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Liubao Tea Extract Attenuates High-Fat Diet and Streptozotocin-Induced Type 2 Diabetes in Mice by Remodeling Hepatic Metabolism and Gut Microbiota

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Abstract: Background: Type 2 diabetes (T2D) has become a serious global public health concern. Liubao tea has demonstrated beneficial effects on gut microbiota and glucose-lipid metabolism, holding promising therapeutic potential for T2D, however, its underlying mechanisms remain unclear. This study aimed to elucidate the potential mechanisms of Liubao tea extract (LBTE) against T2D. **Methods**: LC-MS technology was used to identify the chemical components of LBTE, and combined with network pharmacology and molecular docking to screen its potential active ingredients and targets for improving T2D. Therapeutic efficacy was assessed in high-fat diet/streptozotocin (HFD/STZ)-induced diabetic mice via serum biochemical analyses, histopathological examinations. Serum metabolomics, 16S rRNA sequencing, short-chain fatty acids (SCFAs) quantification, quantitative real-time PCR (qPCR) and antibiotic-treated pseudo-germ-free models were employed to elucidate the underlying mechanisms. **Results**: LBTE effectively reduced blood glucose levels and improved lipid metabolism, primarily by promoting hepatic glycogen synthesis and suppressing glycerophospholipid synthesis. LBTE also alleviated liver inflammation by modulating inflammatory cytokines expression. Additionally, LBTE reshaped the gut microbiota profiles by decreasing harmful bacteria and increasing SCFA-producing bacteria, resulting in elevated fecal SCFAs. SCFAs contributed to improving hepatic metabolism and inflammation, enhancing intestinal barrier function. These effects were abolished by antibiotic-induced microbiota depletion, confirming the microbiota-dependent mechanism of LBTE. Quercetin, luteolin, genistein and kaempferol were considered as potential active ingredients contributing to the antidiabetic effects of LBTE. **Conclusions**: These findings offer novel perspectives on the viability of LBTE as a complementary strategy for T2D prevention and management.

Keywords: Type 2 diabetes; Liubao tea extract; Hepatic metabolism; Gut microbiota; Short-chain fatty acids

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1. Introduction

Diabetes has emerged as a serious global public health challenge [1], with projections estimating that the global diabetic population will reach 783.2 million by 2045, of which approximately 90% being type 2 diabetes (T2D) cases [2]. T2D is a severe and complex metabolic disorder characterized by insulin resistance and impaired insulin secretion, leading to chronic hyperglycemia and disrupted glycometabolism. Current antidiabetic therapies are mainly drug-based, typically requiring lifelong administration and often associating with side effects such as gastrointestinal discomforts and potential organ toxicity [3]. Consequently, there is an urgent need to develop novel and effective strategies for the T2D treatment.

Tea (*Camellia sinensis* (L.) Kuntze) has a long history of medicinal use in China, first documented in the legend of Shen-Nong tasting herbs. The use of tea in China has evolved over thousands of years, with its therapeutic properties documented in various herbal books [4,5]. Among the various tea types, dark tea, a post-fermented tea characterized by its unique organoleptic attributes, has been traditionally used in drug formulations for the prevention and treatment of obesity and diabetes [6]. Notably, Liubao tea (LBT), a nationally recognized geographical indication product in Wuzhou, Guangxi, is a representative Chinese dark tea with a historical origin dating back 1500 years [7]. The earliest medical records of LBT can date back to the Southern and Northern Dynasties [8]. Modern pharmacological studies have revealed that LBT is rich in polysaccharides, polyphenols and flavonoids, exhibiting hypolipidemic, hepatoprotective, and hypoglycemic bioactivities [9]. Our previous studies also found that LBT ameliorates non-alcoholic fatty liver disease (NAFLD) and hyperlipidemia via modulating lipid metabolism and gut microbiota [10,11]. Although some evidence suggests that LBT can alleviate T2D symptoms [12,13], its active ingredients and underlying mechanisms remain poorly understood.

The gut microbiota, a complex and dynamic ecosystem, plays a crucial role in host metabolic homeostasis. Gut microbiota-derived metabolites, such as short-chain fatty acids (SCFAs), influence glucose and lipid metabolism by interacting with G-protein-coupled receptors and activating hepatic signaling pathways [14]. Since the introduction of the microbiome into the biomedical field, the host metabolism mediated by gut microbiota has become an important area of research, playing an important role in the pathogenesis and treatment of metabolic diseases such as diabetes [15]. (-)-Epicatechin has been found to modulate the gut microbiota and liver insulin signaling pathways to alleviate T2D [16]. Similarly, *L. gasseri CKCC1913* may exert antidiabetic effects by increasing the abundance of beneficial bacteria that produce SCFAs, some of which reach the liver to aid in the regulation of glucose and lipid metabolism [17]. These findings underscore the critical role of the gut microbiota and its mediated metabolism in T2D treatment. However, whether LBT can effectively improve T2D by modulating the gut microbiota and hepatic metabolism has not yet been reported, and its underlying mechanisms remain unclear.

Given the complexity of metabolic disease pathogenesis, the integration of bioinformatics and multiomics has emerged as powerful tools to elucidate drug mechanisms and disease pathogenesis [10]. Bioinformatics serves as an important computational tool for analyzing gene expression data and identifying molecular targets and mechanisms involved in various diseases [18]. Multiomics analysis such as metabolomics and gut microbiomes, as a powerful method for discovering natural product targets, can provide insight into the pharmacological mechanisms of natural products from different perspectives [19]. Network pharmacology and molecular docking help identify the bioactive components of natural products, potential targets of action, and the mechanisms of their interactions [20]. When combining with metabolomics, key metabolites and metabolic pathways can be more precisely targeted [21]. Alterations in gut microbiota composition significantly affect metabolic profiles and metabolic pathways [22]. Thus, the integration of

bioinformatics with multiomics holds significant promise for deepening our understanding of the mechanisms by which LBT exerts its therapeutic effects in T2D.

The study aims to elucidate the mechanisms underlying the antidiabetic effect of Liubao tea extract (LBTE), with a particular focus on its modulation on the gut microbiota and its microbiota-mediated metabolism. The chemical composition of LBTE was preliminarily characterized by LC-MS technology. Based on these results, network pharmacology and molecular docking analyses were employed to predict the active components, therapeutic targets, and key pathways involved in the antidiabetic activity of LBTE. Selected active compounds were further validated using chemical standards. To assess the therapeutic efficacy of LBTE, a T2D mouse model was established by high-fat diet/streptozotocin (HFD/STZ) induction. Then, the effects of LBTE treatment were evaluated via serum biochemical analyses and histopathological examination of major tissues. Metabolomics was performed to uncover key metabolic changes in T2D mice after LBTE intervention. Meanwhile, 16S rRNA gene sequencing was used to profile the gut microbiota composition and identify key genus modulated by LBTE. To further explore the underlying mechanisms, quantitative real-time PCR (qPCR) was conducted to assess the expression of genes involved in metabolic and inflammatory pathways. Additionally, pseudo-germ-free mouse models were utilized to validate the microbiota-dependent effects of LBTE. Hence, this study is expected to provide novel insights into anti-diabetes mechanisms of LBTE and support its potential as a promising complementary strategy for the prevention and management of T2D.

2. Materials and Methods

2.1. Chemicals and reagents

MS-grade methanol, water, acetonitrile, and formic acid were purchased from Merck & Co., (Billerica, MA, USA). LBT was provided by China Tea Co., Ltd. (Wuzhou, Guangxi, China) (Batch number: S002/2022), conforming to GB/T 32719.4-2016 (Brick LPT Second class). Standards of quercetin (C15H10O7, HPLC > 99%), luteolin (C15H10O6, HPLC > 99%), genistein (C15H10O5, HPLC > 99%), caffeine (C8H10N4O2, HPLC > 99%), naringenin (C15H12O5, HPLC > 99%) and kaempferol (C15H10O6, HPLC > 99%) were sourced from Chengdu RefMedic Biotech Co., Ltd. (Chengdu, China). Streptozotocin (STZ), metformin hydrochloride, and citrate buffer were obtained from Macklin Co., Ltd. (Shanghai, China). All other chemicals were analytical reagent grade or higher purity.

2.2. Preparation and preliminary chemometric analysis of LBTE

LBTE was prepared following a modified version of a previously reported method [23], and detailed protocols were provided in the supplementary material. Based on the professional standards, major components including total polyphenols (GB/T 8313-2018), total flavonoids (SN/T 4592-2016), total free amino acids (GB/T 8314-2013), and total polysaccharides (NY/T 1676-2008) were quantified using established chemometric protocols, respectively. Total soluble sugars were determined using the anthrone-sulfuric acid method, with glucose as the standard.

2.3. Characterization of the chemical composition of LBTE

LBTE (1.5 mg) was dissolved in 1.5 mL of methanol and then filtered through a microporous membrane (0.22 μm) to prepare the test solution. The sample was analyzed and characterized using a Waters ACQUITY UPLC I-Class PLUS System (Waters, Milford, MA) (SN: L22BSP766G) coupled with a SELECT SERIES Cyclic IMS (Milford, MA, USA) (SN: GBC086). Detailed LC-MS analytical conditions were presented in Tables S1 and S2.

2.4. Network pharmacology analysis

2.4.1. Drug target prediction and disease target identification

Active ingredients in LBTE were screened using the SwissADME database. Potential targets of the active components of LBTE were predicted using the SwissTargetPrediction database. T2D-associated potential targets were gained after collecting and removing duplicate targets from the OMIM and GeneCards databases. The intersection targets of the active components and diseases were extracted and visualized as a Venny diagram. Protein-protein interaction (PPI) analysis was performed using the STRING database and visualized in Cytoscape 3.9.1. GO and KEGG pathway enrichment analyses of the intersecting targets were performed using the Metascape database, with top 10 GO items and top 20 KEGG items visualized using the Wei Sheng Xin cloud platform.

