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Review

Biological Approach for Lead (Pb) Removal from Meat and Meat Products in Bangladesh

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Abstract

Heavy metal contamination, particularly lead (Pb) poisoning, is a significant public health issue worldwide. In Bangladesh, Pb contamination of water, soil, air, and food is detected alarmingly. Chronic exposure to Pb leads to severe health complications in the human body, including neurotoxicity, cardiovascular disease, developmental delays, and kidney damage. Research has established that there is "no safe level" of Pb exposure, as even minimal exposure can cause detrimental effects. Although existing physical and chemical methods are widely used, they come with limitations, such as high costs and the generation of toxic byproducts. As a green, sustainable alternative, the potential of probiotics as an effective biosorption agent has been explored to reduce Pb contamination in food, especially meat, while preserving its nutritional and sensory properties. This paper aims to integrate current knowledge from these two fields and highlight their capacity to decontaminate Pb-laden meat, the primary protein source in Bangladesh. The study also investigates optimal biosorption parameters, including temperature, pH, and exposure time, to enhance effectiveness. The proposed application of lactic acid bacteria (LAB) in meat processing and packaging is expected to significantly lower Pb levels in meat, ensuring safer consumption.

Keywords: lead (Pb) contamination; probiotics; lactic acid bacteria; biosorption; heavy metal; meat

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1. Introduction

Heavy metal contamination has been one of the world's most alarming public health concerns. Lead (Pb), one of the leading heavy metal contaminants, poses serious health risks to the environment, animals, and humans [1]. For centuries, dating back to around 4000 BC, Pb has been used for various purposes. The ancient Romans utilized it for glazing pottery, piping, cooking utensils, and as a sweetener for wine. Pb toxicities were well-documented in ancient Egyptian papyrus rolls, indicating its use for murderous purposes. Throughout history, Pb poisoning has been known by terms such as "the miner's disease", "Pb blindness", "Pb colic", and "plumbism" [2]. It is natural to find Pb in trace amounts in soil and water, but exposure to high amounts of lead ions (Pb^{2+}) can have detrimental effects [1]. Rapid urbanization and uncontrolled industrial waste disposal have increased the levels of Pb in our environment, which is now being absorbed by fish, plants, fruits and vegetables, animal feeds, and being served on the dinner table. Chronic exposure to Pb, even at low levels, is associated with severe health issues (Figure 1), including neurotoxicity, developmental delays, cardiovascular problems, and renal dysfunction [3]. According to the Institute for Health Metrics Evaluation (IHME), Pb exposure was attributed to about

1.5 million deaths globally, primarily due to cardiovascular effects in 2021, and the death toll is rising every year [4]. Pb exposure during pregnancy becomes a source of exposure to the developing fetus. In response, the World Health Organization (WHO) has declared "No Safe Levels" of lead concentration in blood, with several regulatory procedures emphasizing the importance of absolutely minimized exposure to Pb and other heavy metals from all sectors [4]. According to the United Nations Children's Fund (UNICEF), Bangladesh holds the 4th position worldwide for the number of children impacted by lead pollution, and around 35 million children experience developmental issues, learning disabilities, and cardiovascular problems from Pb exposure [5]. The study by Majumder et al. [6] determined Pb concentrations in air (0.09–376.58 μg/m^3, mean 21.31 μg/m^3), river water (0.0009–18.7 mg/L, mean 1.07 mg/L), soil (7.3–445 mg/kg, mean 90.34 mg/kg), and diet items (0.001–413.9 mg/kg; mean 43.22 mg/kg) of samples collected from different areas of Bangladesh. To minimize the Pb-associated problems, several physical (membrane separation, ultrafiltration, sedimentation, adsorption, etc.) and chemical (chemical precipitation, coagulation-flocculation, ion exchange, electrodialysis, etc.) techniques are being used to decontaminate soil and water sources [7]. However, these conventional and expensive techniques come with a list of disadvantages, including the generation of sludge, toxic chemical residues, pretreatment requirements, and the production of corrosive chemicals [8]. Among different decontamination approaches, bio-removal provides a practical, cost-friendly, and easy way to remove heavy metals. Various organisms are utilized to degrade the pollutants from our environment. Probiotics are an excellent choice in that regard [9,10]. As a part of our gut microbiota, these microbes enhance immunity, lower cholesterol levels, and prevent interactions with gut pathogens [11]. When consumed in adequate quantity, these bacteria help to maintain the gastrointestinal microbiota. Recent study shows probiotics can decontaminate Pb^{2+} in both viable and nonviable stages [12]. In a study by Firincă et al. [13], the remarkable bioremediation capability of *Bacillus marisflavi* found in soil was demonstrated, which effectively removed Chromium (Cr), Pb, and Zinc (Zn) by 87%, 86%, and 67%, respectively. This approach is also backed by Giri et al. [14], who reported the efficacy of several probiotic bacteria, including *Lactobacillus casei*, *Lactococcus lactis*, *Lactobacillus reuteri* P16, *Lactiplantibacillus plantarum* SSFM8661, and *Bacillus cereus* in sequestering heavy metals and attenuating their toxicological effects in a fish model. It is worth noting that in a mixture of heavy metals, the efficiency of biosorption of Pb^{2+} depends on several factors such as temperature, pH, size of the particle, concentration, etc. [15]. A silent exposure of Pb is dietary sources, among which meat has grabbed attention across the globe. 11.5–13.5 μg per 100 g have been recorded in meat, meat products, and fish samples in turkey, while high concentrations of Pb were found in sheep, beef, turkey, and ostrich meat samples from Iran [16,17]. Pb values in edible meat samples in Spain were 3.16 μg/kg for chicken, 4.89 μg/kg for pig, 6.72 μg/kg for beef, and 9.12 μg/kg for turkey [18]. A recent study revealed that Pb was detected in 54.9% of chicken meat and 23.3% of fish samples collected from Bangladesh, highlighting the risk of Pb exposure through fish and meat consumption [19]. The best levels of Pb are said to be zero or close to zero. Hence, Pb exposure from every source should be minimized as much as possible. It is essential to find ways to reduce its concentration in meat. Therefore, this study advocates using probiotic bacteria as a biosorption agent that will help reduce Pb concentration from meat products. It also aims to elucidate its ability to obtain safe processed food with greater health benefits and lower the risk.

