Journal of Biological Research

Bollettino della Società Italiana di Biologia Sperimentale



eISSN 2284-0230 - pISSN 1826-883

https://www.pagepressjournals.org/index.php/jbr/index

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J Biol Res 2026 [Online ahead of print]

To cite this Article:

Gu M, Ge H, Wu X, et al. **Sugar chirality modulates the antioxidant and bacterial growth-inhibitory properties of Maillard reaction products from glucose and lysine.** *J Biol Res* doi: 10.4081/jbr.2026.14988

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Submitted: 28 February 2026

Accepted: 25 August 2026

Early access: 11 November 2026

Sugar chirality modulates the antioxidant and bacterial growth-inhibitory properties of Maillard reaction products from glucose and lysine

Mingze Gu, Hui Ge, Xianghuan Wu, Jiao Li, Zhongshuang Hu

Institute of Biomaterials and Biomedicine, School of Food and Pharmacy, Shanghai Zhongqiao Vocational and Technical University, Shanghai, P.R. China

Correspondence: Zhongshuang Hu, Institute of Biomaterials and Biomedicine, School of Food and Pharmacy, Shanghai Zhongqiao Vocational and Technical University, 3888 Caolang Rd, Shanghai 201514, P.R. China. Tel.: +86.021.31616009; Fax: +86.021.31616013. E-mail: hzs@shzq.edu.cn

Key words: antioxidants, glucose-lysine system, growth inhibition, Maillard reaction, stereochemistry.

Abstract

The Maillard reaction generates compounds with antioxidant and bacterial growth-inhibitory properties, but the influence of sugar stereochemistry on Maillard reaction products (MRPs) remains insufficiently explored. This study investigated the impact of glucose chirality on the antioxidant and growth-inhibitory activities of MRPs formed with L-lysine. MRPs were prepared by heating D-glucose or L-glucose with L-lysine under identical aqueous conditions. Antioxidant activities were assessed using 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), Ferric Reducing Antioxidant Power (FRAP), and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assays, while growth inhibition against *Listeria monocytogenes* was evaluated by broth microdilution growth kinetics, apparent Minimum Inhibitory Concentration (apparent MIC) estimation, and colony recovery. D-glucose-derived MRPs (MRP-D-Glu) and L-glucose-derived MRPs (MRP-L-Glu) exhibited similar ABTS and DPPH radical-scavenging capacities, whereas MRP-L-Glu demonstrated significantly higher ferric reducing power. Additionally, both MRPs inhibited *L. monocytogenes* growth at 50% (v/v), but only MRP-L-Glu maintained growth inhibition at 25%

(v/v). Viable colonies were recovered at the highest MRP level, indicating that the minimum bactericidal concentration was not reached. Sugar stereochemistry therefore selectively modulates ferric reducing power and bacterial growth inhibition, although the molecular basis remains unresolved.

Introduction

The Maillard reaction is a widely recognized non-enzymatic process that occurs between reducing sugars and amino groups, contributing significantly to the development of flavor, aroma, and color in thermally processed foods.[1] Beyond sensory properties, Maillard Reaction Products (MRPs) have been shown to exhibit antioxidant and antimicrobial activities, sparking interest in their potential use as functional ingredients in food preservation.[2,3] Importantly, these biological functions depend on the structural heterogeneity of MRPs, which in turn is determined by the identity of the reacting precursors and the reaction conditions. Therefore, the composition and functional performance of MRPs can vary substantially across systems.

Listeria monocytogenes (*L. monocytogenes*), a well-known foodborne pathogen, poses a significant risk due to its ability to tolerate environmental stress and grow at refrigeration temperatures, presenting ongoing challenges in the safety of ready-to-eat and minimally processed foods.[4] While previous studies have demonstrated that certain MRPs inhibit the growth of Gram-positive bacteria, including *L. monocytogenes*, the inhibitory strength and persistence of these effects can vary significantly across different MRP systems.[5,6] This variability suggests that the growth-inhibitory effects may depend on the molecular characteristics of the MRPs.