2.4.2. Molecular docking

The 2D structures of the core compounds were sourced from the PubChem database and energy-minimized using the Molecular Operating Environment (MOE). The crystal structures of key proteins were retrieved from the RCSB PDB database, including AKT1 (PDB ID, 1UNQ; resolution, 0.98 Å), TNF (PDB ID, 5UUI; resolution, 1.40 Å), and GSK3B (PDB ID, 1O6L; resolution, 1.60 Å). Detailed information on the molecular docking analysis was provided in the supplementary material.

2.5. Identification of potential active ingredients in LBTE

Standards of four ingredients (quercetin, luteolin, genistein and kaempferol) were analyzed using instrumental methods consistent with those used for composition analysis of LBTE. Each component was verified based on retention time and fragmentation information. Detailed LC-MS analytical conditions were presented in Tables S1 and S2.

2.6. Quantitative analysis of potential ingredients in LBTE

LBTE (1.5 mg) was dissolved in 1.5 mL of methanol and then filtered through a microporous membrane (0.22 μm) to prepare the test solution. The sample was analyzed using an Agilent 1260 Infinity LC system (SN: DEAEQ48900) and an Agilent 6545 Q-TOF mass spectrometer (SN: SG22202E101), equipped with ESI sources (Santa Clara, CA, USA). The analytical conditions of LC and MS equipment were presented in Tables S3 and S4. Standards of six ingredients were analyzed using instrumental methods consistent with those used for analysis of LBTE. Each compound was quantified based on retention time and exact m/z values using external calibration curves derived from chemical standards.

2.7. Experimental verification

2.7.1. Animal model and treatment

Six-week-old KM male mice (18-22 g) were purchased from SPF (Beijing) Biotechnology Co., Ltd. (license No.110324230101502642). Mice were randomly divided into groups according to the RAND function in Microsoft Excel. The individual mouse was considered the experimental unit within the studies. All experimental mice were housed with free access to food and water under the controlled condition of 25 ± 2 ℃ temperature, 50 ± 5% relative humidity, and a 12 h light/dark cycle.

An established protocol for inducing T2D mice was followed with minor modifications [24,25]. The experiment 1 design was depicted in Fig. S1. After one week of adaptive feeding, the thirty male mice were randomly assigned to five groups (n = 6 per group): normal control (NC) group, T2D model (MC) group, metformin (PC) group, LBTE low-dose (LBTE-L) group, and LBTE high-dose (LBTE-H) group. Except for the NC group (normal-chow diet), all mice from other groups were fed a high-fat diet (HFD) for four

weeks, followed by two intraperitoneal injections of STZ (50 mg/kg), and the NC group received equivalent volumes of citrate buffer. Three days after the final injection, mice with fasting blood glucose (FBG) ≥ 11.1 mmol/L were classified as T2D mice [26]. Subsequently, LBTE-L and LBTE-H groups received 200 and 400 mg/kg LBTE orally for three weeks, respectively; the PC group received metformin (200 mg/kg), while the NC and MC groups received equivalent amount of normal saline. The treatment of mice is performed by the same researcher every day.

To assess the impact of antibiotic treatment, we followed a literature protocol with minor adjustments [27]. The animal experiment 2 design was depicted in Fig. S2. Briefly, eighteen T2D mice were randomly assigned to three groups (n = 6 per group): MC group, MC + Antibiotic mixture (MA) group and LBTE + Antibiotic mixture (LBTEA) group. The mice in the MA and LBTEA groups were orally administered a mixture of antibiotics (ampicillin 130 mg/kg; metronidazole 150 mg/kg; neomycin 100 mg/kg; and vancomycin 130 mg/kg) daily, and mice in the MC group were orally equivalent amount of sterile water daily. The LBTEA group received LBTE (400 mg/kg), whereas the other group received equivalent amount of normal saline. FBG levels, body weight, food intake, and water intake were recorded weekly during the treatment period.

2.7.2. Sample collection

Upon completion of the experiment, mice were euthanized, and blood was collected. Serum was isolated by centrifugation at 5,000 rpm for 8 minutes at 4 °C and stored at -80 °C. Then, the tissues of experimental mice were collected and weighed.

2.7.3. Biochemical index determination

Serum levels of alanine aminotransferase (ALT), aspartate transaminase (AST), total bile acid (TBA), creatinine (Cr), uric acid (UA), total cholesterol (TC), triglycerides (TG), low-density lipoprotein cholesterol (LDL-C) and high-density lipoprotein cholesterol (HDL-C) were measured using test kits from Nanjing Jiancheng Bioengineering Institute (Nanjing, China), following the manufacturer's instructions for each biochemical indicator.

2.7.4. Histopathological analysis

Tissue samples from the liver, adipose tissue, heart, lung, kidney, and colon were fixed in 4% paraformaldehyde, dehydrated, washed, embedded in paraffin, sectioned (4 μm), and baked. Hematoxylin and eosin (H&E) staining was performed on all tissue samples, and liver samples were additionally subjected to Oil Red O staining. Pathological changes in the tissues were examined under an optical microscope.

2.8. Metabolomic analysis of serum samples

Serum sample preparation method followed our previous study [11], using tamoxifen and cholic acid-d4 as internal standards. To ensure the stability and reproducibility of data acquisition, quality control (QC) samples were prepared by mixing equal aliquots (5 μL) of each sample. Untargeted metabolomic analysis of serum samples was conducted using an Agilent 1260 Infinity LC system (SN: DEAEQ48900) and an Agilent 6545 Q-TOF mass spectrometer (SN: SG22202E101), equipped with ESI sources (Santa Clara, CA, USA). The LC and MS conditions used in the metabolomic study were detailed in Tables S5 and S6.

2.9. Gut microbiota analysis

Bacterial DNA extraction from fecal samples in mice, PCR amplification, and sequencing were performed according to the standard procedure of Novogene Co., Ltd., as

detailed in a published article [28]. Specific experimental methods and analyses were provided in the supplementary material.

2.10. Metorigin analysis

The Metorigin platform was employed for traceability analysis of differential metabolites and integrative analysis of the gut microbiome and serum metabolome [29]. This included utilizing Metorigin's deep analysis mode for origin-based metabolite pathway enrichment analysis (MPEA) and Bio-Sankey network analysis, both available on the platform's official website.

2.11. SCFA analysis

The derivatized SCFAs in the fecal samples were extracted and determined following the method described previously [30]. The preparation process of SCFAs and conditions for GC-MS analysis were detailed in supplementary material. SCFAs in samples were quantified using external calibration curves based on the peak areas of SCFAs in standards.

2.12. Determination of gene expression using qPCR

Total RNA was extracted from liver and colon tissues by TransZol Up reagent and reverse-transcribed into cDNA using SweScript All-in-One RT SuperMix. Then, PCR reactions were conducted using the MonAmp SYBR Green qPCR Mix, with GAPDH serving as an internal reference. The gene primers were listed in Table S7. The mRNA expression was calculated using the $2^{-\Delta\Delta CT}$.

2.13. Statistical analysis

The metabolomic data was processed according to the methodology in our previous study [11]. Data were expressed as the mean ± standard deviation (SD), and group comparisons were performed using a *t*-test, with significance defined as $P < 0.05$. Graphs were generated using GraphPad Prism 9.

3. Results

3.1. Chemical composition profiling of LBTE

To characterize the primary chemical constituents of LBTE, the levels of total polysaccharides, total polyphenols, total flavonoids, total free amino acids, and total soluble sugars were quantitatively assessed. Among these components, total flavonoids and total polyphenols exhibited notably high content (Fig. S3), indicating that these constituents may significantly contribute to the therapeutic potential of LBTE. The total ion chromatogram (TIC) of LBTE is presented in Fig. S4, providing the comprehensive chemical fingerprint of LBTE. A total of 34 compounds were preliminarily identified by comparison with the database, including alkaloids, catechins and flavonoids, with flavonoids representing the largest proportion of 30 compounds. The detailed information of these compounds was provided in Table S8.

3.2. Network pharmacology analysis based on chemical constituents in LBTE

A total of 140 potential targets associated with LBTE were identified from the SwissTargetPrediction database. Concurrently, 2051 targets related to T2D were obtained from the disease-related databases. After crossing these targets, 62 overlapping targets were found, suggesting their potential involvement in the antidiabetic effects of LBTE (Fig. 1A). Core compounds were selected through network topology analysis based on degree

centrality values and included quercetin, kaempferol, luteolin, genistein, etc. Subsequent analysis of the 62 intersection targets identified the top 10 hub genes based on degree values: AKT1, TNF, EGFR, SRC, ESR1, PTGS2, MMP9, GSK3B, KDR, and IGF1R (Fig. 1B). These hub genes were considered key therapeutic targets for LBTE in the treatment of T2D. To elucidate the biological relevance of these targets, GO and KEGG pathway enrichment analyses were conducted, and the top 10 GO terms and top 20 KEGG pathways are shown in Fig. 1D-E. Notably, the PI3K-Akt signaling pathway, insulin resistance, and MAPK signaling pathway emerged as key pathways implicated in T2D pathogenesis, with AKT1, TNF, and GSK3B identified as central regulatory nodes. Additionally, a core compound-target-pathway network was constructed to visualize the multi-target and multi-pathway interactions of the core compounds (Fig. 1C). The network revealed that each core compound potentially regulates multiple targets, collectively contributing to the modulation of metabolic and signaling pathways relevant to T2D.