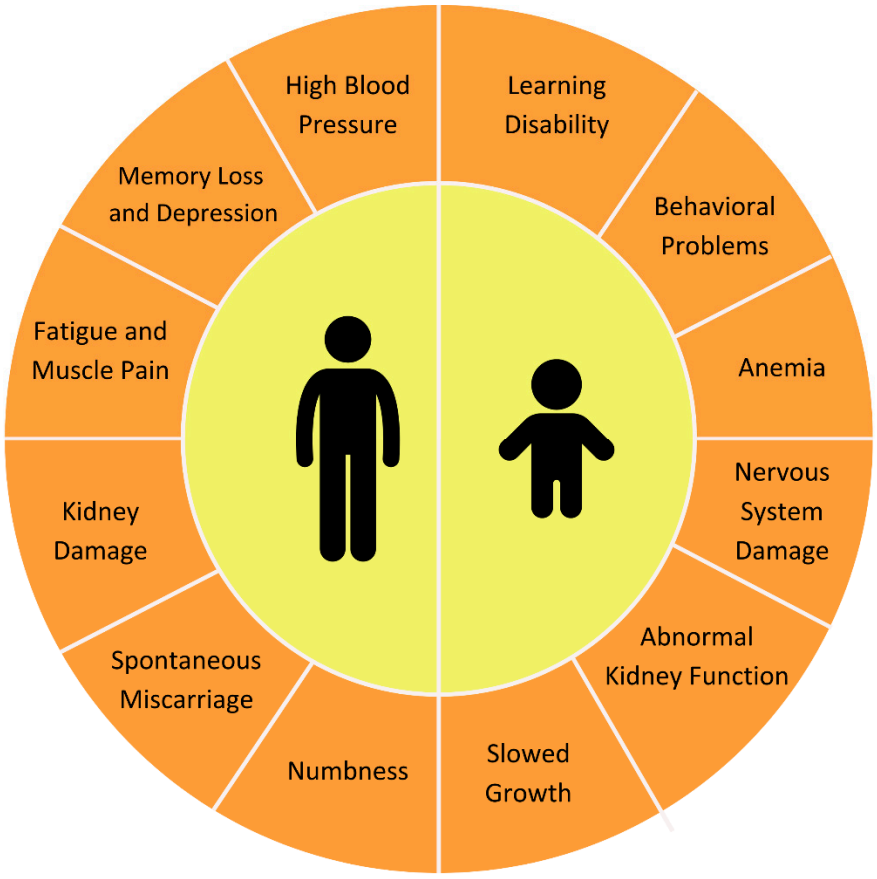


Figure 1. Health hazards in adults and children due to lead (Pb) poisoning.

2. Lead Contamination in Meat and Meat Products in Bangladesh

The Pb poisoning and its severe effects are evident worldwide. Its drastic effects are seen in both children and adults. In children, the effects can range from anemia and slowed growth to severe outcomes such as nervous system damage and seizures [20]. Apart from adults exhibiting signs of high blood pressure, memory problems, nerve damage, and so on, pregnant women are mainly suffering from a higher risk of miscarriage [4,20].

While Pb-contaminated drinking water and soil are leading the way as top contributors to the increasing Pb toxicity in humans, other aspects like using lead-based paint, contamination during industrial processing, and dietary sources are adding to this problem. Fruits and vegetables harvested from contaminated soil or Pb-contaminated water used in their processing are being directly served to the consumer. Additionally, using low-quality Pb-containing animal feed can introduce Pb into animal tissues, which are popular protein sources [21]. While lead-based battery factories can directly pose health hazards to the workers and residents nearby, they can also have far-reaching impacts by contaminating the farms in that area, from which the contaminated food will be distributed nationwide. Contamination in this regard can be so alarming that it might cause the death of the animals as well. In 2020, a study was conducted in Magura, Bangladesh, on unknown cattle deaths caused by grazing near the battery recycling field [22]. Although the usage of lead ammunition in game meat poses a severe problem in different parts of the world, Bangladesh is safe in this regard due to the unpopularity of hunting. However, the risk of contamination during processing in industry or slaughterhouses remains.

Recent studies have all emphasized the alarming presence of Pb in Bangladesh's agricultural sources [19,23]. The concentrations of Pb in meat sources alone have varied across geographic locations, types of markets, animal sources, and even the tissue consumed.

In 2025, Pb levels ranging from 0.289 to 0.915 mg/kg were detected in the primary meat consumed in Bangladesh [24], specifically broiler chicken. Even though the reported Pb concentration in broiler chicken across Bangladesh varies, the range is still alarming in all the regions (Figure 2) [25]. Such a disturbing trend is seen in all meat sources available in Bangladesh (Figure 3) [26].

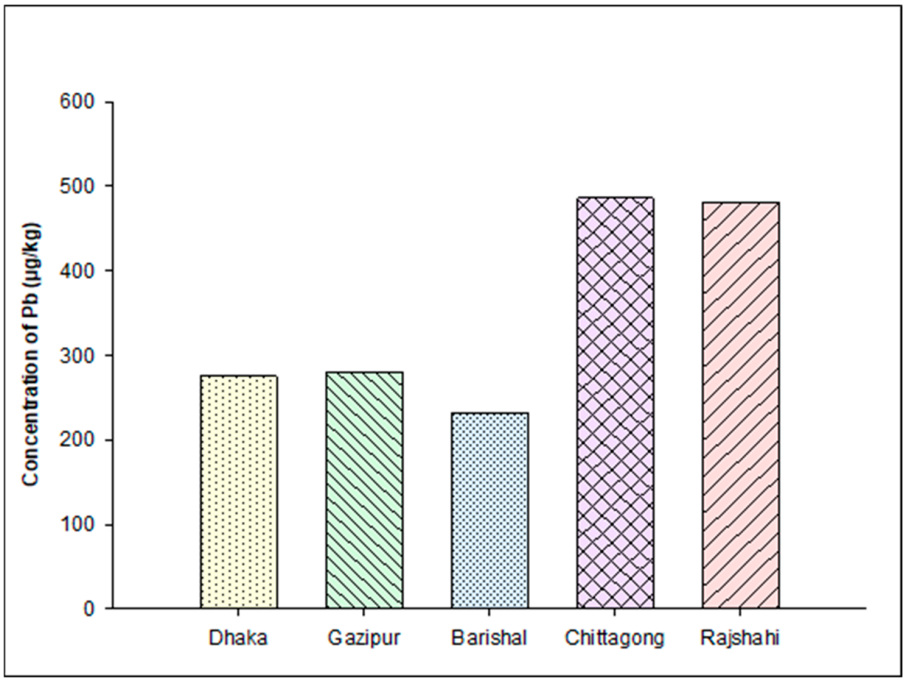


Figure 2. The average lead (Pb) concentration found in broiler chicken samples collected from various regions in Bangladesh, expressed in µg/kg [25].

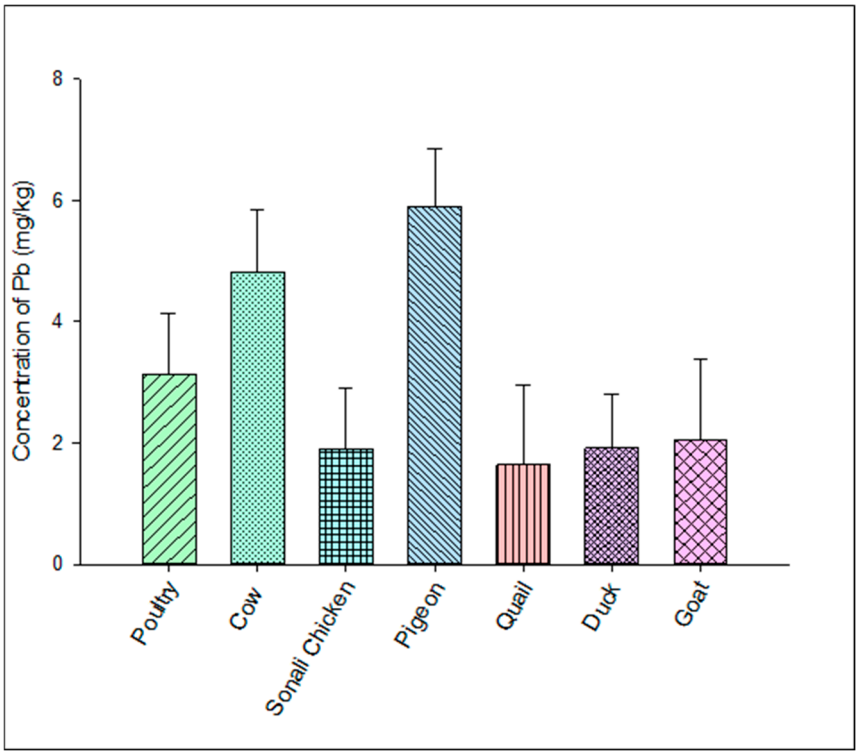


Figure 3. The mean concentration of lead (Pb) in various meat (muscle) sources of Bangladesh, expressed in mg/kg [26].