Lysine is a widely studied amino acid in Maillard reaction systems due to its nucleophilic ε-amino group, which readily forms Schiff bases and Amadori intermediates.[7] Glucose, a prevalent reducing sugar, has been extensively studied in Maillard reactions; however, research has primarily focused on D-glucose, with its stereoisomer L-glucose receiving limited attention, especially outside of metabolic and nutritional contexts.[8] Although D- and L-glucose share identical covalent structures, their opposite chirality leads to different spatial orientations of hydroxyl groups, resulting in distinct

patterns of hydrogen bonding with surrounding water molecules.[9–11] These stereochemically induced variations may subtly alter the solvation microenvironment and the equilibrium distribution between cyclic and open-chain forms of glucose. Given that the reactive open-chain aldehyde form exists only at equilibrium levels, such microenvironmental differences are more likely to influence the progression of the Maillard reaction through solvent-mediated effects rather than by altering the intrinsic carbonyl reactivity of the sugar.[12]

Furthermore, recent research has highlighted that the functional behavior of MRPs is influenced not only by their molecular composition but also by their higher-order structure, including aggregation state, chromophore formation, and surface charge properties that affect interactions with bacterial cell envelopes.[13,14] These observations emphasize that the structural organization of MRPs plays a crucial role in determining their bioactivity. Despite the well-documented effects of sugar type and amino acid identity on MRP structure and activity, the role of sugar stereochemistry has received comparatively little attention. Clarifying this aspect is essential not only for understanding the fundamental chemistry of the Maillard reaction but also for providing a basis for the future design and evaluation of MRPs with bacterial growth-inhibitory activity in food applications.

Therefore, in this study, we compared MRPs formed from D-glucose or L-glucose reacted with L-lysine under identical aqueous thermal conditions. Antioxidant activities were evaluated using 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), ferric reducing antioxidant power (FRAP), and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assays, and bacterial growth-inhibitory activity was assessed through growth kinetics of *L. monocytogenes*. By isolating sugar chirality as the sole structural variable, this work provides new insight into how precursor configuration affects MRP bioactivity, particularly regarding the persistence of growth inhibition upon dilution.

Materials and Methods

Chemicals and bacterial strains

D-glucose (≥97%; Bidepharm, Shanghai, China), L-glucose (≥99%; Adamas, Shanghai, China), and L-lysine (≥99%; Adamas, Shanghai, China) were used in this study. Sodium dihydrogen phosphate (Macklin, Shanghai, China) and disodium hydrogen phosphate (Macklin, Shanghai, China) used for phosphate buffer preparation were of analytical grade. *L. monocytogenes* ATCC 19111 and

Escherichia coli (*E. coli*) ATCC 25922 were obtained from the American Type Culture Collection (ATCC, Manassas, VA, USA). The strains were routinely cultured on Nutrient Agar (NA) plates (Hopebiol, Qingdao, Shandong, China) and subcultured at 37 °C prior to experimentation.

Preparation of MRPs

Reaction mixtures were prepared by dissolving L-lysine and either D-glucose or L-glucose in laboratory-prepared phosphate buffer (PB, 0.067 M, pH 7.0) to final concentrations of 40 mM each. The solutions were aliquoted into sealed heat-resistant glass vials and heated at 121 °C for 1 h in an autoclave. After heating, samples were rapidly cooled in an ice water bath to terminate the reaction and stored at −80 °C in the dark until further analyses. The resulting preparations are referred to as MRP-D-Glu (D-glucose + L-lysine) and MRP-L-Glu (L-glucose + L-lysine). Non-heated glucose-lysine mixtures were prepared in parallel using the same precursor concentrations but without thermal treatment and were used as precursor-mixture controls.

Browning index and absorbance at selected wavelengths

The browning intensity of MRP-D-Glu and MRP-L-Glu was evaluated by measuring absorbance at 420 nm using undiluted samples with a TU-1810 ultraviolet-visible spectrophotometer (Persee, Beijing, China). Absorbance at 280 and 294 nm was also measured using the same instrument after 30-fold dilution with H_2O to provide preliminary information on ultraviolet (UV)-absorbing reaction products. The corresponding non-heated glucose-lysine mixtures were measured under the same conditions to account for the background absorbance of the precursor and buffer matrix.

