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Synergistic Effects of *Averrhoa Bilimbi* and *Ocimum Basilicum* Decoctions on Blood Glucose Control in Diabetes Mellitus Type 2 in Parepare, Indonesia

Efectos Sinérgicos de las Decocciones de *Averrhoa Bilimbi* y *Ocimum Basilicum* en el Control de la Glucosa Sanguínea en la Diabetes Mellitus Tipo 2 en Parepare, Indonesia

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SUMMARY

Background: *Diabetes mellitus is a chronic disorder requiring pharmacological and non-pharmacological treatment. Averrhoa bilimbi L. (bilimbi) and Ocimum basilicum (lemon basil) leaves contain bioactive compounds with hypoglycemic properties. Although these plants are commonly used individually, no prior research has combined them for diabetes management.* **Objective:** *The study aimed to assess whether combining bilimbi and lemon basil leaf decoctions leads to a greater reduction in fasting blood glucose levels than using either herb alone in patients with type 2 diabetes mellitus.* **Methods:** *This is a quasi-experimental design with a non-randomized control group pretest-post-test design involving 60 diabetic patients. They were divided into three groups: the main group (bilimbi and lemon basil leaf combination), comparator group 1 (bilimbi leaf decoction), and comparator group 2 (lemon basil leaf decoction). Data was analyzed using the Pearson Chi-Square Test, Friedman, Kruskal-Wallis, and One Way ANOVA.* **Results:** *All groups showed significant reductions in FBG levels. The main group demonstrated the greatest mean reduction in FBG of -85.70 mg/dL (SD ± 21.09 mg/dL). Comparator group 1 exhibited a mean reduction of -47.70 mg/dL (SD ± 21.73 mg/dL), while comparator group 2 achieved a mean reduction of -59.90 mg/dL (SD ± 30.20 mg/dL). The between-group differences were statistically significant (p<0.0001).* **Conclusion:** *The combination of bilimbi and lemon basil leaf decoctions was more effective in lowering*

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FBG levels than either herb used alone, offering a novel and promising alternative therapy for diabetes management.

Keywords: *Decoction, fasting blood sugar, lemon basil, starfruit, type 2 diabetes mellitus.*

RESUMEN

Antecedentes*: La diabetes mellitus es un trastorno crónico que requiere tratamiento farmacológico y no farmacológico. Las hojas de Averrhoa bilimbi L. (bilimbi) y Ocimum basilicum (albahaca limón) contienen compuestos bioactivos con propiedades hipoglucemiantes. Aunque estas plantas se utilizan habitualmente de forma individual, ninguna investigación previa las ha combinado para el tratamiento de la diabetes.* **Objetivo***: El estudio pretendía evaluar si la combinación de decocciones de bilimbi y hojas de albahaca de limón conduce a una mayor reducción de los niveles de glucosa en sangre en ayunas en comparación con el uso de cualquiera de las dos hierbas por separado en pacientes con diabetes mellitus tipo 2.* **Métodos:** *Se trata de un diseño cuasi-experimental con un diseño pretest-postest de grupo de control no aleatorizado en el que participaron 60 pacientes diabéticos. Se dividieron en tres grupos: el grupo principal (combinación de bilimbi y hojas de albahaca limonera), el grupo de comparación 1 (decocción de hojas de bilimbi) y el grupo de comparación 2 (decocción de hojas de albahaca limonera). Los datos se analizaron mediante la prueba de Chi-Cuadrado de Pearson, Friedman, Kruskal-Wallis y ANOVA de una vía.* **Resultados:** *Todos los grupos mostraron reducciones significativas en los niveles de FBG. El grupo principal demostró la mayor reducción media de FBG de -85,70 mg/dL (SD ± 21,09 mg/dL). El grupo comparador 1 exhibió una reducción media de -47,70 mg/dL (SD ± 21,73 mg/dL), mientras que el grupo comparador 2 logró una reducción media de -59,90 mg/dL (SD ± 30,20 mg/dL). Las diferencias entre grupos fueron estadísticamente significativas (p <0,0001).* **Conclusiones:** *La combinación de decocciones de bilimbi y hojas de albahaca limonera fue más eficaz para reducir los niveles de FBG que cualquiera de las hierbas utilizadas por separado, ofreciendo una terapia alternativa novedosa y prometedora para el tratamiento de la diabetes.*