Furthermore, this study revealed that chicken liver contained the highest concentration of Pb among muscles, liver, and gizzards, ranging from 0.266 to 0.1009 mg/kg [24]. The trend of the liver having more concentration of Pb than other parts is indicated by the high target hazard quotient denoted in cow and goat liver, as mentioned by Chowdhury and Alam et al. [26], than in other consumed parts. A study by Hossain et al. [27] found alarming Pb concentrations in beef markets across Dhaka, Bangladesh, ranging from 11.08 to 69.63 µg/kg in cows. Handling, storing, and processing meat in various market setups available in Bangladesh also play a significant role in Pb exposure (Figure 4) [25].

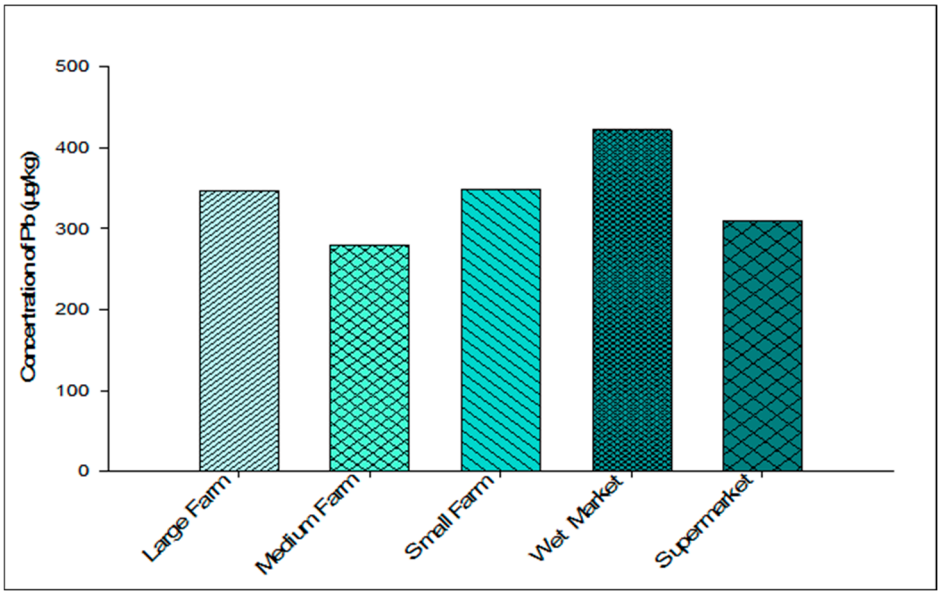


Figure 4. The concentration of lead (Pb) found in broiler meat samples collected from various market setups in Bangladesh, expressed in µg/kg [25].

While biological contaminations can be reduced by simple house techniques like high-temperature cooking techniques, heavy metals are not affected and require specific treatment. In an experimental setup, it was proved that the Pb concentration in a burger prepared by chicken muscle had similar levels of Pb concentration in it, 0.44 mg/kg and 0.41 mg/kg, respectively [28]. Thus, specific mitigation techniques are required to control Pb poisoning from meat sources.

3. Prevalence of Probiotic Bacteria in Bangladesh and Their Lead (Pb) Removing Efficacy

Probiotics are live microorganisms capable of inducing multiple health benefits in human hosts [29]. Health benefits caused by these microbes include the maintenance of a healthy intestinal environment by preventing pathogens, aiding in immunity support, and alleviating allergies. It has also been reported to remove cholesterol in some cases [30]. Probiotics primarily consist of lactic acid-producing bacteria (LABs). Among them, *Lactococcus*, *Lactobacillus*, *Leuconostoc*, and *Pediococcus* genera are noteworthy [31]. However, beyond its physiological influence in the human host, in recent times, probiotics have been intensely studied for their heavy metal binding ability, which can be utilized for bio-decontamination of heavy metals present in our environment [11]. Biological methods provide an easy, efficient, cost-effective way to remove heavy metals without generating additional toxic waste to the environment, as is the case with chemical methods [31]. Probiotic bacteria can mostly decontaminate Pb in viable and nonviable states through biosorption [32]. In a study by Petrova et al. [33], the ability of probiotics to bind Pb was reported for multiple LAB species, such as *Lp. plantarum* LAB-32, *Lp. plantarum* PTCC 1896, *Lactobacillus acidophilus* ATCC

20552, *Propionibacterium freudenreichii* spp. *shermanii* JS, *Limosilactobacillus reuteri* Pb71-1, *Pediococcus acidilactici* As105-7. Other studies also showed that *Lactobacillus rhamnosus* can reduce Pb absorption in the intestinal epithelium, while *Lactobacillus bulgaricus* KLDS1.0207 has lessened Pb enrichment in tissues [34,35]. Due to its culinary diversity, Bangladesh has a wide range of probiotics in its diet. LABs demonstrate significant probiotic potential and possess effective Pb biosorption properties (Table 1).

Table 1. A list of commonly available probiotic potential lactic acid bacteria (LABs) in Bangladesh with lead (Pb) biosorption properties.

Lactic Acid Bacteria (LAB)	Lead (Pb) Removal Ability *	Reference
Lactobacillus acidophilus DSM 20079	Moderate	[36]
Lb. acidophilus NCFM	Low	[36]
Pediococcus pentosaceus	Moderate	[30]
Bifidobacterium longum FPL 19312	Weak	[36]
B. longum Morinaga	Low	[36]
Lactiplantibacillus plantarum LAB-32	High	[33]
Lp. plantarum PTCC 1896	Moderate	[33]
Lactobacillus rhamnosus ATCC 9595	Moderate	[36]
Lb. rhamnosus ATCC 53103 (GG)	Low	[36]
Lb. rhamnosus Lr-32	Moderate	[36]
Lb. rhamnosus FPL 19125	Moderate	[36]
Lactobacillus delbrueckii DSM 20081	High	[36]
Limosilactobacillus fermentum DSM 20055	High	[36]
Lactobacillus fermentum FPL 19124	High	[36]
Lactobacillus farciminis DSM 20184	High	[36]
Lactobacillus casei DSM 20011	Moderate	[36]
Lb. casei BL23	Low	[36]
Leuconostoc mesenteroides DSM 20343	High	[36]
Levilactobacillus brevis DSM 20054	High	[36]
Lactococcus lactis MG1363	Weak	[36]
Weissella confusa DSM 20196	High	[36]
Lactobacillus farciminis DSM 20184	High	[36]

* Weak (0–25%); Low (26–50%); Moderate (51–75%); High (76–100%).

4. Mechanisms of Heavy Metal Binding by LABs

Food is often contaminated by non-degradable and toxic heavy metals, including Pb, cadmium (Cd), mercury (Hg), arsenic (As), etc. These contaminated foodstuffs have been a source of concern for people worldwide for a long time. Even though chemical and physical methods exist to reduce heavy metal contamination to a certain extent, they have some drawbacks [37]. Decontamination of heavy metals using physical or chemical methods may generate additional toxic waste or be extremely expensive for the ordinary people of Bangladesh to rely upon for an extended period [38]. The use of biological methods prevails in removing heavy metals. In this scenario, LABs present more effective, selective, and accessible alternatives for heavy metal decontamination [33].