Antioxidant activity assays

The antioxidant capacities of the MRP samples were assessed using ABTS radical-scavenging (Solarbio, Beijing, China; Cat. No. BC4770), FRAP (Grace Bio, Suzhou, Jiangsu, China; Cat. No. G0152F), and DPPH radical-scavenging assays (Macklin, Shanghai, China; Cat. No. T930413). All assays were performed according to the procedures provided with the respective commercial kits. Briefly, the ABTS assay was incubated for 6 min at 25 ± 2 °C and measured at 405 nm; results were calculated using a vitamin C calibration curve and expressed as Vitamin C Equivalents (VCE). The

FRAP assay was incubated for 10 min at 25 ± 2 °C and measured at 590 nm; results were calculated using a Fe^{2+} calibration curve and expressed as Fe^{2+} equivalents. The DPPH assay was incubated for 20 min at 25 ± 2 °C in the dark and measured at 515 nm; results were expressed as percentage radical-scavenging activity relative to the assay control. Absorbance measurements were recorded using either a Multiskan FC microplate reader (Thermo Scientific, Waltham, MA, USA) or a TU-1810 UV-visible spectrophotometer (Persee, Beijing, China). The corresponding calibration curves are provided in Supplementary Materials, Figure S1. DPPH radical-scavenging activity was calculated as the percentage decrease in absorbance relative to the assay control.

Growth-inhibitory activity assays

Growth-inhibitory effects were evaluated using broth microdilution-based growth-kinetic assays. Fresh cultures of *L. monocytogenes* were suspended in sterile saline, adjusted to 0.5 McFarland turbidity, and further diluted in tryptic soy broth (TSB, Hopebio, Qingdao, Shandong, China) to yield an inoculum of approximately 5×10^5 colony-forming units (CFU)/mL.

For the growth-kinetic assay, 100 µL of inoculated TSB was mixed with 100 µL of MRP preparation or control solution in each well of a 96-well plate, giving a final volume of 200 µL. The original, 0.5-fold diluted, and 0.25-fold diluted MRP preparations therefore corresponded to final reaction-mixture proportions of 50%, 25%, and 12.5% (v/v), respectively. PB containing 0.1% peptone but no MRPs served as the vehicle control, whereas non-heated glucose-lysine mixtures served as precursor-mixture controls. Plates were incubated at 37 °C, and optical density at 600 nm (OD_{600}) values were recorded at 1, 2, 4, 8, 12, and 16 h using a Multiskan FC (Thermo Scientific, Waltham, MA, USA).

An apparent Minimum Inhibitory Concentration (apparent MIC) was estimated based on 24 h visual inspection. Because the tested preparations were unpurified reaction mixtures and were expressed as final reaction-mixture proportions in % (v/v), these values represent apparent MIC estimates under the present assay conditions. To assess whether the growth inhibition reflected bactericidal activity, colony recovery was performed from MRP-treated wells after incubation. Aliquots from the wells were spread onto nutrient agar plates and incubated at 37 °C. Abundant colony recovery in wells below the inhibitory level was recorded as viable growth recovery, whereas quantitative CFU

counts were reported for the highest tested MRP level. The absence of colony recovery was considered evidence for a Minimum Bactericidal Concentration (MBC) endpoint, whereas recovery of viable colonies indicated that the MBC was not reached within the tested range.

To examine whether the growth-inhibitory effect extended to a representative Gram-negative bacterium, *E. coli* ATCC 25922 was tested under the same growth-kinetic assay conditions as described above. *E. coli* ATCC 25922 was cultured in Mueller-Hinton Broth (MHB; Hopebio, Qingdao, Shandong, China) at 37 °C and tested using the same 96-well growth-kinetic format.

Statistics

All assays were conducted in triplicate using independently prepared MRP batches. Data are presented as mean ± Standard Deviation (SD). Antioxidant assay results were analyzed using one-way Analysis Of Variance (ANOVA) followed by Tukey's post hoc test. Growth kinetics data were assessed using two-way repeated-measures ANOVA with treatment and time as fixed factors, followed by Tukey's post hoc testing when required. Adjusted p values are reported for multiple comparisons. Exact p values, ANOVA statistics, confidence intervals, and effect-size estimates for the main comparisons are provided in Supplementary Materials, Tables S1 and S2. Data analysis and figure preparation were performed using GraphPad Prism 10.1.2 (GraphPad Software, San Diego, CA, USA), with $p < 0.05$ considered statistically significant.

Results

Preliminary chemical characterization of glucose-lysine MRPs

Selected-wavelength absorbance measurements were performed to provide preliminary chemical characterization of the heated glucose-lysine reaction mixtures. Browning intensity was evaluated as the absorbance at 420 nm (A420), which was used as a conventional browning index. The A420 values of MRP-D-Glu and MRP-L-Glu were 0.806 ± 0.020 and 0.859 ± 0.027 ($p < 0.05$), respectively (Table 1). In addition, compared with the corresponding non-heated precursor mixtures, both MRP-D-Glu and MRP-L-Glu showed markedly increased absorbance at 280 and 294 nm after heating, indicating the formation of UV-absorbing MRPs (Table 1).

