acid               |
| Gulonic acid                                   | C₆H₁₂O₇          | 14.17 ± 0.10    | Sugar acid               |
| Gulose                                         | C₆H₁₂O₆          | 361.01 ± 2.59   | Sugar substitute         |
| Lactose                                        | C₆H₁₂O₁₃         | 125.72 ± 0.01   | Sugar substitute         |
| Levoglucosan                                   | C₆H₁₀O₅          | 1.32 ± 0.01     | Sugar substitute         |
| Lyxopyranose                                   | C₅H₁₀O₅          | 1654.75 ± 1.82  | Sugar substitute         |

Table 4. Sugar derivatives detected in culture supernatant of dual *Lactobacillus plantarum* and *Bacillus subtilis* fermentation in prawn shell waste and 20% glucose in deionized water.
Table 4. Cont.

| Metabolite                          | Molecular Formula | Quantity (mg/L) | Biological Characteristic |
|-------------------------------------|-------------------|-----------------|--------------------------|
| Lyxose                              | C₅H₁₀O₅           | 603.81 ± 2.35   | Sugar substitute          |
| Maltose                             | C₁₂H₂₂O₁₁         | 5653.05 ± 5.87  | Sugar substitute          |
| Mannitol                            | C₆H₁₄O₆           | 177.42 ± 0.80   | Sugar alcohol             |
| Mannofuranose                       | C₆H₁₂O₆           | 1009.76 ± 5.57  | Sugar substitute          |
| Mannofuranuronic acid               | C₄H₈O₆            | 51.35 ± 0.01    | Sugar acid                |
| Mannonic acid                       | C₆H₁₂O₇           | 2567.14 ± 1.67  | Sugar acid                |
| Mannopyranose                       | C₄H₁₂O             | 358.11 ± 0.21   | Sugar substitute          |
| Mannose                             | C₆H₁₂O₆           | 5744.85 ± 7.73  | Sugar substitute          |
| Melibiose                           | C₁₂H₂₂O₁₃         | 0.69 ± 0.01     | Sugar substitute          |
| 2,5-Methylene-D,L-rhamnitol         | C₇H₁₄O₅           | 1.33 ± 0.01     | Sugar substitute          |
| Methyl-D-galactofuranoside          | C₇H₁₄O₆           | 481.33 ± 1.13   | Sugar substitute          |
| Methyl-D-gluco.pyranoside           | C₇H₁₄O₆           | 4908.57 ± 6.54  | Sugar substitute          |
| Methyl-D-lyxofuranoside             | C₆H₁₂O₅           | 499.24 ± 4.75   | Sugar substitute          |
| Methyl-D-mannopyranoside            | C₅H₁₄O₆           | 131.27 ± 0.01   | Sugar substitute          |
| Methyl-D-ribofuranoside             | C₆H₁₂O             | 120.28 ± 0.01   | Sugar substitute          |
| Methyl-D-xylopyranoside             | C₆H₁₂O₅           | 1.23 ± 0.01     | Sugar substitute          |
| Myo-inositol                        | C₆H₁₂O₆           | 130.33 ± 0.50   | Sugar substitute          |
| Pentitol                            | C₆H₁₂O₅           | 185.84 ± 0.01   | Sugar Alcohol             |
| Phenyl-D-galactopyranoside          | C₁₂H₁₆O₆          | 9584.87 ± 0.01  | Sugar substitute          |
| D-ribos-2-hexulose                  | C₆H₁₂O₆           | 5.77 ± 0.03     | Sugar substitute          |
| Ribonic acid                        | C₅H₁₀O₆           | 89.50 ± 0.70    | Sugar acid                |
| Ribopyranose                        | C₅H₁₀O₅           | 1427.89 ± 7.29  | Sugar substitute          |
| Ribose                              | C₅H₁₀O₅           | 249.45 ± 3.50   | Sugar substitute          |
| Sorbopyranose                       | C₆H₁₂O₆           | 39.12 ± 0.11    | Sugar substitute          |
| Talose                              | C₆H₁₂O₆           | 800.65 ± 2.15   | Sugar substitute          |
| Threitol                            | C₅H₁₀O₄           | 121.12 ± 1.66   | Sugar alcohol             |
| Threonic acid                       | C₁₇H₂₃O₅          | 30.15 ± 0.01    | Sugar acid                |
| Turanose                            | C₁₂H₂₂O₁₁         | 66.04 ± 0.40    | Sugar substitute          |
| Xylofuranose                        | C₅H₁₀O₅           | 508.27 ± 0.44   | Sugar alcohol             |
| Xylofuranose                        | C₅H₁₀O₅           | 88.69 ± 0.01    | Sugar substitute          |
| D-xyl-2-hexulose                    | C₅H₁₀O₅           | 2.66 ± 0.02     | Sugar substitute          |
| Xylonic acid                        | C₅H₁₀O₅           | 156.31 ± 1.43   | Sugar acid                |
| Xylofuranose                        | C₅H₁₀O₅           | 88.69 ± 0.01    | Sugar substitute          |
| Xylopyranose                        | C₅H₁₀O₅           | 915.86 ± 0.30   | Sugar substitute          |
| Xylose                              | C₅H₁₀O₅           | 1417.45 ± 1.36  | Sugar substitute          |
| Xylulose                            | C₅H₁₀O₅           | 7.30 ± 0.01     | Sugar substitute          |