LABs are the most abundant group of probiotics [39]. These gram-positive bacteria constitute a thick layer of peptidoglycan, minor components (teichoic acid and lipoteichoic acid), and S-layer proteins (SLP) that facilitate binding to Pb^{2+}. Cell wall polysaccharides are diverse (based on branching, chargeless structures, and complexity) for LABs, giving each bacterial species its unique characteristics [30]. According to Kirillova et al. [40] observed that the cell wall composition and structure of LABs are modified according to environmental changes. Additionally, LABs extracted exopolysaccharides that can be either excreted or bound to the surface, containing glucose, galactose, rhamnose, mannose, N-acetylglucosamine, and *N*-acetylgalactosamine in most cases [41]. LABs exhibit a unique structural composition characterized by the presence of two distinct types of teichoic acids (TAs), such as polyglycerol phosphate and polyribitol phosphate. Additionally, they feature

noteworthy anionic polymers that are integrated into the peptidoglycan layer, and this combination plays a significant role in enhancing the robustness and functionality of the LABs' cell wall [33]. In contrast, LAB-derived lipoteichoic acid binds to plasma membranes via a glycolipid anchor [41].

The *Lactobacillus* genus produces an SLP that is highly basic in nature, forming a protective outer shell on the cell wall. SLP is non-covalently attached to the peptidoglycan layer, and teichoic acid stabilizes this attachment. A study conducted by Sagmeister et al. [42] discusses that treatment with heat and acid may denature the SLP structure, causing it to expose new binding sites. This can be a possible reason why SLPs are negatively charged despite being basic in nature. The presence of carboxyl and phosphoryl groups in cell wall structures and all these factors create a net negative charge in LABs [35].

LABs can effectively bind to heavy metals through various mechanisms, notably a metabolism-independent process known as biosorption and a metabolism-dependent process known as bioaccumulation, showcasing their remarkable capability to interact with and potentially mitigate environmental contaminants [36,40]. Biosorption, a passive surface-binding mechanism, can be used to remove metals in both viable and nonviable stages, enabling Pb^{2+} metal to interact with anionic groups in bacterial cell walls [33,43]. The overall negative charge across the cell wall of LABs facilitates interaction with positively charged metal ions like Pb^{2+} [44]. In contrast, bioaccumulation is an active, metabolism-dependent process of ion binding by microbes that involves the transport of metal ions across the cell membrane through specific transmembrane proteins. This mechanism is highly regulated by cellular metabolism and occurs exclusively in viable cells, often serving as a microbial strategy to cope with heavy metal stress [40]. In such cases, the uptake of metal ions requires energy, as it involves active transport across the cell membrane and carrying out metabolic functions. Bacterial cell walls, composed of a complex matrix of polysaccharides and proteins, separate metal ions due to their numerous active sites. According to a study by Lin et al. [15], two hypothesized models have been proposed for this separation. The first model suggests metal ions are transported to cytoplasm and isolated in a specific region to minimize damage to other cellular components. The latter involves a metal-binding protein that aids in metal detoxification through the formation of stable metal chelates [15]. Moreover, in a comprehensive review by Massoud and Zoghi [11], it was highlighted that some LABs also produce exopolysaccharides (EPS) layers composed of negatively charged carboxyl, hydroxyl, amine, acetate, sulfate, and phosphate groups, increasing the bacterial cell negativity. This claim was backed by Chapot-Chartier and Kulakauskas [44], where it was stated that dead or nonviable bacterial cells can passively bind to heavy metals by several physiochemical mechanisms, such as ion exchange, complexation, adsorption, and chelating (Figure 5) [11]. Heavy metal ions can replace protons that are initially bound to functional groups on the bacterial cell membrane. Negatively charged moieties in LABs, such as carboxyl, phosphate, and hydroxyl, act as proton exchange sites. Research has demonstrated that LAB strains exhibiting a higher net negative surface charge show enhanced binding affinity for Pb^{2+} ions [15]. The ion exchange mechanism is often a rapid process compared to the other. Complexation involves the formation of coordination bonds between metal ions and electron-donating functional groups located on the bacterial cell wall. Carboxyl (-COOH) groups of peptidoglycan polymers and the carboxyl (-COOH) groups and phosphate ($-PO_4^{3-}$) groups of phosphoric acid act as ligands that bind to heavy metal ions such as Pb^{2+} through non-covalent interactions [45]. The overall negative charge on the cell membrane of LABs facilitates the chelation of various transition metal ions. These metal-binding sites, rich in macromolecules such as proteins and polysaccharides containing teichoic acids or exopolysaccharides, enable the accumulation of Pb^{2+} through stable interactions once the sites become saturated [46]. In another study, Tian et al. [47]

proved that nonviable *Lb. plantarum* CCFM8661 showed almost similar Pb^{2+} binding ability as viable cells, with the highest biosorption level of 53 mg/g dry mass. These mechanisms enable rapid and stable binding of Pb^{2+}, making LABs efficient Pb^{2+} removal agents.

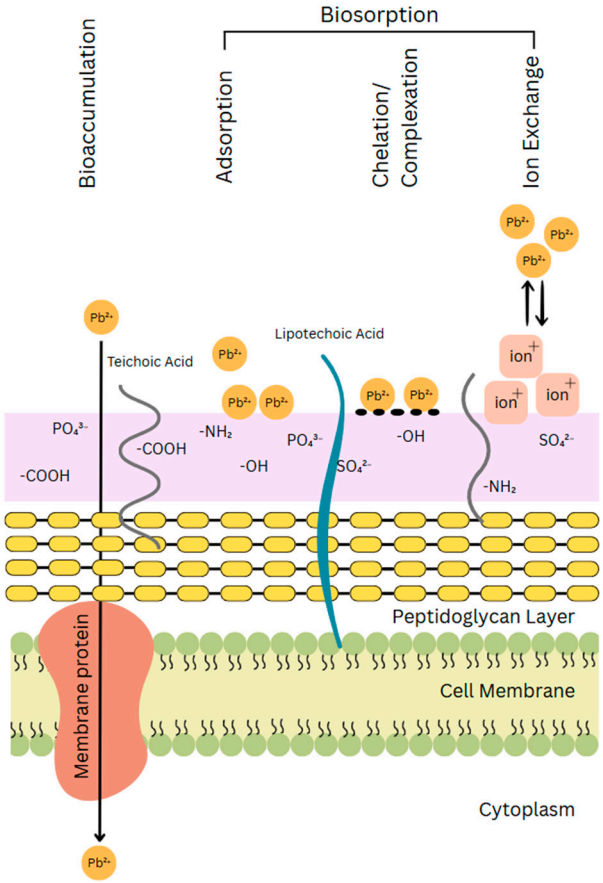


Figure 5. Lead (Pb) binding mechanisms by lactic acid bacteria (LAB).

As such, LABs can be used as biosorption agents to reduce Pb^{2+} concentration in meat products. It is worth mentioning that different factors may influence this binding ability, and these should be considered during the decontamination process [47].

5. Lead Removal from Meat Using Probiotics: A Strategic Approach

LABs are well-recognized for their numerous health benefits. In addition to directly benefiting human and animal health, LABs have significantly affected bioremediation processes. The interaction of LABs with heavy metals generally involves bioremediation and detoxification in the human gut. Biosorption is a promising mechanism for addressing Pb contamination. Furthermore, introducing probiotic bacteria like LABs aids the human gut by reducing the amount of free Pb^{2+} available for adsorption, improving the gut barrier by decreasing its permeability, and ultimately excreting it through defecation without allowing it to enter the bloodstream, thus preventing the harmful effects of Pb poisoning [36].

Studies have repeatedly shown that LABs in aqueous solutions can bind to Pb^{2+}, reducing their bioavailability [11,12,48,49]. Introducing Pb-contaminated raw meat to an aqueous solution of LABs allows the organisms to interact with the meat, binding to the available Pb^{2+} present in it (Figure 6). The timing of introducing LABs to the meat needs to be calculated so that the organisms have sufficient time to maximize ion binding but not long enough to cause fermentation that changes the raw meat's overall quality.