Palabras clave: *Decocción, azúcar en sangre en ayunas, albahaca limonera, starfruit, diabetes mellitus tipo 2.*

INTRODUCTION

Diabetes is a prevalent chronic metabolic disorder characterized by elevated blood glucose levels, leading to organ damage over time. Type 2 diabetes (T2DM), associated with insulin resistance or inadequate insulin production, is increasing globally, with urgent public health measures warranted (1). The proportion of diabetes mellitus incidence is mostly in type 2 diabetes mellitus, which is 85 % - 95 % of all diabetes cases in the world (2). Globally, in 2021 as many as 537 million people worldwide have diabetes, which is 10.5 % of the world's population. In 2022, 14 % of adults aged 18 years and older were living with diabetes, an increase from 7 % in 1990. More than half (59 %) of adults aged 30 years and over living with diabetes were not taking medication for their diabetes in 2022. The prevalence of diabetes mellitus is expected to increase to 643 million (11.3 %) by 2030 and reach 783 million (12.2 %) by 2045. Among these, three out of four adults with diabetes live in low- and middle-income countries (LMICs) (3). This fact demonstrates the enormous burden faced by these countries, where medical resources, often limited health infrastructure and inadequate early detection, as well as socioeconomic disparities affect the ability of individuals to manage the disease effectively (4).

Indonesia, with one of the highest diabetes burdens in Southeast Asia, plays a significant role in the regional prevalence of diabetes mellitus (3). According to Basic Health Research (RISKESDAS) conducted by the Ministry of Health in 2018, the prevalence of diabetes mellitus in Indonesia was 10.9 % of the total population, which increased to 11.7 % in 2023 among individuals aged >15 years, based on blood glucose measurements (5). South Sulawesi is among the top 15 provinces with the highest diabetes prevalence, recording a rate of 1.3 % (5).

In Parepare City, South Sulawesi, the diabetes burden is particularly pronounced. According to the 2023 report from the Parepare City Health Office, the prevalence of diabetes mellitus reached 31.14 %. Among local healthcare facilities, Puskesmas Lakessi had the highest prevalence at 42.40 %, followed by Puskesmas Lumpue at 25.22 % and Puskesmas Madising at 16.77 % (6). The challenges of managing diabetes in this region are compounded by limited healthcare infrastructure, the high cost of synthetic antidiabetic drugs, and low awareness of preventive measures. These factors underscore the urgency for affordable and accessible alternative therapies that align with local needs and resources.

Diabetes mellitus management is divided into two aspects: the pharmacological treatment using drugs and non-pharmacological treatment through methods other than the use of drugs. Pharmacotherapy for T2DM aims to prevent complications and improve quality of life. Synthetic antidiabetic drugs, while effective, often come with side effects, limited accessibility, and high costs, making them less viable for many patients in LMICs (7,8). Common side effects include gastrointestinal disturbances, hypoglycemia, and even long-term risks like lactic acidosis or cardiovascular complications (9,10). In contrast, herbal medicines have gained popularity due to their natural composition, lower toxicity, cultural acceptance, ease of access, and affordability. These medicines offer additional benefits in glycemic control, cost-effectiveness, and alignment with cultural preferences (11,12). Herbal remedies, dietary supplements, and mind-body practices have shown promising results in managing T2DM and improving patient outcomes. These advantages make herbal-based therapies an attractive complementary or alternative approach for managing T2DM (13,14).

Bilimbi leaves (*Averrhoa bilimbi*) and lemon basil leaves (*Ocimum basilicum*) are promising candidates in natural medicine therapies. Bilimbi leaves are rich in active compounds such as flavonoids, alkaloids, saponins, and tannins. Flavonoids inhibit α-amylase and α-glucosidase activity, preventing carbohydrate digestion and glucose production and reducing glucose absorption by blocking glucose transporters (15). Alkaloids in bilimbi leaves enhance insulin secretion and decrease glucose absorption by inhibiting carbohydrate-degrading enzymes (16). Saponins act as antidiabetic agents by stimulating pancreatic β-cells to increase insulin production (17). Tannins promote β-cell production in the pancreas, which is essential for insulin regulation, and inhibit glucose absorption in the intestines (18).