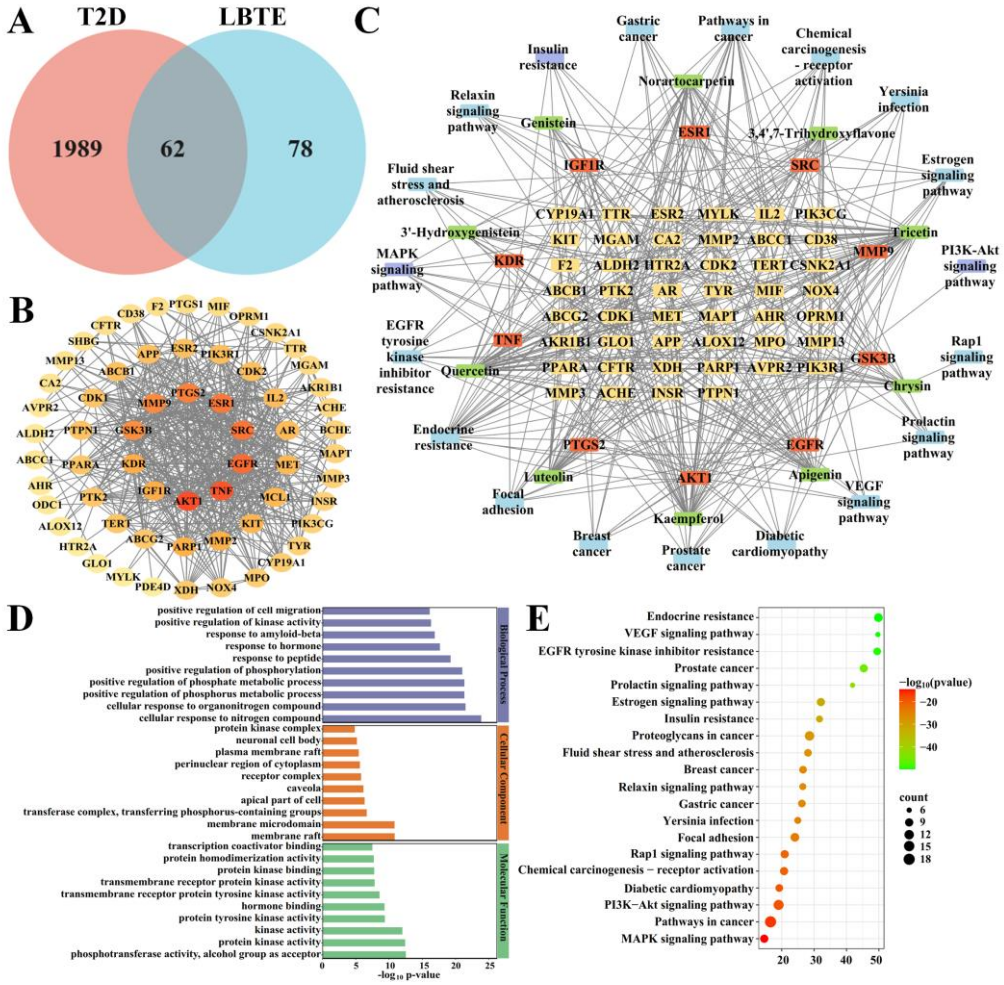


Figure 1. Network pharmacology analysis of Liubao tea extract (LBTE) intervening type 2 diabetes (T2D). (**A**) Venny diagram of the intersection targets of LBTE and T2D. (**B**) PPI (Protein-protein interaction) network. Color depth indicates target degree. (**C**) Core compounds-targets-pathways network. The light blue, green, purple, yellow, and red indicate KEGG pathways, top 10 compounds, key KEGG pathways, targets, and top 10 targets, respectively. (**D**) GO enrichment analysis. (**E**) KEGG pathway analysis.

3.3. Identification of potential active ingredients in LBTE by LC-MS technique

The four potential active ingredients including quercetin, luteolin, genistein and kaempferol in LBTE were successfully identified by matching their exact mass, mass error,

retention time and fragmentation patterns with those of chemical standards analyzed under identical conditions (Table S9, Fig. S5).

3.4. Qualification of potential ingredients in LBTE

Each component was validated by comparing retention time and mass spectral fragmentation data of chemical standards and their contents were quantified using an external calibration curve based on peak area (Fig. 2). The quantified content of the caffeine, genistein, naringin, quercetin, luteolin and kaempferol in LBTE were as follows: 30.1± 1.8, 1.04 ± 0.05, 0.47 ± 0.07, 1.2 ± 0.02, 0.62 ± 0.12 and 0.76 ± 0.01 mg/g, respectively. These results highlighted the abundant presence of multiple flavonoids and alkaloids, potentially contributing to the antidiabetic effects of LBTE.

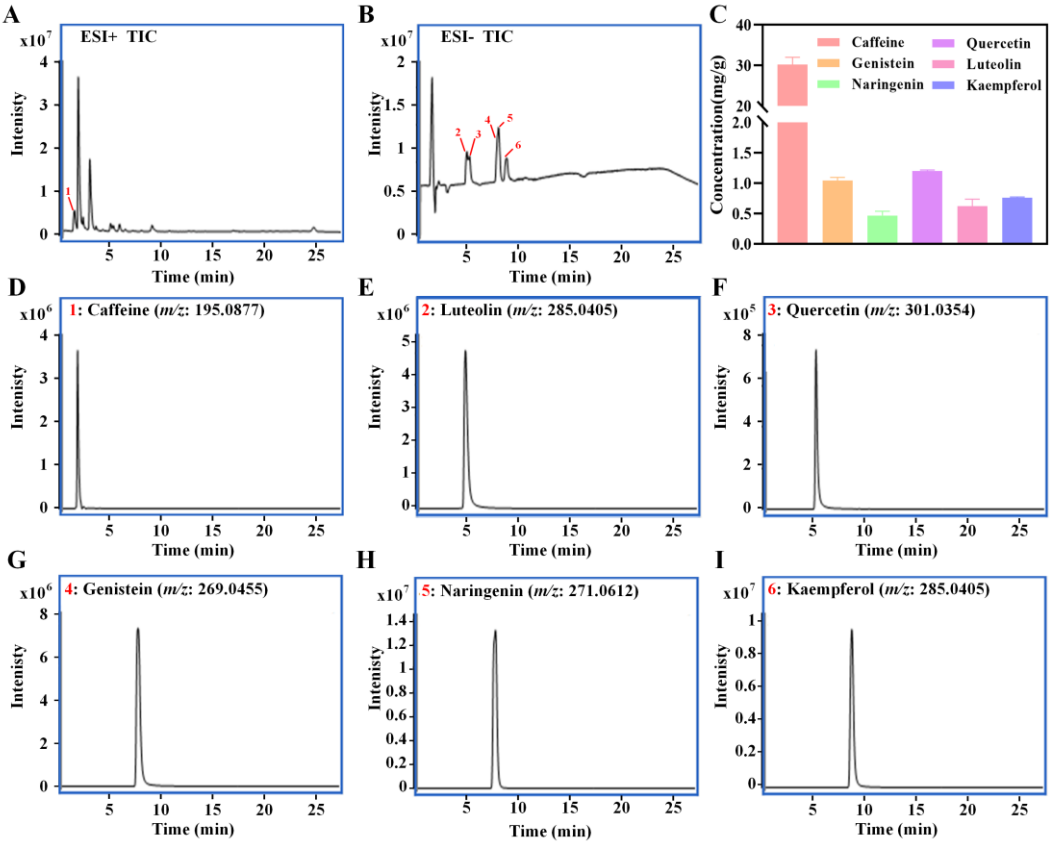


Figure 2. The qualification of potential ingredients in LBTE. (**A, B**) The total ion chromatogram. (TIC) of standards detected by LC-MS in the ESI+ and ESI- modes, respectively. (**C**) The content of potential ingredients in LBTE. (**D-I**) The extracted ion chromatogram of individual standards.

3.5. Molecular docking analysis

Based on the network pharmacology results, AKT1, TNF, and GSK3B were identified as key targets and subsequently selected for molecular docking analysis. As summarized in Table S10, the docking scores (S score) and detailed binding interactions were displayed between the core compounds (quercetin, luteolin, genistein and kaempferol) and the protein targets. The docking results demonstrated favorable binding conformations and strong affinities (Fig. S6). These findings support the hypothesis that LBTE exerts its antidiabetic effects through multi-targets, particularly involving AKT1, TNF, and GSK3B.

3.6. Amelioration of LBTE on T2D mice

As shown in Fig. 3A, the body weight of T2D mice was significantly lower than that of NC group between week 6 and 9. Treatment with LBTE and metformin further reduced body weight compared to the MC group, with a significant reduction observed in the high-dose LBTE group ($P < 0.05$). These results suggested that LBTE may partially exert its metabolic benefits in T2D mice through weight modulation. Despite no significant differences in food and water intake among the groups, FBG levels were notably reduced following LBTE administration, particularly in the high-dose group ($P < 0.05$) (Fig. 3B-D). Interestingly, FBG levels in the PC group were comparable to those in the LBTE-L group and did not show a significant reduction relative to the MC group (Fig. 3B). The comparison of two different administered dose methods revealed nearly identical FBG levels in both groups (Fig. S7A). Further evaluation of different dosing regimens revealed that triple dosing produced a more pronounced glucose-lowering effect than single dosing (Fig. S7B-C), suggesting that hypoglycemic efficacy depends on dosing frequency and drug exposure duration, consistent with the reported elimination half-life (~5 hours) of metformin [31], it could be hypothesized that the hypoglycemic efficacy of metformin and LBTE was strongly influenced by dosing frequency and duration of exposure. Serum lipid analyses showed that the levels of TC, TG, LDL-C, and HDL-C were significantly altered in the MC group compared to the NC group ($P < 0.05$) (Fig. 3T-W). LBTE treatment significantly reversed these changes ($P < 0.05$).