Rigorous washing with clean, contamination-free water will wash away the surface Pb-LAB complexes, while those residing inside may remain. Washing has demonstrated

a 60% reduction in Pb concentration in a study conducted on rice bran and is thus an important step to consider [50]. As the washed meat undergoes home cooking techniques or industrial processing, even if the varying environmental conditions affect bacterial cell viability, Pb^{2+} may remain firmly bound to the bacterial cell membrane, resisting the acidic conditions of the stomach, as seen with toxin-LAB complexes [11]. The biosorption process is a physical binding mechanism rather than a metabolically active one. Another study indicated that heat and acid-killed bacteria exhibited a higher binding capacity than live cells [51]. Since the binding of Pb^{2+} is also achieved through biosorption, similar results can be anticipated, further supporting our application hypothesis. Direct consumption of this meat will not allow the gut to absorb Pb^{2+} ions through the intestinal epithelium, as shown by Daisley et al. [34], as *Lb. rhamnosus* GR-1 reduces Pb^{2+} adsorption across human epithelial colorectal adenocarcinoma cells (Caco-2), which represent the intestinal barrier. Thus, the remaining Pb may be consumed after washing but will be safely excreted from the body, minimizing Pb poisoning.

In industrial meat processing, an effective step is to incorporate probiotic potential LABs before packaging and immediately storing the products at 4 °C. This approach can enhance the benefits of probiotic intake in the human body while controlling the growth of LABs, which may alter the taste of the meat product [52]. Additionally, it helps reduce residual lead (Pb) adsorption in the human gut and minimizes the effects of Pb-associated poisoning.

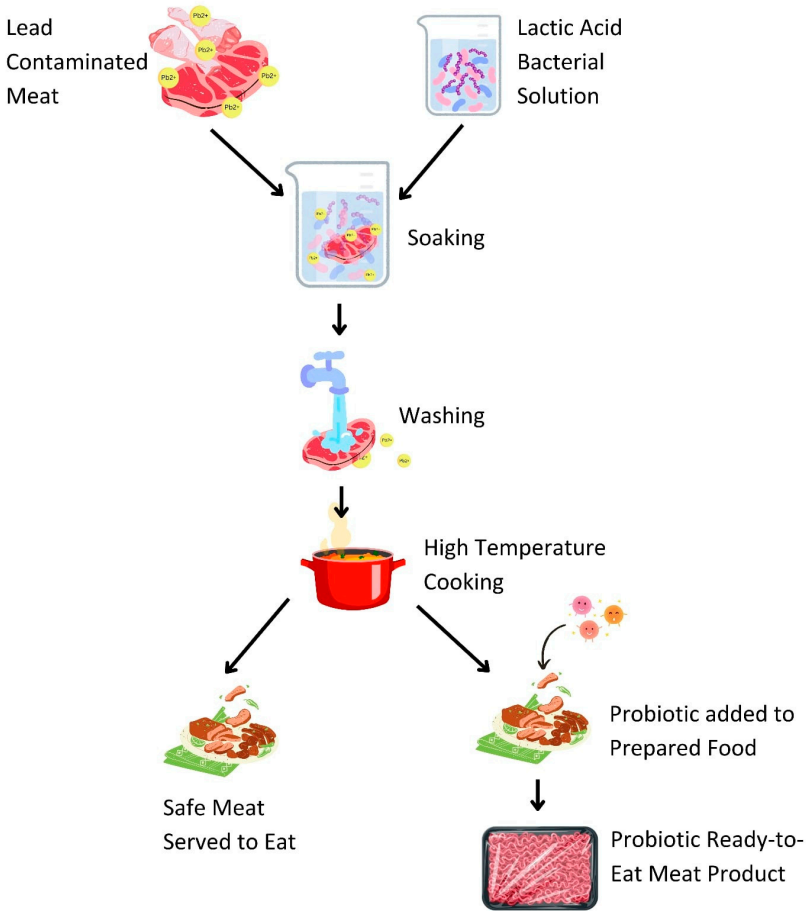


Figure 6. Hypothesized lactic acid bacteria (LAB) treatment for lead (Pb) decontamination from meat.

6. Optimizing the Parameters for the Hypothesized Treatment

Several modifiable environmental conditions significantly impact the efficacy of the biosorption process, ultimately dictating the effectiveness of the treatment (Figure 7). The

temperature and pH of the LAB solution in which meat is soaked are vital factors in this regard. The metal binding capability of LABs increases with temperature within an optimum range, influencing the cell wall structure, metal ion stability, and the binding force of the metal-LAB complex. However, this statement does not apply universally. While *Lb. acidophilus*, *Lb. rhamnosus*, *Lp. plantarum*, and *S. thermophilus* exhibited higher binding capabilities at elevated temperatures; *Enterococcus faecium* exhibited minimal sensitivity to temperature fluctuations regarding its adsorption capacity [53]. During later cooking stages, the meat is subjected to higher temperatures, which may raise concerns about the process as the cells become inactive. Nevertheless, heating or boiling treatments have been shown to yield better biosorption results as more binding sites are exposed. A study by Li et al. [54] investigated the effects of boiling *Weissella viridescens* ZY-6 at 100 °C for 60 min. The results showed a nearly 11% increase in the bacterium's ability to absorb Cd^{2+}, suggesting that heat treatment could enhance its potential in bioremediation of Cd-contaminated environments. However, the optimal pH for maximum adsorption varies based on the metal and bacteria involved. In the case of Pb, *Lb. rhamnosus*, *Limosilactobacillus fermentum*, and *Lactobacillus fermentum* bind more Pb^{2+} as the pH increases until reaching neutral conditions [51]. In contrast, *Saccharomyces cerevisiae* shows the highest biosorption of Pb^{2+} at slightly acidic conditions, specifically between pH 5.0 and 7.0 [55].

As the probiotic solution used for soaking the meat is central to this process, the concentration of bacteria and contact time are crucial factors in maximizing Pb adsorption. As the bacterial load increases, the number of Pb-binding receptors also rises, leading to higher adsorption. Massoud et al. [56] reported the highest adsorption rate of 75% in their study with Lb. acidophilus when the bacterial biomass concentration was increased to 1×10^{12}. However, this is considered an optimal concentration because, while adsorption increases with bacterial load, it decreases after a certain point. This decline may be due to the clustering of bacterial cells, the significant secretion of organic acids that could alter the optimal pH or even the production of cationic ions that compete with Pb^{2+} ions [57].

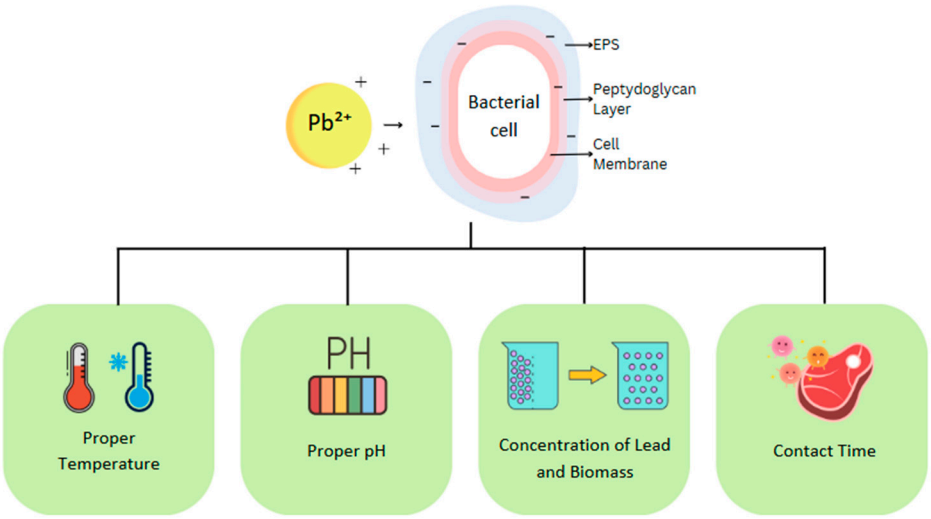


Figure 7. Factors influencing the biosorption of lactic acid bacteria (LAB) for optimum results of the treatment.