Antioxidant activities of glucose-lysine MRPs

The antioxidant activities of MRP-D-Glu and MRP-L-Glu were assessed using ABTS, FRAP, and DPPH assays (Figure 1). Both MRPs exhibited measurable antioxidant capacities, confirming the formation of redox-active MRPs under the tested heating conditions.

In the ABTS assay, MRP-L-Glu showed a slightly higher radical-scavenging capacity (65.79 μM VCE/mL) than MRP-D-Glu (60.35 μM VCE/mL), although the difference was not statistically significant ($p > 0.05$). A similar trend was observed in the DPPH assay, where MRP-L-Glu displayed a modestly higher radical-scavenging activity (18.6%) compared to MRP-D-Glu (16.6%) ($p > 0.05$). In contrast, a significant difference was detected in the FRAP assay. MRP-L-Glu exhibited a higher ferric reducing power (207.0 μM Fe^{2+} equivalents/mL) than MRP-D-Glu (158.9 μM Fe^{2+} equivalents/mL) ($p < 0.05$). This indicates that sugar chirality influenced the reducing capacity of the resulting MRPs, whereas no statistically significant differences were detected in the ABTS or DPPH radical-scavenging assays.

Growth inhibition of L. monocytogenes

The effects of MRP-D-Glu and MRP-L-Glu on the growth of *L. monocytogenes* were evaluated by monitoring OD_{600} over 16 h in TSB medium. As shown in Figures 2 and 3, both MRP samples markedly suppressed bacterial growth at a final 50% (v/v) reaction-mixture proportion throughout the incubation period. Interestingly, at a final 25% (v/v) reaction-mixture proportion, a clear divergence emerged between the two MRPs. MRP-L-Glu continued to inhibit bacterial growth across the full incubation period, whereas the inhibitory effect of MRP-D-Glu progressively weakened after the early exponential phase. By 12-16 h, the OD_{600} values in the MRP-D-Glu group approached those of the 0.1% peptone control, whereas the OD_{600} values in the MRP-L-Glu group remained lower ($p < 0.05$). These results indicate that sugar chirality influences the persistence of growth inhibition, even though the initial inhibitory capacity at 50% (v/v) reaction-mixture proportion is comparable.

Apparent MIC estimation and colony recovery analysis

The apparent MIC was estimated based on 24 h visual inspection. As shown in Table 2, MRP-D-Glu inhibited visible growth only at a final 50% (v/v) reaction-mixture proportion. No

consistent inhibition was observed for MRP-D-Glu at a final 25% (v/v) reaction-mixture proportion. In contrast, MRP-L-Glu inhibited visible growth at both final 50% and 25% (v/v) reaction-mixture proportions, while the inhibitory effect was largely lost at the final 12.5% (v/v) reaction-mixture proportion. Therefore, the apparent MIC estimate corresponded to a final 50% (v/v) reaction-mixture proportion for MRP-D-Glu and a final 25% (v/v) reaction-mixture proportion for MRP-L-Glu.

Colony recovery was performed from MRP-treated wells after incubation. Abundant colony recovery was observed in wells below the inhibitory level and was recorded as viable growth recovery. Quantitative CFU counts were reported for the highest tested MRP level, corresponding to a final 50% (v/v) reaction-mixture proportion (Table 2). Viable colonies were still recovered at this level, with recovered counts of 150 ± 74 CFU/well for MRP-D-Glu and 94 ± 26 CFU/well for MRP-L-Glu. Therefore, the MBC was not reached within the tested range. These results indicate that the observed activity was mainly growth-inhibitory or bacteriostatic-like rather than bactericidal.

Furthermore, to evaluate whether the observed growth-inhibitory effect could be extended beyond *L. monocytogenes*, *E. coli* ATCC 25922 was tested under the same growth-kinetic assay conditions. Unlike the results observed for *L. monocytogenes*, neither MRP-D-Glu nor MRP-L-Glu showed detectable inhibition against *E. coli* growth at the 16-h endpoint (Supplementary Materials, Table S3). These results indicate that the growth-inhibitory effect of the tested glucose-lysine MRPs was not broad-spectrum under the present conditions and may be dependent on the bacterial species tested.