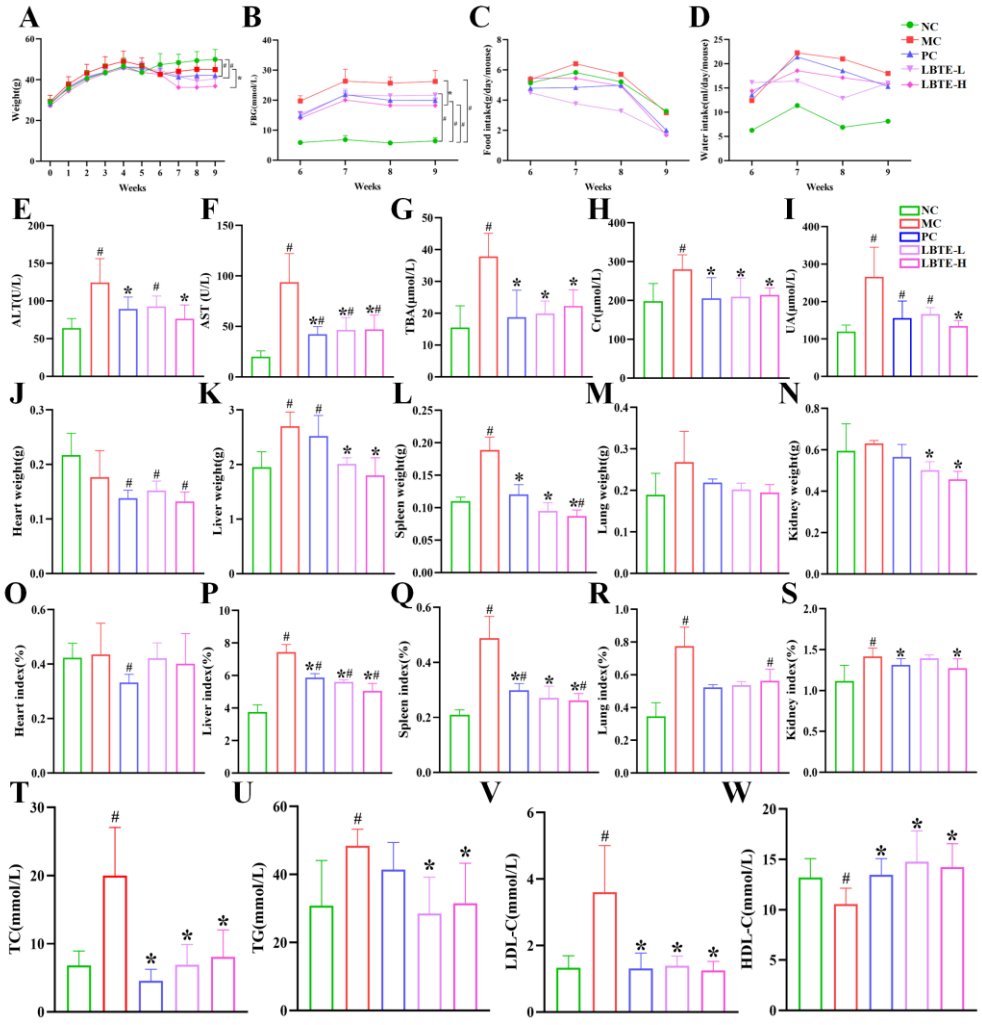


Figure 3. LBTE showed improvement effect on T2D mice. (**A**) Body weight. (**B**) Fasting blood glucose (FBG). (**C**) Food intake. (**D**) Water intake. (**E**) ALT, (**F**) AST, (**G**) TBA, (**H**) Cr, (**I**) UA, (**J**) Heart weight, (**K**) Liver weight, (**L**) Spleen weight, (**M**) Lung weight, (**N**) Kidney weight, (**O**) Heart index,

(**P**) Liver index, (**Q**) Spleen index, (**R**) Lung index, (**S**) Kidney index, (**T**) TC, (**U**) TG, (**V**) LDL-C, and (**W**) HDL-C. NC, normal-chow diet; MC, high-fat diet (HFD); PC, HFD + Metformin (200 mg/kg); LBTE-L, HFD + LBTE (200 mg/kg); LBTE-H, HFD + LBTE (400 mg/kg). Data are expressed as mean ± standard deviation (SD) (n = 5). $^{\#}$ $P < 0.05$ compared with the NC group; * $P < 0.05$ compared with the MC group.

Histopathological examination revealed that MC group exhibited obvious hepatic structure, lipid droplet accumulation, and inflammatory infiltration relative to NC group, whereas LBTE markedly ameliorated these pathological changes (Fig. 4A-B). Adipose tissue also revealed fat accumulation in the MC group, which was alleviated by LBTE, particularly at high doses (Fig. 4C). Consistently, liver weight and index were significantly elevated in the MC group but significantly reduced following LBTE treatment ($P < 0.05$) (Fig. 3K, P). The levels of ALT, AST, and TBA were significantly elevated in the MC group compared with NC group and normalized upon LBTE intervention ($P < 0.05$) (Fig. 3E-G), suggesting hepatoprotective effects of LBTE for T2D mice. Moreover, LBTE treatment significantly reversed the changes in kidney weight and index observed in the MC group ($P < 0.05$) (Fig. 3N, S). Serum levels of Cr and UA levels were also markedly elevated in the MC group compared to the NC group, indicating renal dysfunction, while LBTE intervention significantly lowered Cr and UA levels ($P < 0.05$) (Fig. 3H-I). Although no obvious pathological changes were observed in kidney tissues across all groups (Fig. 4F), the biochemical improvements suggested that LBTE conferred renal protective effects. Additionally, spleen weight and index were significantly elevated in MC group and dose-dependently normalized following LBTE treatment ($P < 0.05$, Fig. 3L, Q), suggesting a potential immunomodulatory effect. While no significant changes were observed in lung weight and index (Fig. 3M, R), histological analysis revealed that LBTE alleviated alveolar wall thickening and inflammatory infiltration present in T2D mice (Fig. 4E), suggesting a protective effect against pulmonary inflammation. Finally, no significant differences in heart weight or index were observed (Fig. 3J, O), and no pathological changes were noted in heart tissues across all groups (Fig. 4D), suggesting that neither T2D nor LBTE treatment had a significant impact on cardiac morphology during the study period. In the colon, the MC group showed disrupted colonic tissue structure and increased inflammatory infiltration, whereas LBTE treatment effectively restored colon integrity and alleviated the inflammatory state (Fig. 4G), highlighting a protective effect on intestinal barrier function.

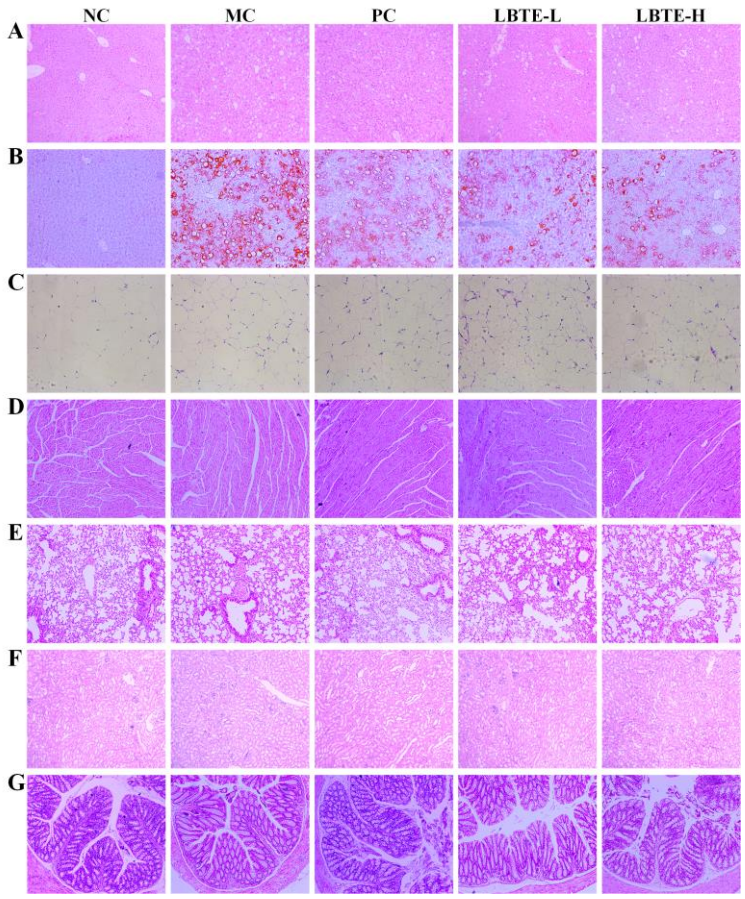


Figure 4. Effects of LBTE administration on the organ histopathologic changes of mice. (**A**) H&E staining of liver tissue (200 ×). (**B**) Oil Red O staining of liver tissue (100 ×). (**C**) H&E staining of adipose tissue (200 ×). (**D**) H&E staining of heart tissue (100 ×). (**E**) H&E staining of lung tissue (100 ×). (**F**) H&E staining of kidney tissue (200 ×). (**G**) H&E staining of colon tissue (100 ×).

3.7. Influence of LBTE treatment on the serum metabolic profiles of T2D mice

To evaluate the metabolic impact of LBTE on T2D mice, serum untargeted metabolomics was performed. As shown in Fig. S8, the TIC of QC samples exhibited substantial overlap, indicating excellent instrument performance and validating the reliability of the acquired data. Subsequently, an orthogonal partial least squares-discriminant analysis (OPLS-DA) revealed clear clustering and separation across all groups. As expected, samples from the MC group were distinctly separated from those of the NC group, reflecting pronounced metabolic disturbances induced by T2D. Notably, the metabolic profile of the LBTE-H group diverged significantly from the MC group and trended toward the NC group (Fig. 5A-B), suggesting a restorative effect of LBTE on T2D-associated metabolic dysfunction. Model validity and predictive accuracy were evaluated using R^2 and Q^2 values, and permutation tests (n = 200) further confirmed the robustness of the OPLS-DA model and excluded overfitting (Fig. 5C-D). Key differential metabolites were screened based on the OPLS-DA models using the following criteria: fold change (FC) > 1.5 or < 0.67, variable importance in projection (VIP) > 1, and $P < 0.05$. The differential metabolites were classified into several chemical categories, mainly including amines, prenol lipids, sterol lipids, fatty acids (FAs), glycerophospholipids (GPs), sphingolipids (SPs), glycerolipids, lipids, amino acids (AAs) and xanthines (Fig. 5E-G). Among these, GPs accounted for the largest fraction, exceeding 50% of all differential metabolites, followed by FAs and SPs.