Prolonged exposure to LAB suspension can affect the meat's nutritional value, color, and odor, potentially leading to acidification. Preserving the meat's nutritional value and quality while preventing spoilage is a significant food safety concern. Therefore, the soaking time must be carefully calibrated to ensure optimal adsorption and minimal risks. A study by Kumar and Dwivedi [58] emphasizes the importance of contact time, identifying the first ten minutes as the peak for adsorption. However, under optimal conditions, *S. cerevisiae*

demonstrates 99.5% Pb biosorption efficacy at 60 min, while *Lb. acidophilus* shows 80% Pb biosorption by day 4 [55,56]. This suggests that optimal contact time varies depending on the bacterial strain. Nevertheless, strains that require the least amount of time for maximum efficiency are preferred to avoid altering product characteristics. Experimental results from all factors indicate variability in the optimal conditions. A study conducted by Jena et al. [55] demonstrated that the best conditions for Pb biosorption using *S. cerevisiae* require temperatures between 20 °C and 30 °C, a pH range of 5.0 to 7.0, and a contact time of 60 min. These conditions are crucial for achieving maximum biosorption efficiency in single or mixed bacterial cultures.

7. Study Limitations and Future Plans

There are some limitations to using LABs as Pb^{2+} removal agents:

- More research is required to optimize the parameters affecting the efficacy of the process in both in vivo and in vitro. This, however, might have economic constraints.
- Contamination during storage and transportation is still not protected by this proposed method.
- Biosorption of other heavy metals to the binding sites may lower the adherence of Pb^{2+} ions.
- Although the methodology is backed up by in vitro scientific arguments, in vivo results might differ based on various factors. They thus cannot be implemented before proper animal and human testing.

Achieving such a green strategy will revolutionize ready-to-eat meat products. In addition to reducing heavy metal contamination, adding probiotics aims to provide consumers with more health benefits, such as improved gut health, enhanced digestion, boosted immunity, and overall well-being. Incorporating these into edible coatings before food packaging will address the recontamination issue, ensuring safe food for everyone. Furthermore, the large-scale development of the proposed LAB solution or dried biomass for use in water can be marketed to households for meat purchased at wet markets, which typically do not undergo any processing. Therefore, the proposed methodology can significantly address the problem of Pb contamination in meat for households and industries while also opening new avenues for developmental experiments in food safety and security.

8. Conclusions

The concerning Pb contamination in meat and meat products poses significant public health risks and needs attention to develop effective and sustainable mitigation strategies. The availability of a wide range of fermented food products in Bangladesh, acting as a reservoir of LABs and flourishing food industries already working extensively to bring forth probiotic dietary options, provides a strong foundation to deploy LAB-based heavy metal bioremediation. The existence of infrastructure and easy availability of LABs help to reduce the economic burden to a significant extent. This study proposes a simple, innovative bioremediation strategy highlighting the potential of LABs as a cost-effective biosorption agent to reduce Pb levels in meat without compromising its nutrition and sensory values while ensuring food safety. Its versatility in processing and packaging addresses the Pb contamination problem while providing additional health benefits to consumers. Although the proposed methodology offers a promising solution, further testing is required to optimize the parameters affecting proper biosorption. Implementing the proposed treatment into the existing infrastructure of Bangladesh is a locally available solution and requires minimal investment. Thus, this approach could transform the meat safety practices and the meat industry as well as benefit the consumer.

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References

1. Angon, P.B.; Islam, M.S.; Das, A.; Anjum, N.; Poudel, A.; Suchi, S.A. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon* **2024**, *10*, e28357. [CrossRef]
2. Zhang, H.; Lee, J.; Nasti, G.; Handy, R.; Abate, A.; Grätzel, M.; Park, N. Lead immobilization for environmentally sustainable perovskite solar cells. *Nature* **2023**, *617*, 687–695. [CrossRef]
3. Collin, M.S.; Venkatraman, S.K.; Vijayakumar, N.; Kanimozhi, V.; Arbaaz, S.M.; Stacey, R.G.S.; Anusha, J.; Choudhary, R.; Lvov, V.; Tovar, G.I.; et al. Bioaccumulation of lead (Pb) and its effects on human: A review. *J. Hazard. Mater. Adv.* **2022**, *7*, 100094. [CrossRef]
4. World Health Organization (WHO). Lead Poisoning. Available online: https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health (accessed on 5 February 2025).
5. United Nations Children's Fund (UNICEF). An Alarming Rate of Blood Lead Levels Among Children: UNICEF Urges the Interim Government to Implement a Strategy for a Lead-Free Bangladesh. Available online: https://www.unicef.org/bangladesh/en/press-releases/alarming-rate-blood-lead-levels-among-children-unicef-urges-interim-government (accessed on 17 March 2025).
6. Majumder, A.K.; Nayeem, A.A.; Islam, M.; Akter, M.M.; Carter, W.S. Critical review of lead pollution in Bangladesh. *J. Health Pollut.* **2021**, *11*, 210902. [CrossRef] [PubMed]
7. Ahmad, I.; Asad, U.; Maryam, L.; Masood, M.; Saeed, M.F.; Jamal, A.; Mubeen, M. Treatment methods for lead removal from wastewater. In *Lead Toxicity: Challenges and Solution*; Kumar, N., Jha, A.K., Eds.; Springer: Cham, Switzerland, 2023; pp. 197–226. [CrossRef]
8. Patel, B.; Gundaliya, R.; Desai, B.; Shah, M.; Shingala, J.; Kaul, D.; Kandya, A. Groundwater arsenic contamination: Impacts on human health and agriculture, *ex situ* treatment techniques and alleviation. *Environ. Geochem. Health* **2022**, *45*, 1331–1358. [CrossRef]
9. Toushik, S.H.; Mizan, M.F.R.; Hossain, M.I.; Ha, S.D. Fighting with old foes: The pledge of microbe-derived biological agents to defeat mono- and mixed-bacterial biofilms concerning food industries. *Trends Food Sci. Technol.* **2020**, *99*, 413–425. [CrossRef]
10. Ashrafudoulla, M.; Park, J.; Toushik, S.H.; Shaila, S.; Ha, A.J.W.; Rahman, M.A.; Park, S.H.; Ha, S.D. Synergistic mechanism of UV-C and postbiotic of *Leuconostoc mesenteroides* (J. 27) combination to eradicate *Salmonella Thompson* biofilm in the poultry industry. *Food Control* **2024**, *164*, 110607. [CrossRef]
11. Massoud, R.; Zoghi, A. Potential probiotic strains with heavy metals and mycotoxins bioremoval capacity for application in foodstuffs. *J. Appl. Microbiol.* **2022**, *133*, 1288–1307. [CrossRef]
12. Mirza Alizadeh, A.; Hosseini, H.; Mohseni, M.; Mohammadi, M.; Hashempour-Baltork, F.; Hosseini, M.J.; Eskandari, S.; Sohrabvandi, S.; Aminzare, M. Bioremoval of lead (pb) salts from synbiotic milk by lactic acid bacteria. *Sci. Rep.* **2025**, *15*, 9101. [CrossRef]
13. Firincă, C.; Zamfir, L.-G.; Constantin, M.; Răut, I.; Capră, L.; Popa, D.; Jinga, M.-L.; Baroi, A.M.; Fierăscu, R.C.; Corneli, N.O.; et al. Microbial removal of heavy metals from contaminated environments using metal-resistant indigenous strains. *J. Xenobiot.* **2023**, *14*, 51–78. [CrossRef]
14. Giri, S.S.; Kim, H.J.; Jung, W.J.; Lee, S.B.; Joo, S.J.; Gupta, S.K.; Park, S.C. Probiotics in addressing heavy metal toxicities in fish farming: Current progress and perspective. *Ecotoxicol. Environ. Saf.* **2024**, *282*, 116755. [CrossRef] [PubMed]
15. Lin, D.; Ji, R.; Wang, D.; Xiao, M.; Zhao, J.; Zou, J.; Li, Y.; Qin, T.; Xing, B.; Chen, Y.; et al. The research progress in mechanism and influence of biosorption between lactic acid bacteria and Pb(II): A review. *Crit. Rev. Food Sci. Nutr.* **2017**, *59*, 395–410. [CrossRef]
16. Demirezen, D.; Uruç, K. Comparative study of trace elements in certain fish, meat, and meat products. *Meat Sci.* **2006**, *74*, 255–260. [CrossRef] [PubMed]
17. Raeeszadeh, M.; Gravandi, H.; Akbari, A. Determination of some heavy metals levels in the meat of animal species (sheep, beef, turkey, and ostrich) and carcinogenic health risk assessment in Kurdistan province in the west of Iran. *Environ. Sci. Pollut. Res.* **2022**, *29*, 62248–62258. [CrossRef] [PubMed]