3.2. Chitin Yield and Purity Calculations

From 5.0 g of prawn shell waste, 20 g of glucose, and 100 g of deionized water, the dry weight of crude extracted chitin was found to be 0.50 ± 0.01 g, translating to an overall fermentation yield of 0.50/125.0 × 100% = 0.4%.

Lowry’s test was performed on 1 mL of supernatant extracted from 50 mg chitin heated in 10 mL NaOH and its absorbance was found to be 0.213, corresponding to 20 µg of protein when compared against the protein calibration curve (Figure 1). This translates to a residual protein of 200 µg per 50 mg chitin, which is a residual protein content of 200/50,000 × 100% = 0.4%.
Bacteria species coexist with neighboring microorganisms in a dynamic community by producing small metabolites in response to environmental changes such as biotic and abiotic stresses. These volatile organic and inorganic compounds are released during interspecies bacteria interactions due to competition and cooperation, forming soluble metabolites in the supernatant [134]. Detection and quantification of these bacteria volatile compounds have always been of great interest in the food, cosmetic, flavor, and fragrance bioprocessing industry as well as in the clinical and medical field. However, analysis of bacteria volatile compounds has remained challenging due to the wide abundance of metabolites and the complexity of the culture medium from where they are extracted.

The co-fermentation of prawn shell waste and 20% glucose by Lactobacillus plantarum and Bacillus subtilis for chitin extraction produced bacteria volatile metabolites of various chemical classes. Fatty acid derivatives such as hydrocarbons, ketones and alcohols, organic acids, as well as sulphur and nitrogen-containing compounds were detected in the culture supernatant. These metabolites were generally produced by different catabolic pathways such as glycolysis, proteolysis, and lipolysis to break down the proteins, fats, and minerals residual in the prawn shell waste [135]. Linear-chained hydrocarbons detected were most probably derived from products of the fatty acid biosynthetic pathway. Both short-chain alkanes and longer-chain hydrocarbons were found in the culture supernatant, testifying to the ability of the microbial strains to synthesize branched hydrocarbons.

Methyl ketones detected were probably produced from the decarboxylation of fatty acids [136]. For example, 3-hydroxy-2-butanone (72.50 mg/L) or acetoin detected might have been derived from pyruvate fermentation. Long-chain aliphatic alcohols such as 1-decanol (1.75 mg/L) were probably produced through the oxidation of fatty acid derivatives. Significant production of butanediol (139.50 mg/L) was detected due to the presence of glucose as the main nutrient in the growth medium. Short-chain branched alcohols such as 3,3-dimethyl-1-butanol (18.60 mg/L) detected might have been produced from the enzymatic conversion of branched chain amino acids such as leucine.

