Enhancing lactic acid production from food waste through cavitation pretreatment and biocatalyst amendment

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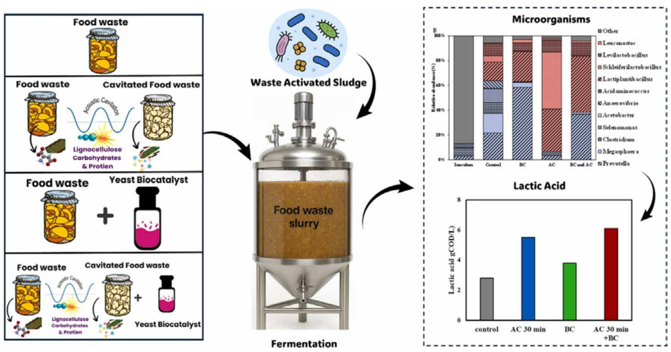
Authors: Encarnación Díaz-Domínguez, Aisha Khan Khanzada, Zahra Askarniya, Sławomir Ciesielski, Xianbao Xu, Grzegorz Boczkaj, Xiang Li, Francisco Jesús Fernández-Morales, Jacek Mąkinia, José L. García-Morales

Abstract

Food waste (FW) fermentation into valuable lactic acid (LA) aligns with circular economy goals, but is constrained by low substrate conversion efficiency and mixed product spectrum. This study evaluated the effects of acoustic cavitation pretreatment, biocatalyst (yeast extract) supplementation, and their combination on the targeted LA production. Acoustic cavitation (20 kHz and 450 W/L for 30 min) enhanced FW solubilization by 9.6-fold and increased LA yield to 0.40 g COD/g VSS. With biocatalyst amendment, the hydrolysis phase was improved, and the highest LA yield reached 0.34 g COD/g VSS. When combined, the yield slightly increased to 0.42 g COD/g VSS, exhibiting only a marginal synergistic effect over the individual treatments. The treatments suppressed volatile fatty acid (VFA) formation and promoted LA accumulation. Microbial community analysis revealed an increased abundance of lactic acid bacteria, particularly Schleiferilactobacillus, Lactiplantibacillus, and Levilactobacillus, with concurrent suppression of VFA-producing bacteria, such as Prevotella and Megasphaera. The findings provide new insights into optimizing chiral LA production from complex waste streams and highlight the potential of integrated bioprocessing strategies.



Introduction

Approximately one-third of all food produced for human consumption is either lost or wasted globally, generating an estimated 1.3 billion tons of food waste (FW) annually [1]. In Europe, FW generation ranges from 33 kg to 142 kg per capita per year [2]. FW poses significant environmental and public health risks due to its potential to generate greenhouse gases, harbor pathogens, and contaminate soil and water systems [3]. However, its rich polysaccharide content makes it a promising feedstock for bioconversion into value-added products, such as lactic acid (LA) [4], [5]. The total carbohydrate content in FW, which encompasses these fermentable components, is typically reported in the literature within the range of 35.5–69.0 % (Uçkun Kiran *et al*., 2014).

LA is a versatile organic acid that occurs naturally and is of great value as an industrial chemical. It is used as an acidifier and preservative in the food sector and has applications in the pharmaceutical, leather, and textile industries [6], especially as the precursor of biodegradable plastic polylactic acid (PLA) [7], [8]. Depending on the specific bacteria involved, there are two optical isomers: D-LA and L-LA [7]. The second quarter's price in Europe for 88 % liquid LA CFR Rotterdam in the Netherlands was recorded at USD 1120/MT [9]. Currently, over 90 % of the world's LA is produced by biological fermentation [10]. In the context of FW valorization, which serves as a mixed fermentation substrate due to its complex and carbohydrate-rich composition, the production mechanism, carried out by lactic acid bacteria (LAB) under anaerobic conditions from sugars and other fermentable carbohydrates to LA (Li *et al*., 2021), develops through two key stages: hydrolysis and acidogenesis [5], [11]. Hydrolysis, as the first step of fermentation, is a crucial phase responsible for the solubilization of organic matter, breaking down complex polymers into simple, bioavailable sugars. A limitation in the efficiency of hydrolysis acts as a primary bottleneck, restricting substrate availability and subsequently impairing the final product yield [12]. Nevertheless, FW offers significant potential for LA [13], [14], while the degradation of FW is influenced by its physical, chemical, and biological properties [15].