18. González-Weller, D.; Karlsson, L.; Caballero, A.; Hernández, F.; Gutiérrez, A.; González-Iglesias, T.; Marino, M.; Hardisson, A. Lead and cadmium in meat and meat products consumed by the population in Tenerife Island, Spain. *Food Addit. Contam.* **2006**, *23*, 757–763. [CrossRef]
19. Begum, R.; Akter, R.; Dang-Xuan, S.; Islam, S.; Siddiky, N.A.; Uddin, A.A.; Mahmud, A.; Sarker, M.S.; Grace, D.; Samad, M.A.; et al. Heavy metal contamination in retailed food in Bangladesh: A dietary public health risk assessment. *Front. Sustain. Food Syst.* **2023**, *7*, 1085809. [CrossRef]
20. Lin, Y.C.; Chang, W.H.; Li, T.C.; Iwata, O.; Chen, H.L. Health risk of infants exposed to lead and mercury through breastfeeding. *Expo. Health* **2023**, *15*, 255–267. [CrossRef]
21. Korish, M.A.; Attia, Y.A. Evaluation of heavy metal content in feed, litter, meat, meat products, liver, and table eggs of chickens. *Animals* **2020**, *10*, 727. [CrossRef]
22. Syed, H. Assessing Lead in Milk and Environmental Samples Elicited from a Used Lead Acid Battery Separation Factory in Dinajpur District of Bangladesh. Doctoral Dissertation, Chattogram Veterinary & Animal Sciences University, Chittagong, Bangladesh, 2022. Available online: http://dspace.cvasu.ac.bd/bitstream/123456789/2496/1/THESIS%20%28MS%29%20Dr%20Syed%281%29.pdf%20final.pdf (accessed on 21 March 2025).
23. Kumar, S.; Islam, R.; Akash, P.B.; Khan, M.H.R.; Proshad, R.; Karmoker, J.; MacFarlane, G.R. Lead (Pb) contamination in agricultural products and human health risk assessment in Bangladesh. *Water Air Soil Pollut.* **2022**, *233*, 257. [CrossRef]
24. Shahriar, S.M.S.; Haque, N.; Hasan, T.; Sufal, M.T.A.; Hassan, M.T.; Hasan, M.; Salam, S.M.A. Heavy metal pollution in poultry feeds and broiler chickens in Bangladesh. *Toxicol. Rep.* **2025**, *14*, 101932. [CrossRef]
25. Bokhtiar, S.M.; Islam, M.R.; Ahmed, M.J.; Rahman, A.; Rafiq, K. Assessment of heavy metals contamination and antimicrobial drugs residue in broiler edible tissues in Bangladesh. *Antibiotics* **2023**, *12*, 662. [CrossRef] [PubMed]
26. Chowdhury, A.I.; Alam, M.R. Health effects of heavy metals in meat and poultry consumption in Noakhali, Bangladesh. *Toxicol. Rep.* **2024**, *12*, 168–177. [CrossRef]
27. Hossain, M.M.; Hannan, A.S.M.A.; Kamal, M.M.; Hossain, M.A. Detection of heavy metals and evaluation of beef procured from the different market of Dhaka in Bangladesh. *Eur. J. Food Sci. Technol.* **2022**, *10*, 1–10. [CrossRef]
28. Haque, M.N.; Islam, M.M.T.; Hassan, M.T.; Shekhar, H.U. Determination of heavy metal contents in frequently consumed fast foods of Bangladesh. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2018**, *89*, 543–549. [CrossRef]
29. Toushik, S.H.; Kim, K.; Park, S.H.; Park, J.H.; Ashrafudoulla, M.; Ulrich, M.S.I.; Mizan, M.F.R.; Hossain, M.I.; Shim, W.B.; Kang, I.; et al. Prophylactic efficacy of *Lactobacillus curvatus* B67-derived postbiotic and quercetin, separately and combined, against *Listeria monocytogenes* and *Salmonella enterica* ser. Typhimurium on processed meat sausage. *Meat Sci.* **2023**, *197*, 109065. [CrossRef] [PubMed]
30. Mirmahdi, R.S.; Zoghi, A.; Mohammadi, F.; Khosravi-Darani, K.; Jazaiery, S.; Mohammadi, R.; Rehman, Y. Biodecontamination of milk and dairy products by probiotics: Boon for bane. *Ital. J. Food Sci.* **2021**, *33*, 78–91. [CrossRef]
31. Toushik, S.H.; Roy, A.; Alam, M.; Rahman, U.H.; Nath, N.K.; Nahar, S.; Matubber, B.; Uddin, M.J.; Roy, P.K. Pernicious attitude of microbial biofilms in agri-farm industries: Acquisitions and challenges of existing antibiofilm approaches. *Microorganisms* **2022**, *10*, 2348. [CrossRef] [PubMed]
32. Zhang, Z.; Shu, G.; Zheng, Q.; Chen, L.; Du, G.; Zhang, M. Removal of cadmium, lead, and chromium by *Lactobacillus helveticus* KD-3: Influential factors, adsorption mechanism, and application in goat milk powder. *LWT* **2025**, 117899. [CrossRef]
33. Petrova, P.; Arsov, A.; Tsvetanova, F.; Parvanova-Mancheva, T.; Vasileva, E.; Tsigoriyna, L.; Petrov, K. The complex role of lactic acid bacteria in food detoxification. *Nutrients* **2022**, *14*, 2038. [CrossRef]
34. Daisley, B.A.; Monachese, M.; Trinder, M.; Bisanz, J.E.; Chmiel, J.A.; Burton, J.P.; Reid, G. Immobilization of cadmium and lead by *Lactobacillus rhamnosus* GR-1 mitigates apical-to-basolateral heavy metal translocation in a Caco-2 model of the intestinal epithelium. *Gut Microbes* **2018**, *10*, 321–333. [CrossRef]
35. Li, B.; Jin, D.; Yu, S.; Evivie, S.E.; Muhammad, Z.; Huo, G.; Liu, F. *In vitro* and *in vivo* evaluation of *Lactobacillus delbrueckii* subsp. *bulgaricus* KLDS1.0207 for the alleviative effect on lead toxicity. *Nutrients* **2017**, *9*, 845. [CrossRef] [PubMed]
36. George, F.; Mahieux, S.; Daniel, C.; Titécat, M.; Beauval, N.; Houcke, I.; Neut, C.; Allorge, D.; Borges, F.; Jan, G.; et al. Assessment of Pb(II), Cd(II), and Al(III) removal capacity of bacteria from food and gut ecological niches: Insights into biodiversity to limit intestinal biodisponibility of toxic metals. *Microorganisms* **2021**, *9*, 456. [CrossRef] [PubMed]
37. Azhar, U.; Ahmad, H.; Shafqat, H.; Babar, M.; Munir, H.M.S.; Sagir, M.; Arif, M.; Hassan, A.; Rachmadona, N.; Rajendran, S.; et al. Remediation techniques for elimination of heavy metal pollutants from soil: A review. *Environ. Res.* **2022**, *214*, 113918. [CrossRef]
38. Sarker, A.; Kim, J.E.; Islam, A.R.M.T.; Bilal, M.; Rakib, M.R.J.; Nandi, R.; Rahman, M.M.; Islam, T. Heavy metals contamination and associated health risks in food webs—A review focuses on food safety and environmental sustainability in Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 3230–3245. [CrossRef] [PubMed]
39. Toushik, S.H.; Kim, K.; Ashrafudoulla, M.; Mizan, M.F.R.; Roy, P.K.; Nahar, S.; Kim, Y.; Ha, S.D. Korean kimchi-derived lactic acid bacteria inhibit foodborne pathogenic biofilm growth on seafood and food processing surface materials. *Food Control* **2021**, *129*, 108276. [CrossRef]