To disclose the potential mechanisms underlying T2D pathogenesis and the therapeutic effects of LBTE, metabolic pathway enrichment analysis was conducted based on serum differential metabolites. In T2D mice, obvious dysregulation was observed in both sphingolipid (SP) and glycerophospholipid (GP) metabolism, with statistical thresholds of $P < 0.05$ or impact factor (IF) > 0.1 (Fig. 5H). Remarkably, these metabolic disturbances were attenuated following LBTE intervention (Fig. 5I-J), suggesting that modulation of these pathways could be involved in the therapeutic effects of LBTE. Further analysis identified 16 shared serum differential metabolites across four groups (Fig. S9). To assess their diagnostic and therapeutic relevance, ROC analysis was employed, with stringent screening criteria of AUC > 0.95 and FC > 5 to minimize false positives. Among these, 13 metabolites demonstrated excellent discriminatory power between the NC and MC groups, with AUC values reaching up to 1.00, thereby underscoring their potential as robust diagnostic biomarkers for T2D (Fig. S10A-M). ROC analysis of the differential metabolites from comparing the MC group with the LBTE-L and LBTE-H groups identified four and five metabolites, respectively, with AUC values exceeding 0.95 (Fig. S10N-V). Notably, metabolites such as PS 38:0, PC 40:7, PE 38:2, PE 41:3, and 1-methylhistamine, mainly derived from GPs and amines, were considered as the key indicators of LBTE's therapeutic benefits in T2D. Consequently, LBTE exerted its anti-T2D effects primarily through the modulation of GP metabolism.

3.8. Regulation of LBTE on expression of key genes involved in inflammatory response, glucose and lipid metabolism pathways

As depicted in Fig. 5K-R, the mRNA expression levels of *IL-10* and *AKT1* were significantly decreased in the MC group compared to the NC group, whereas the expression levels of *IL-6*, *TNF-α*, *GSK3B*, *AGPAT*, *GPAT*, and *PAP* were significantly increased ($P < 0.05$). Notably, the administration of LBTE significantly reversed these alterations, restoring the gene expression profiles close to those of the NC group ($P < 0.05$). The results indicated that LBTE alleviated T2D by suppressing inflammation and modulating key pathways involved in glucose utilization and lipid synthesis, thereby improving metabolic imbalances.

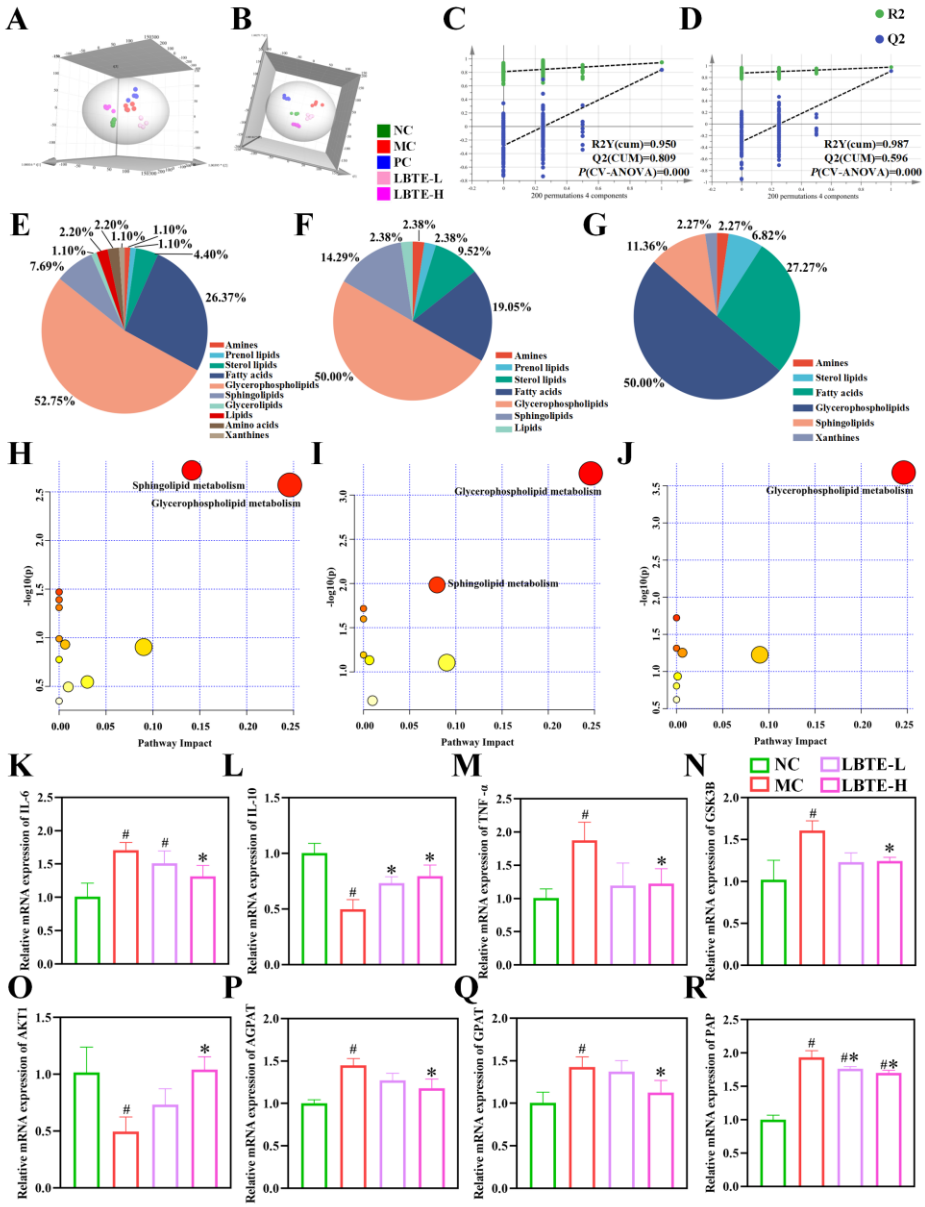


Figure 5. Effects of the serum metabolic profiling and the gene expression level of *IL-6*, *IL-10*, *TNF-α*, *GSK3B*, *AKT1*, *AGPAT*, *GPAT*, and *PAP* in mice treated with LBTE. (**A, B**) OPLS-DA of serum metabolic profiling among the five groups in both ESI modes, respectively. (**C, D**) OPLS-DA model permutation test for both ESI modes, respectively. (**E-G**) The composition ratio of serum differential metabolites in the NC vs. MC groups, LBTE-L vs. MC groups, and LBTE-H vs. MC groups, respectively. (**H-J**) The analysis of metabolic pathways of serum differential metabolites in the NC vs. MC groups, LBTE-L vs. MC groups, and LBTE-H vs. MC groups, respectively. The relative mRNA expression level of *IL-6* (**K**), *IL-10* (**L**), *TNF-α* (**M**), *GSK3B* (**N**), *AKT1* (**O**), *AGPAT* (**P**), *GPAT* (**Q**) and *PAP* (**R**). Data are displayed with mean ± SD (n = 5). $^{\#}$ P <0.05 compared with the NC group; * P < 0.05 compared with the MC group.

3.9. LBTE administration modulated the gut microbiota profiles in T2D mice

To evaluate the impact of LBTE on gut microbial ecology, 16S rRNA sequencing was conducted on fecal samples. A total of 176 amplicon sequence variants (ASVs) were identified across all samples, with 165 ASVs unique to the MC group and 163 ASVs unique to the LBTE-H group (Fig. 6B), highlighting distinct microbial signatures between disease and treatment conditions. Analysis of α-diversity indexes, including chao1, observed_species, pielou_e, and shannon indexes, revealed no significant differences

between the NC and MC groups as well as between the MC and LBTE groups (Fig. 6D-G). However, the α-diversity indexes in the LBTE-H group were more similar to those in the NC group, indicating a partial restoration of microbial richness and evenness following LBTE treatment. β-diversity analysis of gut microbiota, assessed by OPLS-DA (Fig. 6I) and hierarchical clustering (Fig. 6H), revealed clear distinctions between the NC and MC groups, as well as between the MC and LBTE-H groups, with notable proximity in microbial profiles between the NC and LBTE-H groups. These results indicated that LBTE administration remodeled the gut microbial community structure disrupted by T2D. At the phylum level (Fig. 6A), the gut microbiota was predominantly composed of *Firmicutes*, *Bacteroidetes*, *Verrucomicrobiota* and *Patescibacteria*. The MC group exhibited an increased abundance in *Firmicutes* and a decreased abundance in *Bacteroidetes* compared to the NC and LBTE-H groups. LBTE treatment partially reversed this dysbiosis in T2D mice, restoring a microbial composition more similar to healthy mice.