Discussion

This study demonstrates that MRPs generated from D-glucose and L-glucose with L-lysine exhibit measurable antioxidant responses and a growth-inhibitory effect against *L. monocytogenes*. Although both preparations showed measurable ABTS, DPPH, and FRAP responses, a difference emerged in the reducing power, with the L-glucose-derived MRPs exhibiting higher FRAP values than the D-glucose-derived MRPs. In growth-inhibition assays against *L. monocytogenes*, both MRPs suppressed growth at a final 50% (v/v) reaction-mixture proportion; however, at a final 25%

(v/v) reaction-mixture proportion, only MRP-L-Glu continued to inhibit bacterial proliferation during later incubation. Taken together, the results indicate that sugar stereochemistry contributes to quantitative differences in MRP function, particularly in the persistence of growth inhibition under dilution.

In terms of antioxidant performance, the difference between the two MRPs was most apparent in the FRAP assay, whereas the ABTS and DPPH radical-scavenging activities were broadly comparable. Because the FRAP assay primarily reflects electron-donating or reducing capacity, while ABTS and DPPH involve a mixture of electron-transfer and hydrogen atom-transfer pathways, the higher FRAP value observed for MRP-L-Glu suggests that sugar chirality influenced the distribution of reducing components rather than producing a global shift in antioxidant behavior.[15] The absence of significant differences in the ABTS and DPPH assays further suggests that the stereochemical effect was selective for reducing capacity and did not substantially alter the radical-scavenging activity measured under the present assay conditions. The A420 browning index and absorbance at 280 and 294 nm provide preliminary support for the formation of brown-colored and UV-absorbing reaction products after heating. However, these absorbance measurements do not identify individual MRP components, such as molecular weight distribution or functional groups. Therefore, the observed functional differences cannot be attributed to specific chemical species based on the present data. This interpretation aligns with previous reports showing that antioxidant capacity in Maillard systems arises from the combined contributions of low-molecular-weight Amadori intermediates, reductones, and higher-molecular-weight melanoidin chromophores, rather than a single dominant antioxidant species.[12,16,17] At present, the precise structural features responsible for this difference remain to be determined, and future work involving molecular weight profiling and chromophore characterization would be valuable to clarify the underlying basis.

A more pronounced difference was observed in the growth-inhibition assays. Both MRP preparations inhibited the growth of *L. monocytogenes* at a final 50% (v/v) reaction-mixture proportion, in agreement with earlier findings that MRPs can suppress Gram-positive bacteria.[18,19] However, only the L-glucose-derived MRPs maintained growth suppression at a final 25% (v/v) reaction-mixture proportion, whereas the inhibitory effect of the D-glucose-derived MRPs diminished during later incubation. This outcome indicates that the difference between the two

MRPs lies not in whether a growth-inhibitory effect is present, but in how long the inhibitory effect is sustained under dilution. Importantly, OD_{600} growth curves mainly reflect turbidity-based growth changes and do not by themselves distinguish bacteriostatic-like from bactericidal effects. The endpoint colony recovery results showed that viable colonies were recovered even at the highest tested MRP level, indicating that no MBC endpoint was reached. Therefore, the observed effect should be interpreted as growth-inhibitory or bacteriostatic-like rather than bactericidal. An established antimicrobial agent, such as ampicillin or nisin, was not included as a positive control in the present study. Therefore, the present data permit only relative comparisons between the two MRP preparations under the tested conditions and do not allow their antimicrobial potency to be compared with that of established antimicrobial agents.

The growth-inhibitory effects of MRPs have been shown to act by modifying bacterial growth kinetics, such as prolonging the lag phase or reducing the exponential growth rate, depending on precursor composition and microbial target.[18,20] Previous studies have proposed that MRPs may affect bacterial growth kinetics through interactions with bacterial envelopes or redox-related stress. However, these mechanisms were not directly examined in the present study and should be regarded as possible mechanisms requiring future investigation.[5] Within this framework, the more sustained suppression observed for the L-glucose-derived MRPs may reflect a greater relative abundance of growth-modulating components capable of exerting inhibitory effects at lower effective concentrations, although structural confirmation is needed to substantiate this interpretation.