Among pretreatment techniques, acoustic cavitation has shown promise in increasing the solubilization of organic components within FW [16], [17]. According to the literature, the mechanical effect of cavitation, such as extreme shear wall stress, which is predominant in low-frequency acoustic cavitation compared to high-frequency one, is mainly responsible for a decrease in the size of particles and a rise in solubility in the pretreatment stage [18]. In the case of FW, cavitation can increase soluble chemical oxygen demand (SCOD) in a range from 9 % to 172 %, stimulate enzyme activities, and reduce mass transfer resistance [18]. Cavitation has widely been reported in the production of methane [19], hydrogen [20], and volatile fatty acids (VFA) [12]. However, the effect of cavitation pretreatment on chiral L-LA and D-LA production, as well as the LAB community structure, is not well understood.

Mixed culture FW fermentation benefits from microbial synergy, resulting in enhanced substrate utilization, resilience to contamination, and low operational costs [21]. However, key LA-producing LAB often require complex nitrogen sources, such as yeast extract, for optimal performance [22], [5]. Yeast extract is chosen as the nitrogen source because it provides essential growth cofactors, including amino acids, peptides, and vitamins, which LAB require due to their limited synthetic capacity. This supplementation is crucial for stimulating microbial metabolism, promoting rapid growth, and achieving high LA yields [23]. In this context, the use of biocatalyst, particularly those composed primarily of yeast extract, is utilized to fulfill the role of the complex nitrogen source required by the LAB. Though its effect on chiral LA production in FW-based mixed cultures has not been widely investigated. Furthermore, the combined impact of acoustic cavitation and yeast extract supplementation on both fermentation performance and microbial community dynamics remains largely unexplored.

Building upon the current literature and identified knowledge gaps, the main objective of this study was the evaluation of the individual and combined effects of acoustic cavitation pretreatment and biocatalyst (yeast extract-based) supplementation on LA production efficiency during FW fermentation. This was achieved by evaluating the influence of these treatments on: the chiral LA distribution (specifically the differentiated production of D-LA and L-LA), the competing VFA production, and the corresponding microbial community shifts. These findings aim to provide valuable insights into enhanced and selective LA recovery from FW by comparing the maximum LA yield and purity achieved under different operational conditions, thus supporting circular bioeconomy objectives.

Substrate preparation and inoculum

The inoculum used in the fermentation process was obtained from a municipal wastewater treatment plant

(WWTP) in Gdynia, Poland. It consisted of a heterogeneous culture of bacteria from an anaerobic digester for treating waste activated sludge. To ensure the efficacy of the fermenters, the inoculum was carefully preserved at 20°C before use in the fermentation experiments.

The substrate used in this study was a mixture of FW from the University canteen, consisting of 21% vegetables, 13%.

LA production

A comparative analysis of LA production across different operational strategies reveals the variation of L-LA, D-LA, and Total LA, along with LA productivity and yield (Fig. 1). Additional data are provided in Figure S1. This figure shows that the trials (with and without the biocatalyst) conducted with a cavitation treatment duration of 30 min achieved better results.

The trial with no pretreatment or use of additives (control) shows a production curve for LA that is characterized by a gradual.

Conclusion

The novel contribution of this study is the pioneering validation of a dual strategy combining acoustic cavitation pretreatment with the addition of a yeast extract-based biocatalyst for LA production from FW. The superior impact of this approach is explained by a key selective mechanism: both treatments successfully restructure the microbial community, achieving the effective suppression of VFA-producing bacteria (Prevotella, Megasphaera) and the enrichment of key LAB.

Credit authorship contribution statement

Aisha Khan Khanzada: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. Zahra Askarniya: Methodology, Investigation. Encarnación Díaz-Domínguez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. Jacek Mąkinia: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization. José L. García-Morales: Writing – review & editing,

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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