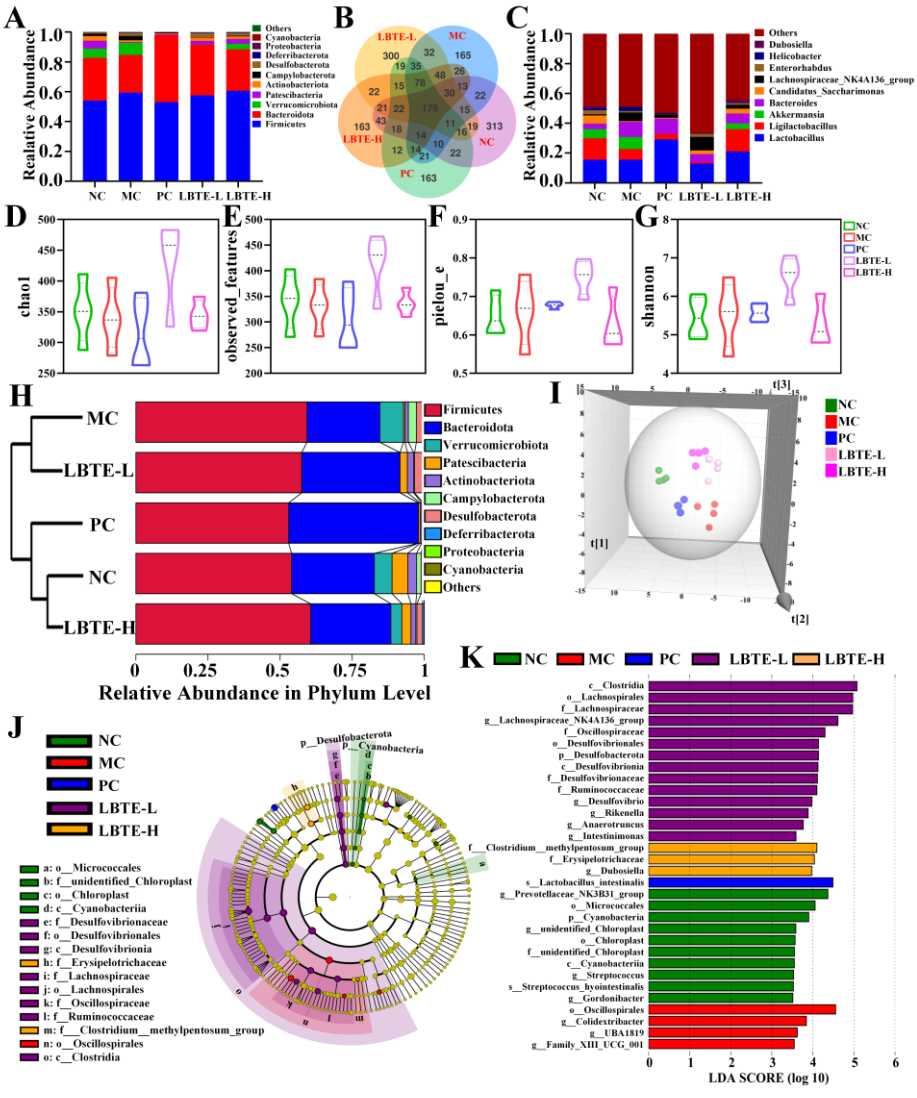


Figure 6. Remodeling effects of LBTE administration on the gut microbiota in T2D mice. (**A, C**) Relative abundance at phylum and genus level. (**B**) Venn diagram of ASVs identified in the gut microbiota. (**D-G**) Alpha diversity of gut microbiota evaluated by chao1, observed_species, pielou_e, and shannon indexes. (**H**) Hierarchical clustering tree analysis. (**I**) Beta diversity of gut microbiota evaluated by weighted OPLS-DA score plot. (**J**) Cladogram generated from LEfSe analysis. (**K**) LDA score derived from LEfSe analysis.

At the genus level (Fig. 6C), *Akkermansia*, *Lactobacillus*, *Ligilactobacillus*, and *Bacteroides* were dominant across all groups. The relative abundance of *Lachnospiraceae_NK4A136_group*, *Akkermansia*, *Bacteroides*, *Lactobacillus* and *Helicobacter* was increased, while the *Ligilactobacillus*, *Candidatus_Saccharimonas* and *Enterorhabdus* were decreased in the MC group. These alterations were reversed following LBTE-H treatment (Fig. S11A-H). Further, Linear Discriminant Analysis Effect Size (LEfSe) analysis with an LDA threshold of three was conducted to reveal specific bacterial changes. The MC group was enriched in *Oscillospirales* at the order level, the NC group in *Micrococcales*, *Chloroplast*, and *Cyanobacteriia*, while LBTE-H group was characterized by *Erysipelotrichaceae* and *Clostridium_methylpentosum _group* (Fig. 6J-K). To assess functional shifts in microbial metabolism, PICRUSt2 was employed for predictive metagenomic analysis. As shown in Fig. S11I, the top 10 most abundant functional proteins were primarily involved in bacterial material transport and carbohydrate metabolism. Notably, genes encoding K07024 (sucrose-6-phosphatase, SPP) and K15634 (probable phosphoglycerate mutase, gpmB) were down-regulated in the MC group but restored following LBTE treatment, suggesting that LBTE may enhance microbial-mediated carbohydrate metabolism.

3.10. Metorigin tracing analysis of differential metabolites

In the comparison between the NC and MC groups, 136 differential metabolites associated with T2D were identified (Fig. S12B-C). MPEA revealed that these metabolites were involved in 13 co-metabolism pathways (Fig. S12D). Among them, SP and GP metabolism (log0.05 $P > 2$) were identified as the most significantly enriched pathways in the co-metabolism between gut microbiota and the hosts, indicating their pivotal role in the pathogenesis of T2D (Fig. S12A). In the GP metabolism-related metabolic reaction R01320, PC 40:7 was identified as the key metabolite, with *Helicobacter* being the primary associated genus, showing a strong positive correlation (Fig. S12E). Similarly, PS 38:0 was the major metabolite in reaction R01800, which involved four bacterial genera related to GP metabolism. Among these, *Bacteroides*, *Akkermansia*, and *Helicobacter* exhibited positive correlations with PS 38:0, whereas *Ligilactobacillus* showed a negative correlation (Fig. S12F). In addition, three key metabolites including sphingosine, sphinganine, and phytosphingosine were identified in the metabolic reactions R01494, R06518, and R06528, respectively, related to SP metabolism, underscoring their contribution to lipid dysregulation in T2D (Fig. S13A-C).

In the comparison between the MC and LBTE-L groups, 70 differential metabolites were identified (Fig. S14B-C). MPEA revealed that nine significantly enriched co-metabolic pathways, with GP metabolism being the most notably modulated (Fig. S14A, D). Similarly, in the comparison between the MC and LBTE-H groups, 68 differential metabolites were identified (Fig. S15B-C). MPEA indicated that modulation of seven co-metabolic pathways was associated with co-metabolism pathway databases, among which GP metabolism was most significantly affected (Fig. S15A, D). Consistently, PC 40:7 and *Helicobacter* remained central elements in metabolic reaction R01320, which showed a positive correlation (Fig. S14E, S15E). Moreover, PS 38:0 and its associated genera (*Bacteroides*, *Akkermansia*, *Helicobacter* and *Ligilactobacillus*) were repeatedly highlighted in reaction R01800, further supporting their involvement in GP metabolism (Fig. S14F, S15F). Therefore, LBTE exerted its anti-T2D effects primarily by modulating GP metabolism, likely mediated by restructuring the abundance of key microbiota, thereby restoring host-microbiota metabolic balance to alleviate T2D.

3.11. LBTE enhanced the intestinal barrier function by promoting SCFA production and regulating GPCR gene expression

To evaluate the impact of LBTE on gut microbial metabolism, fecal SCFAs were quantitatively analyzed. The levels of three major SCFAs, as well as the total SCFA content, were significantly elevated in the NC and LBTE-treated groups compared to the MC group ($P < 0.05$) (Fig. 7A). These findings suggested that LBTE facilitated the recovery of gut microbial metabolic activity impaired by T2D. In the MC group, the mRNA expression levels of *GPR41* and *GPR109A* in both colon and liver tissues were significantly downregulated compared to the NC group, whereas LBTE treatment significantly upregulated the expression of these receptors, with more pronounced effects observed in the high-dose group ($P < 0.05$) (Fig. 7D-G). In addition, the mRNA expression levels of tight junction proteins, *ZO-1* and *Occludin*, were significantly lower in the MC group compared to the NC group, indicating compromised intestinal barrier function. LBTE treatment significantly restored the mRNA expression levels of these proteins, thereby effectively improving intestinal barrier function ($P < 0.05$) (Fig. 7B-C). LBTE exerted protective effects in T2D mice by promoting SCFA production, upregulating the expression of GPCRs and tight junction proteins, thereby contributing to the restoration of gut barrier function.

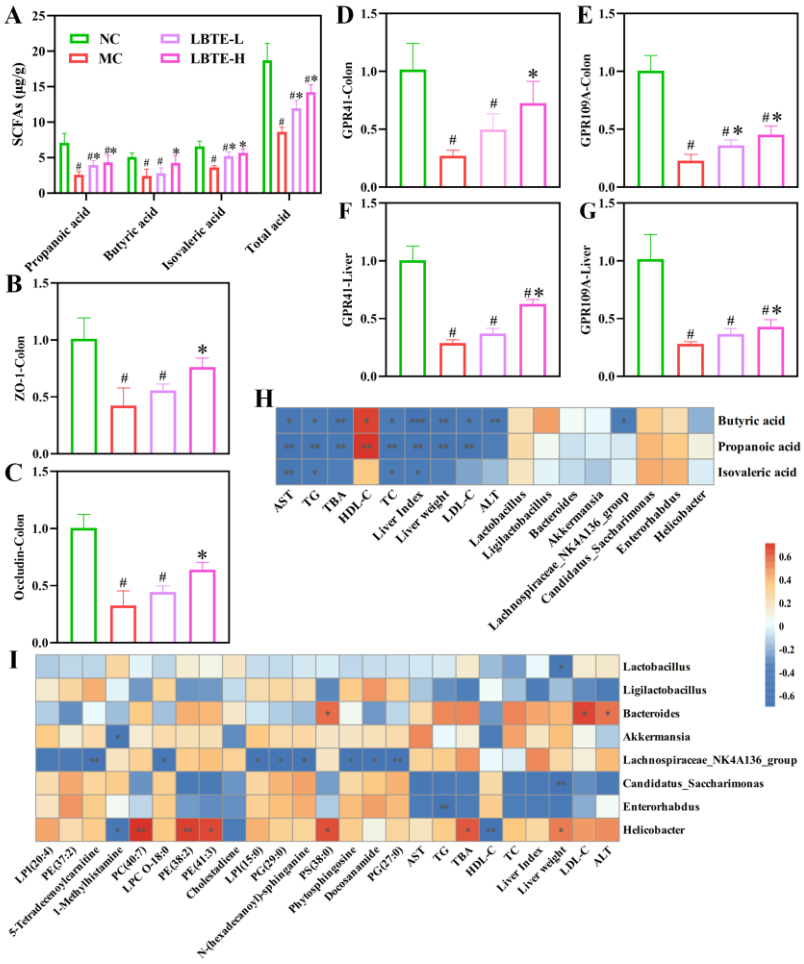


Figure 7. Regulatory effect of LBTE on fecal SCFAs and the intestinal barrier function in T2D mice. (**A**) The levels of SCFAs. (**B-E**) The mRNA levels of *ZO-1*, *Occludin*, *GPR41* and *GPR109A* in the colon tissue. (**F-G**) The mRNA levels of *GPR41* and *GPR109A* in the liver tissue. (**H**) The correlation analysis between SCFAs and gut microbiota or biochemical indicators. (**I**) The correlation analysis between gut microbiota and differential metabolites or biochemical indicators. In panel A-G, data are displayed with mean ± SD (n = 5). $^{\#}$ P <0.05 compared with the NC group; * $P < 0.05$ compared with the MC group. In panel H-I, significant correlations are marked by * $P < 0.05$, and ** $P < 0.01$ in the heatmap. Red and blue squares indicate positive and negative correlations, respectively.