This explanation aligns with evidence that the functional properties of Maillard products are determined not by a single antimicrobial constituent but by the relative distribution of reducing and chromophoric melanoidin structures formed during polymerization.[16] Importantly, because antimicrobial agents in real food matrices are frequently subject to dilution and dispersal, the duration of growth-inhibitory activity can be more relevant to practical application than the initial magnitude of inhibition.[5,21] The present results therefore extend previous work by suggesting that precursor sugar configuration may contribute to differences in the durability of growth-inhibitory effects when concentration decreases.

Importantly, we did not investigate the structural composition or aggregation state of the MRPs in this study. Therefore, we cannot attribute the observed differences to specific molecular species or

interaction mechanisms. However, the consistent divergence in inhibitory persistence between MRP-D-Glu and MRP-L-Glu supports the view that sugar chirality can influence functional behavior in microbial contexts, even when antioxidant properties remain broadly comparable. Further analytical characterization using High-Performance Liquid Chromatography (HPLC), Liquid Chromatography–Mass Spectrometry (LC–MS), and Fourier-Transform Infrared Spectroscopy (FTIR), together with molecular-weight profiling of melanoidins and characterization of chromophore development and nano-aggregate organization, would be valuable for clarifying how stereochemistry contributes to the observed effects. Although non-heated glucose–lysine mixtures were included as precursor-mixture controls, separate glucose-only and lysine-only controls were not systematically evaluated in the present study. Therefore, the present data support an association between growth inhibition and heated Maillard reaction mixtures, but do not fully exclude all possible effects of individual unreacted precursors. Further studies including individual precursor controls and additional formulation controls would strengthen this conclusion.

The absence of detectable growth inhibition against *E. coli* suggests that the effect observed for *L. monocytogenes* may be species-dependent. This may reflect differences in bacterial susceptibility, including cell envelope differences between Gram-positive and Gram-negative bacteria. Because only one representative Gram-negative strain was tested, additional strains would help clarify the inhibitory spectrum of these MRPs.

Conclusions

In summary, this study demonstrates that D-glucose and L-glucose, when reacted with L-lysine under identical thermal aqueous conditions, generate MRPs with comparable ABTS and DPPH radical-scavenging activities but different ferric reducing power and persistence of bacterial growth inhibition. These results indicate that sugar stereochemistry can subtly influence the functional outcomes of Maillard reactions, particularly in the persistence of bacterial growth inhibition. However, the molecular basis of these stereochemical effects remains unresolved and requires further molecular-level characterization.

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Table 1. Selected-wavelength absorbance measurements of glucose-lysine MRPs

Measurement	**D-Glu/Lys non-heated**	**L-Glu/Lys non-heated**	**MRP-D-Glu**	**MRP-L-Glu**	p value
A420	-0.010±0.001	0.014±0.011	0.806±0.020	0.859±0.027	0.0259
A280	0.019±0.000	0.019±0.000	0.682±0.079	0.855±0.100	0.0348
A294	0.018±0.000	0.017±0.000	0.713±0.081	0.878±0.115	0.0805

Data are presented as mean ± SD (n = 3). A420 was measured using undiluted samples and used as the browning index. A280 and A294 were measured after 30-fold dilution with H_2O. The p values refer to comparisons between MRP-D-Glu and MRP-L-Glu. Small negative values resulted from blank correction and were considered as no detectable browning. Abbreviations: Maillard reaction product prepared from D-glucose and L-lysine (MRP-D-Glu); Maillard reaction product prepared from L-glucose and L-lysine (MRP-L-Glu); non-heated D-glucose/L-lysine mixture (D-Glu/Lys non-heated); non-heated L-glucose/L-lysine mixture (L-Glu/Lys non-heated); absorbance at 420, 280, and 294 nm (A420, A280, and A294, respectively); standard deviation (SD).

Table 2. Apparent MIC estimation and colony recovery analysis of glucose-lysine MRPs against *L. monocytogenes*

Treatment	Final reaction-mixture proportion at apparent MIC	CFU recovery	MBC
MRP-D-Glu	50% (v/v)	150 ± 74 CFU/well	Not reached
MRP-L-Glu	25% (v/v)	94 ± 26 CFU/well	Not reached

Data are presented as mean ± SD (n = 3). MRP-D-Glu and MRP-L-Glu denote heated MRPs prepared from D-glucose or L-glucose with L-lysine, respectively. Quantitative CFU recovery was reported for a final 50% (v/v) reaction-mixture proportion. Colony recovery was also observed in wells below the inhibitory level but with abundant growth. “Not reached” indicates that viable colonies were recovered even at the highest tested MRP level; therefore, a bactericidal endpoint was not achieved within the tested range of reaction-mixture proportions. Abbreviations: apparent minimum inhibitory concentration (apparent MIC); colony-forming units (CFU); minimum bactericidal concentration (MBC); Maillard reaction product prepared from D-glucose and L-lysine (MRP-D-Glu); Maillard reaction product prepared from L-glucose and L-lysine (MRP-L-Glu); standard deviation (SD).