Several short-chain fatty acids were detected in the culture supernatant such as acetic acid (71.94 mg/L), propanoic acid (1184.32 mg/L), and butanoic acid (4399.87 mg/L). These saturated aliphatic organics acids most probably resulted from bacteria fermentation of carbohydrates. Glyoxylic acid (4.68 mg/L) detected could either have been produced in the tricarboxylic acid cycle or generated during amino acid metabolism, for example during the degradation of glycine (25.56 mg/L),
threonine (91.73 mg/L), and proline (91.76 mg/L). Indole (22.32 mg/L) biosynthesis, another by-product of amino acid catabolism, was also detected in the fermentation supernatant [137].

An oxidative deamination of many amino acids might have also led to the production of aldehydes, ketones, or alcohols detected. For example, the degradation of 1,4-dihydrophenyalanine (2.92 mg/L) might have served as the first step of aromatic volatile compounds synthesis, producing benzene, its carbohydrate derivatives, as well as other benzenoid volatiles. Many volatile organic compounds produced by *Lactobacillus plantarum* and *Bacillus subtilis* have been reported to display antimicrobial activity. Among these known antimicrobial metabolites, benzenoids are the most represented in quantity compared to alkanes, aldehydes, ketones, acids, and alcohols. While a huge majority of antimicrobial benzenoid volatiles have a benzene core linked to a fatty acids derivative, benzenoids are very diverse and can be linked with carbohydrate chains containing nitrogen and sulphur [138].

The antimicrobial mode of action of these bacteria volatile organic compounds might arise from their lipophilic nature, which enables them to destabilize the cell membrane integrity of antagonistic pathogens, inhibiting their growth [139]. Besides benzenoids, nitrogen-containing volatile organic compounds are another important group of antimicrobial metabolites, consisting of non-cyclic amides and amines as well as cyclic azoles, pyrazines, pyridazines, and pyrimidines. Pyrazine (33.19 mg/L), pyridazine (3.29 mg/L), and pyrrolopyrimidine (3.33 mg/L) were detected in the *Lactobacillus plantarum* and *Bacillus subtilis* co-fermentation supernatant. Pyrazine, which is the most strongly represented in antimicrobial activity among them, is either formed from the non-enzymatic animation of acyloins or derived from aminoketone intermediates produced from amino acid catabolism. This testifies to the successful breakdown of amino acids from the prawn shell waste.

Antimicrobial active metabolites may have potential use as natural preservatives to control the growth and inactivate undesired microorganisms in food [140]. For example, lactic acid (1055.39 mg/L) and acetic acid (71.94 mg/L) are produced by *Lactobacillus plantarum* in probiotics to compete for nutrients with other foodborne pathogens. Other organic acids such as propanoic acid (1184.32 mg/L) and butanoic acid (4399.87 mg/L) are also produced, which further reduce the pH of the culture medium. The production of other substances such as ethanol (31.01 mg/L), fatty acids such as 3-hydroxybutyric acid (18.19 mg/L), 3-hydroxysebacic acid (4.09 mg/L), and 3-hydroxypruvic acid (1.32 mg/L), as well as 3-hydroxy-2-butanone (72.5 mg/L) further intensify its antimicrobial activity. The metabolomics results show that *Lactobacillus plantarum* is more heterofermentative than homofermentative as a variety of metabolites are generated from the degradation of hexoses.

5. Conclusions

Many useful metabolites are produced when *Lactobacillus plantarum* and *Bacillus subtilis* are fermented with prawn shell waste together with 20% glucose as a carbon source. Besides lactic acid, a variety of organic acids such as fatty acids and amino acids as well as several antimicrobial molecules were detected in the culture supernatant. This shows that protease-mediated protein hydrolysis of the prawn shells is successful in removing proteins, minerals, and fats from the prawn shells. While harnessing the solid fraction of the fermentation as chitin, the nutrient-rich liquid fraction may be used for probiotics applications.

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