3.12. Correlation analysis

Correlation analyses were conducted to elucidate the interactions among T2D-related biochemical indicators, key metabolites, key bacteria genera, and SCFA levels. As shown in Fig. 7I, the relative abundances of *Helicobacter* showed significant positive correlation with those of PE 38:2, PE 41:3, PS 38:0 and PC 40:7 ($P < 0.05$). Moreover, the relative abundances of *Bacteroides* exhibited significant positive correlations with the levels of LDL-C and ALT ($P < 0.05$). The relative abundances of *Helicobacter* exhibited significant positive correlations with the levels of TBA and liver weight, while presenting significant negative correlations with the levels of HDL-C ($P < 0.05$). However, the *Ligilactobacillus*, *Candidatus_Saccharimonas*, and *Enterorhabdus* showed the opposite trends, displaying negative correlations with these metabolites and biochemical indicators. As shown in Fig. 7H, the levels of SCFAs were negatively correlated with the relative abundances of *Helicobacter*, *Akkermansia* and *Bacteroides*, while positively correlated with the relative abundances of *Candidatus_Saccharimonas*, *Enterorhabdus*, and *Ligilactobacillus*. In addition, the levels of SCFAs were negatively correlated with the levels of all T2D-related biochemical indicators except HDL-C, which was positively correlated with SCFA levels. These findings further suggested that gut microbiota play a role in improving metabolism disorders, and protecting liver function through enhancing SCFA production, thereby alleviating T2D.

3.13. LBTE alleviated T2D pathology depending on gut microbiota

To confirm whether gut microbiota was involved in the improvement effects of LBTE on T2D, a pseudo-germ-free mouse model was established using a cocktail of broad-spectrum antibiotics. After antibiotic treatment, the α-diversity indexes including chao1, observed_species, pielou_e and shannon of both the MA and LBTEA groups were significantly lower and close to zero compared to MC group ($P < 0.05$), confirming the successful establishment of the pseudo-germ-free mouse model (Fig. 8A-D). NMDS analysis further disclosed that the gut microbiota compositions of the MA and LBTEA groups were highly similar, yet distinctly separated from that of the MC group (Fig. 8E). In addition, antibiotic intervention significantly altered the microbial community, transforming it from a highly diverse community to one dominated by *Proteobacteria*. Compared with the MC group, the abundance of *Firmicutes* and *Bacteroidota* significantly decreased, while *Proteobacteria* sharply increased in the MA and LBTEA groups (Fig. 8F). Importantly, LBTE treatment failed to restore the gut microbiota profiles in the presence of antibiotic intervention, suggesting a loss of its therapeutic efficacy in the absence of a functional microbiota. We further evaluated the impact of these microbiota changes on SCFA production. As shown in Fig. S16A, propionic acid levels were significantly lower in the MA and LBTEA groups compared to the MC group ($P < 0.05$), whereas butyric acid and isovaleric acid were almost undetectable. Histological examination revealed that, similar to the MC group, mice in both the MA and LBTEA groups exhibited crypt damage and inflammatory cell infiltration in colonic tissues (Fig. S16B). The inability of LBTE to ameliorate colonic histopathological abnormalities was closely associated with the reduced SCFA levels following antibiotic treatment.

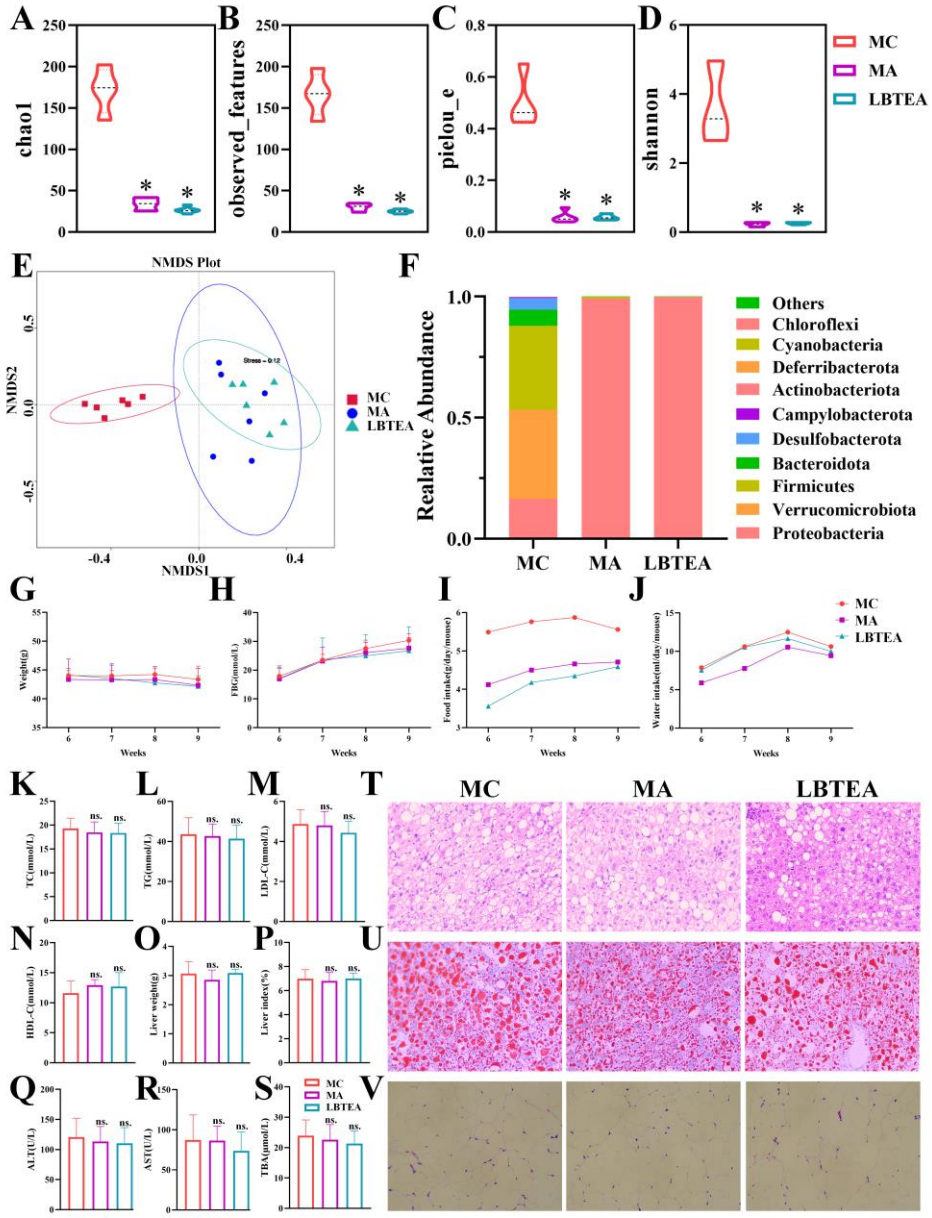


Figure 8. LBTE exerted improvement effect in T2D depending on gut microbiota. (**A-D**) Alpha diversity of gut microbiota evaluated by chao1, observed_species, pielou_e, and shannon indexes. (**E**) Beta diversity of gut microbiota evaluated by weighted NMDS plot. (**F**) Relative abundance at phylum level. (**G**) Body weight. (**H**) FBG. (**I**) Food intake. (**J**) Water intake. (**K**) TC, (**L**) TG, (**M**) LDL-C, (**N**) HDL-C, (**O**) Liver weight, (**P**) Liver index, (**Q**) ALT, (**R**) AST, and (**S**) TBA. (**T**) H&E staining of liver tissue (200 ×). (**U**) Oil Red O staining of liver tissue (200 ×). (**V**) H&E staining of adipose tissue (200 ×). MC, high-fat diet (HFD); MA, HFD + antibiotic; LBTEA, HFD + antibiotic + LBTE (400 mg/kg). Data are expressed as mean ± standard deviation (SD) (n = 5). * $P < 0.05$ compared with the MC group; $^{ns.}$ $P > 0.05$ compared with the MC group.

Regarding physiological parameters, the body weight of mice in the MC group continued to decrease throughout the experiment, and body weight trends in the MA and LBTEA groups mirrored those of the MC group, with no significant differences observed (Fig. 8G). Meanwhile, the FBG levels were persistently elevated across all three groups, with no significant differences between them, indicating that the hypoglycemic effect of LBTE was abolished after antibiotic intervention (Fig. 8H). Although no significant difference in water intake among the three groups of mice (Fig. 8J), the food intake in the MA and LBTEA groups decreased compared to the MC group (Fig. 8I), likely due to the

profound disruption of gut microbiota. There were no significant differences in TC, TG, LDL-C, and HDL-C levels between the MA group and the LBTEA group compared to the MC group (Fig. 8K-N). This indicated that the modulatory effects of LBTE on lipid metabolism disorders were abolished after gut microbiota disruption. Histopathological analysis of adipose tissues further confirmed these findings, revealing that antibiotic intervention reversed the LBTE improvements in lipid accumulation induced by T2D (Fig. 8V). Similarly, no significant differences were observed in the liver weight, liver index, serum ALT, AST, and TBA levels between the MA, LBTEA, and MC groups (Fig. 8O-S). H&E staining and Oil Red O staining of liver tissues showed the liver tissues of mice in the MC group showed significant lipid accumulation and inflammation, whereas antibiotics combined with LBTE failed to alleviate liver injury in mice with T2D (Fig. 8T-U). Therefore, antibiotic intervention effectively negated the therapeutic benefits of LBTE, resulting in the loss of its ability to improve metabolic disorders, reduce lipid accumulation, and alleviate liver damage. These findings supported that the antidiabetic effect of LBTE critically depended on gut microbiota mediation.