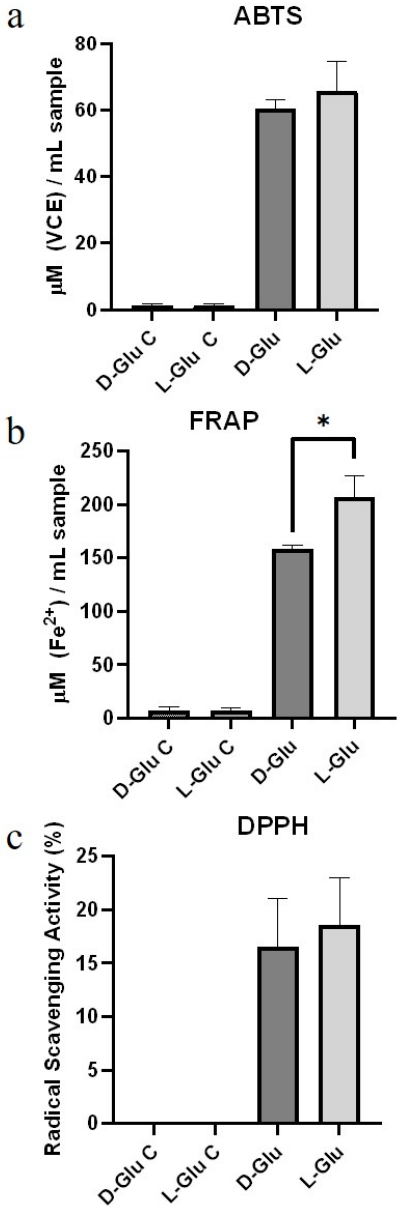

Figure 1. Antioxidant activities of MRP-D-Glu and MRP-L-Glu.

Antioxidant activities were measured by (a) ABTS, (b) FRAP, and (c) DPPH assays. For the ABTS assay, antioxidant capacity was expressed as vitamin C equivalent concentration (μM/mL VCE). FRAP values were calculated as Fe^{2+} equivalents (μM/mL Fe^{2+}), and DPPH scavenging activity was presented as the percentage decrease in absorbance relative to the assay control. Data are mean ± SD (n = 3); *, $p < 0.05$. Abbreviations: Maillard reaction product prepared from D-glucose and L-lysine (MRP-D-Glu); Maillard reaction product prepared from L-glucose and L-lysine (MRP-L-Glu); non-heated D-glucose/L-lysine control (D-Glu C); non-heated L-glucose/L-lysine control (L-Glu C); vitamin C equivalents (VCE); standard deviation (SD).

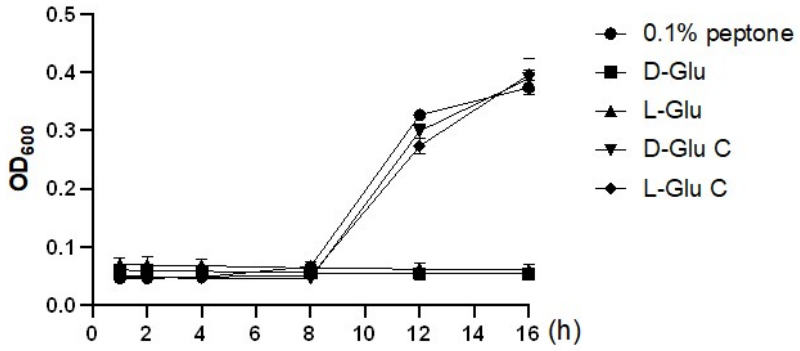

Figure 2. Growth inhibition of *L. monocytogenes* at a final 50% (v/v) reaction-mixture proportion. Bacterial growth was monitored at OD_{600} over 16 h in TSB at 37 °C. MRP-D-Glu and MRP-L-Glu denote heated MRPs prepared from D-glucose or L-glucose with L-lysine, respectively. D-Glu C and L-Glu C denote the corresponding non-heated D-glucose/L-lysine and L-glucose/L-lysine precursor-mixture controls, respectively. PB containing 0.1% peptone but no MRPs was used as the vehicle control. Curves represent mean ± SD (n = 3). Abbreviations: optical density at 600 nm (OD_{600}); tryptic soy broth (TSB); phosphate buffer (PB); MRP prepared from D-glucose and L-lysine (MRP-D-Glu); MRP prepared from L-glucose and L-lysine (MRP-L-Glu); non-heated D-glucose/L-lysine control (D-Glu C); non-heated L-glucose/L-lysine control (L-Glu C); standard deviation (SD).