40. Kirillova, A.V.; Danilushkina, A.A.; Irisov, D.S.; Bruslik, N.L.; Fakhrullin, R.F.; Zakharov, Y.A.; Bukhmin, V.S.; Yarullina, D.R. Assessment of resistance and bioremediation ability of *Lactobacillus* strains to lead and cadmium. *Int. J. Microbiol.* **2017**, *2017*, 9869145. [CrossRef]
41. Korcz, E.; Varga, L. Exopolysaccharides from lactic acid bacteria: Techno-functional application in the food industry. *Trends Food Sci. Technol.* **2021**, *110*, 375–384. [CrossRef]
42. Sagmeister, T.; Gubensäk, N.; Buhlheller, C.; Grininger, C.; Eder, M.; Đordić, A.; Millán, C.; Medina, A.; Murcia, P.A.S.; Berni, F.; et al. The molecular architecture of *Lactobacillus* S-layer: Assembly and attachment to teichoic acids. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2401686121. [CrossRef]
43. Mostafidi, M.; Sanjabi, M.R.; Mojgani, N.; Eskandari, S.; Bidgoli, S.A. Heavy metal bioremediation potential of autochthonous lactic acid bacteria for use in edible leafy vegetables. *J. Food Qual.* **2023**, *1*, 8730676. [CrossRef]
44. Chapot-Chartier, M.; Kulakauskas, S. Cell wall structure and function in lactic acid bacteria. *Microb. Cell Fact.* **2014**, *13*, S9. [CrossRef]
45. Xu, Y.; Shu, G.; Liu, Z.; Wang, Z.; Lei, H.; Zheng, Q.; Kang, H.; Chen, L. Preliminary Study on Screening and Genetic Characterization of Lactic Acid Bacteria Strains with Cadmium, Lead, and Chromium Removal Potentials. *Fermentation* **2024**, *10*, 41. [CrossRef]
46. Wang, Y.; Han, J.; Ren, Q.; Liu, Z.; Zhang, X.; Wu, Z. The involvement of lactic acid bacteria and their exopolysaccharides in the biosorption and detoxification of heavy metals in the gut. *Biol. Trace Elem. Res.* **2023**, *202*, 671–684. [CrossRef]
47. Tian, F.; Zhai, Q.; Zhao, J.; Liu, X.; Wang, G.; Zhang, H.; Zhang, H.; Chen, W. *Lactobacillus plantarum* CCFM8661 alleviates lead toxicity in mice. *Biol. Trace Elem. Res.* **2012**, *150*, 264–271. [CrossRef]
48. Elsanhoty, R.M.; Al-Turki, I.A.; Ramadan, M.F. Application of lactic acid bacteria in removing heavy metals and aflatoxin B1 from contaminated water. *Water Sci. Technol.* **2016**, *74*, 625–638. [CrossRef] [PubMed]
49. Liu, G.; Geng, W.; Wu, Y.; Zhang, Y.; Chen, H.; Li, M.; Cao, Y. Biosorption of lead ion by lactic acid bacteria and the application in wastewater. *Arch. Microbiol.* **2023**, *206*, 18. [CrossRef]
50. Mohammadi, F.; Marti, A.; Nayebzadeh, K.; Hosseini, S.M.; Tajdar-Oranj, B.; Jazaeri, S. Effect of washing, soaking and pH in combination with ultrasound on enzymatic rancidity, phytic acid, heavy metals and coliforms of rice bran. *Food Chem.* **2020**, *334*, 127583. [CrossRef] [PubMed]
51. Raman, J.; Kim, J.S.; Choi, K.R.; Eun, H.; Yang, D.; Ko, Y.J.; Kim, S.J. Application of lactic acid bacteria (LAB) in sustainable agriculture: Advantages and limitations. *Int. J. Mol. Sci.* **2022**, *23*, 7784. [CrossRef]
52. Trisnawita, Y.; Silalahi, J.; Sinaga, S.M. The effect of storage condition on viability of lactic acid bacteria in probiotic product. *Asian J. Pharm. Clin. Res.* **2018**, *11*, 84. [CrossRef]
53. Abdelshafy, A.M.; Mahmoud, A.R.; Abdelrahman, T.M.; Mustafa, M.A.; Atta, O.M.; Abdelmegiud, M.H.; Al-Asmari, F. Biodegradation of chemical contamination by lactic acid bacteria: A biological tool for food safety. *Food Chem.* **2024**, *460*, 140732. [CrossRef]
54. Li, W.; Chen, Y.; Wang, T. Cadmium biosorption by lactic acid bacteria *Weissella viridescens* ZY-6. *Food Control* **2020**, *123*, 107747. [CrossRef]
55. Jena, P.S.; Pradhan, A.; Nanda, S.P.; Dash, A.K.; Naik, B. Biosorption of heavy metals from wastewater using *Saccharomyces cerevisiae* as a biosorbent: A mini review. *Mater. Today Proc.* **2022**, *67*, 1140–1146. [CrossRef]
56. Massoud, R.; Khosravi-Darani, K.; Sharifan, A.; Asadi, G.; Zoghi, A. Lead and cadmium biosorption from milk by *Lactobacillus acidophilus* ATCC 4356. *Food Sci. Nutr.* **2020**, *8*, 5284–5291. [CrossRef] [PubMed]
57. Ma, X. Heavy metals remediation through lactic acid bacteria: Current status and future prospects. *Sci. Total Environ.* **2024**, *946*, 174455. [CrossRef]
58. Kumar, V.; Dwivedi, S.K. Mycoremediation of heavy metals: Processes, mechanisms, and affecting factors. *Environ. Sci. Pollut. Res.* **2021**, *28*, 10375–10412. [CrossRef] [PubMed]

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