4. Discussion

This study revealed the potential mechanism of LBTE in improving T2D by integrating bioinformatics analysis, multi-omics technology and *in vivo* experimental verification. Network pharmacology combined with targeted metabolomics revealed that quercetin, luteolin, genistein, and kaempferol were potential bioactive compounds in LBTE, exerting anti T2D effects by regulating signaling pathways such as PI3K-Akt, insulin resistance, and MAPK. Molecular docking demonstrated that these flavonoids have strong binding ability to key targets such as AKT1, GSK3B, and TNF-α. Among them, luteolin and quercetin have been shown to improve the disorders of glucose and lipid metabolism [32,33], genistein has both hypoglycemic and insulin resistance-reducing properties [17], and kaempferol reduces the inflammatory response by inhibiting the NF-κB pathway [34], which provided the theoretical basis for the subsequent *in vivo* experiments.

In order to investigate the ameliorative effect of LBTE *in vivo*, studies were conducted in T2D mice, which exhibit T2D-related characteristics consistent with previous studies [35]. In the T2D mouse model, LBTE significantly reduced FBG and improved dyslipidemia, while reversing hepatic lipid accumulation and inflammation, alveolar wall thickening and colonic tissue intestinal barrier damage. Metabolomics further revealed that LBTE exerted its ameliorative effects mainly through the regulation of SP and GP metabolic pathways. Previous studies have highlighted the crucial role of SPs in causing glucose disturbances, as well as abnormal GP metabolism as a factor in the pathophysiology of diabetes [36,37]. The research findings were consistent with these studies, with LBTE being particularly critical in regulating GP metabolism. T2D is a chronic metabolic disease characterized by hyperglycemia and disorders of lipid metabolism [38]. LBTE promoted the conversion of glucose to glycogen in the liver by up-regulating the expression of *AKT1* and down-regulating the expression of *GSK3B*, thereby reducing blood glucose. Meantime, glucose undergoes the glycolysis pathway to produce Glycerol-3-phosphate (G-3-P), which is a substrate in GP synthesis pathway [39]. LBTE could block the metabolic flow of G-3-P to diacylglycerol (DAG) by down regulating the expression of related genes involved in the GP synthesis pathway (including *GPAT*, *AGPAT* and *PAP*) [40], thereby reducing the synthesis and accumulation of GP and TG in the liver, and improving dyslipidemia. Metabolic disorders can lead to abnormal inflammation [38], which is often accompanied by lipid accumulation, thereby exacerbating liver injury [41,42]. LBTE significantly reduced the expression levels of *TNF-α* and *IL-6*, while increasing the expression level of *IL-10* in liver. The protective effect of LBTE on the liver may be related to regulating metabolic disorders and alleviating inflammatory states.

Studies have shown that alterations in the composition of gut microbiota affect the onset of diabetes [43]. The MC group exhibited a higher *Firmicutes* to *Bacteroidetes* (F/B) ratio compared to other groups, which contributed to metabolic disorders and insulin resistance [44]. LBTE reversed the F/B ratio, enriching beneficial bacteria such as *Candidatus_Saccharimonas* and *Ligilactobacillus*, while inhibiting the proliferation of harmful bacteria including *Bacteroides*, *Akkermansia* and *Helicobacter*. *Bacteroides* are linked to increased LPS levels and decreased insulin sensitivity, and *Akkermansia* are enriched in T2D samples [45,46]. An increase in *Helicobacter* promotes insulin resistance, accelerating diabetes progression. *Ligilactobacillus* helps improve function of the intestinal microbiota and intestinal barrier as well as promote carbohydrate metabolism [47]. *Candidatus_Saccharimonas*, an acid-producing bacterium important for maintaining intestinal pH [48]. Previous studies have suggested that the gut microbiota could reshape host metabolism [49]. LBTE regulated GP metabolism by modulating the levels of certain beneficial and harmful gut bacteria. The specific resident bacteria in the gut can metabolize indigestible carbohydrates into various SCFAs molecules [50]. Enzymes like SPP and gpmB play crucial roles in bacterial carbohydrate metabolism [51]. the increased carbohydrate metabolism observed in the LBTE-H group reflected an increase in carbohydrate-utilizing bacteria such as *Candidatus_Saccharimonas* and *Ligilactobacillus*.

As metabolites of intestinal flora, SCFAs are produced in the colon and partially enter the liver through the portal vein [52]. SCFAs help maintain intestinal barrier integrity and regulate host inflammatory responses. LBTE significantly increased the content of fecal SCFAs, among them, butyric acid has been widely proven to enhance intestinal barrier function by upregulating the expression levels of tight junction proteins *ZO-1* and *Occludin* [46]. T2D is usually characterized by insulin resistance, mainly causing directly or indirectly by increased inflammation [53]. SCFA reduces the release of pro-inflammatory factors such as TNF-α, IL-6, and IL-1β by activating signaling pathways mediated by GPR41 and GPR109A receptors [54], thereby synergistically alleviating inflammatory responses and reducing liver injury [55]. Inhibiting inflammation is an important strategy for LBTE treatment of liver injury. Meantime, inflammation can disrupt the insulin signaling pathway and mediate glucose intolerance, with TNF-α further exacerbating metabolic disorders by interfering the PI3K-Akt signaling pathway [56]. As the core effector molecule of this pathway, AKT promotes glycogen synthesis by inhibiting GSK3B, thereby maintaining blood glucose homeostasis [57]. Elevated levels of serum TG and TC are also important factors in inducing insulin resistance. SCFAs effectively reduce TG and TC levels by inhibiting hepatic adipogenesis and inflammatory cell infiltration [58]. Correlation analysis further confirmed that SCFAs were significantly negatively correlated with lipid indices and liver injury markers, highlighting their metabolic protective effects. The critical role of gut microbiota in mediating the antidiabetic effects of LBTE was further validated in a pseudo-germ-free mouse model. Antibiotic-induced depletion of the gut microbiota led to the modulatory effects of LBTE on the structure of the gut microbiota, the production of SCFAs, and the metabolism of glucose and lipids were virtually lost.

5. Conclusions

To the best of our knowledge, this study represented the first systematic investigation into the antidiabetic mechanisms of LBTE, with a focus on its dual modulation of hepatic metabolism and gut microbiota in T2D mice. LBTE effectively ameliorated hepatic glucose and lipid metabolic dysregulation primarily by promoting hepatic glycogen synthesis and inhibiting glycerophospholipid and triglyceride synthesis via regulation of key metabolic genes. Furthermore, LBTE reshaped the gut microbiota by inhibiting harmful bacteria and enriching SCFA-producing bacteria in T2D mice. The elevated SCFAs enhanced intestinal barrier integrity and attenuated hepatic inflammation and metabolic perturbation by

activating the GPR43/GPR109A-mediated signaling pathway. Additionally, quercetin, luteolin, genistein and kaempferol were identified as the potential active ingredients contributing to the antidiabetic effects of LBTE. Taken together, this study provides new insight into the potential of LBTE as complementary strategy for T2D prevention and management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/doi/s1, Figure S1: Schematic diagram of the experimental design; Figure S2: Schematic diagram of the experimental design for pseudo-germ-free mouse; Figure S3: Primary chemical constituents of LBTE. LBTE, Liubao tea extract; Figure S4: Total ion chromatogram (TIC) of compounds in LBTE detected by LC-MS; Figure S5: Identification of key active ingredients in LBTE; Figure S6: Molecular docking analysis of the key targets and key core compounds; Figure S7: Effects of different modes of metformin administration on blood glucose in mice; Figure S8: Reproducibility assessment of QC samples in the serum metabolomic analysis; Figure S9: Level distribution of serum differential metabolites shared in the comparison among the four groups; Figure S10: ROC analysis to evaluate the discriminative performance of serum differential metabolites between two groups; Figure S11: Analysis of discriminative gut microbiota and KEGG functional enrichment; Figure S12: Metorigin analysis on gut microbiota and differential metabolites between NC and MC groups; Figure S13: BIO-Sankey Network of gut microbiota and differential metabolites between the NC and MC groups; Figure S14: Metorigin analysis on gut microbiota and differential metabolites between MC and LBTE-L groups; Figure S15: Metorigin analysis on gut microbiota and differential metabolites between MC and LBTE-H groups; Figure S16: Effects of LBTE treatment on the short-chain fatty acids (SCFAs) levels and the intestinal barrier function;Table S1: Chromatographic conditions for chemical composition analysis of LBTE;. Table S2: Mass spectrometric conditions for chemical composition analysis of LBTE; Table S3: Chromatographic conditions for quantitative analysis of potential ingredients in LBTE; Table S4: Mass spectrometric conditions for quantitative analysis of potential ingredients in LBTE; Table S5: Chromatographic conditions for serum metabolomic analysis; Table S6: Mass spectrometric conditions for serum metabolomic analysis; Table S7: Primer sequences for the qPCR analysis; Table S8: Characterization of compounds in LBTE via LC-MS; Table S9: Identification information of the potential bioactive ingredients in LBTE against T2D; Table S10: Interaction between the key proteins and the potential bioactive compounds from LBTE.

Author Contributions: Conceptualization, J.L. and Q.Z.; methodology, J.L.; software, X.L.; validation, J.L., Y.T. (Yuru Tan), B.Y. and M.W.; formal analysis, J.L.; investigation, J.L. and Z.W.; resources, Q.Z.; data curation, J.L., Y.T. (Ying Tong), X.G., P.Z. and S.X.; writing—original draft preparation, J.L., Z.W.and Y.T. (Yuru Tan); writing—review and editing, J.L., Z.W. and Q.Z.; visualization, J.L.; supervision, Q.Z.; project administration, Q.Z.; funding acquisition, Q.Z. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Animal Experimental Ethics Committee of Guangxi University (No. GXU-2023-0226, 27 December 2023).

Informed Consent Statement: Not applicable.

Data Availability Statement: All data associated with this study are present in the paper. Data are available upon request to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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