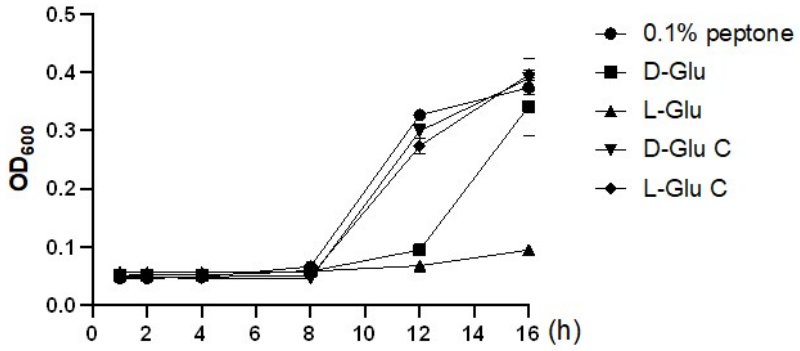

Figure 3. Growth inhibition of *L. monocytogenes* at a final 25% (v/v) reaction-mixture proportion. Bacterial growth was monitored at OD_{600} over 16 h in TSB at 37 °C. MRP-D-Glu and MRP-L-Glu denote heated MRPs prepared from D-glucose or L-glucose with L-lysine, respectively. D-Glu C and L-Glu C denote the corresponding non-heated D-glucose/L-lysine and L-glucose/L-lysine precursor-mixture controls, respectively. PB containing 0.1% peptone but no MRPs was used as the vehicle control. Curves represent mean ± SD (n = 3). Abbreviations: optical density at 600 nm (OD_{600}); tryptic soy broth (TSB); phosphate buffer (PB); MRP prepared from D-glucose and L-lysine (MRP-D-Glu); MRP prepared from L-glucose and L-lysine (MRP-L-Glu); non-heated D-glucose/L-lysine control (D-Glu C); non-heated L-glucose/L-lysine control (L-Glu C); standard deviation (SD).

Contributions: Mingze Gu, Hui Ge, investigation, data curation, writing–original draft; Xianghuan Wu, methodology, supervision, writing–review and editing; Jiao Li, writing–review & editing, funding acquisition; Zhongshuang Hu, conceptualization, supervision, project administration, writing–review & editing, funding acquisition. All authors reviewed and agreed upon their individual roles in the final manuscript.

Conflict of interest: the authors declare that they have no competing interests.

Ethics approval and consent for publication: not applicable.

Availability of data and material: the datasets used and/or analyzed during the current study are available upon reasonable request from the corresponding author.

Funding: this work was supported by Shanghai Zhongqiao Vocational and Technical University Research Fund (Grant Nos. ZQZR202427 and 2026ZQZR68). The funding institution had no role in the study design, data collection, analysis, manuscript preparation, or decision to publish.

Use of artificial intelligence tools: during the preparation of this work, artificial intelligence tools (ChatGPT 5.2, OpenAI) were used to improve the readability and language of the manuscript, and subsequently, the authors revised and edited the content produced by the artificial intelligence tools as necessary, taking full responsibility for the ultimate content of the present manuscript.

Acknowledgements: the authors gratefully acknowledge Zhiyi Jiang for valuable support in laboratory preparation and technical assistance during the experimental work.

Online supplementary materials

Table S1. Statistical summary of antioxidant activity and selected-wavelength absorbance measurements.

Table S2. Statistical summary of two-way repeated-measures ANOVA and selected post hoc comparisons for growth-kinetic assays against *L. monocytogenes* ATCC 19111.

Table S3. Growth response of *E. coli* ATCC 25922 exposed to glucose-lysine MRPs and control treatments.

Figure S1. Calibration curves and calculation method used for antioxidant activity assays.