Lemon basil leaves are rich in eugenol, a compound that stimulates insulin secretion, alleviates inflammation, and inhibits glucose absorption, while also enhancing glucose uptake through mechanisms such as GLUT4 translocation and AMPK activation (19). Previous research demonstrated that ethanol extracts from basil leaves significantly lower blood glucose levels, supporting their potential as an effective adjunct therapy in managing type 2 diabetes mellitus (20). This finding aligns with another study that showed that ethanol extracts of papaya and basil leaves have varying effects on reducing blood glucose levels in mice, with basil leaf extract proving more effective in lowering glucose levels. The hypoglycemic individual impact of these plants is well-documented, but their combined potential remains unexplored (21).

Synergy in phytotherapy offers a compelling rationale for combining bilimbi and lemon basil leaves. Synergy refers to the interaction between phytochemicals from different plants, resulting in a therapeutic effect greater than the sum of their actions. This phenomenon is grounded in the idea that various bioactive compounds can complement and enhance each other's mechanisms of action, leading to improved efficacy, reduced side effects, and broader therapeutic outcomes (22). This principle is foundational in many traditional medical practices, such as traditional Chinese medicine, where multiple herbs are combined in formulations to promote the beneficial interactions of their active compounds, thereby amplifying their overall pharmacological benefits (23). For example, bilimbi's flavonoids may improve insulin sensitivity, while basil's eugenol simultaneously inhibits glucose absorption, yielding a greater hypoglycemic effect than either plant could achieve alone.

Scientific research supports the concept of synergy in plant-based therapies, with numerous studies demonstrating how combining specific plants can lead to enhanced therapeutic outcomes. For example, the mixture BETE (Bryonia Evernia Telephium Extract) significantly reduced the viability of HT-29, PC-3, and A-549 cancer cells and strongly suppressed vascularization *in vivo* at 200 μg/mL, without showing toxicity in Perdix embryos or non-cancerous cells, highlighting the potential of synergistic plant combinations for developing new treatments (24). By leveraging these mechanisms, the combination of bilimbi and lemon basil leaves offers a novel approach to diabetes management, potentially providing a safer, more accessible, cost-effective alternative to synthetic antidiabetic drugs.

Despite the growing evidence supporting the hypoglycemic effects of bilimbi and basil, there is no report related to their combined impact on fasting blood glucose (FBG) levels in diabetic patients. This study aims to address this gap by evaluating whether combining bilimbi and lemon basil leaf decoctions leads to a greater reduction in FBG levels than using either herb alone in patients with type 2 diabetes mellitus. By addressing this unexplored area, the study provides an innovative approach to herbal therapy and contributes valuable evidence toward developing affordable, herbal-based interventions for diabetes management.

METHODOLOGY

This quasi-experimental study used a nonrandomized control group pre-test post-test design with three intervention groups: a main group receiving a combination of bilimbi leaves and basil leaf decoction, comparator group 1 receiving only bilimbi leaves decoction, and comparator group 2 receiving only basil leaf decoction. It was conducted in Parepare City's Lumpue, Lakessi, and Madising health center from August to September 2024.

Population and sample

The population in this study was 60 people with Type 2 Diabetes Mellitus who were registered in the chronic disease management program at the Lumpue, Lakessi, and Madising Health Centers in Parepare City. The Federer formula determined the sample size. Sample selection was carried out by purposive sampling based on certain criteria. The inclusion criteria for this study were as follows: 1) Fasting blood glucose level ≥100 mg/dL measured from capillary plasma, 2) disease duration ≤5 years, 3) patients aged ≥35 years, and 4) patients currently taking antidiabetic drugs. Exclusion criteria included: 1) patients with chronic conditions such as stroke, heart disease, kidney disease, or Gastroesophageal reflux disease (GERD), 2) patients aged ≥60 years, 3) insulin-dependent diabetes, and 4) pregnancy.

A total of 60 respondents who met the inclusion and exclusion criteria were divided into three groups, with 20 participants in each group. All respondents in every group continued their regular anti-diabetic medication, Metformin (biguanide), to standardize treatment and isolate the additional effects of the herbal interventions. The main intervention group received a decoction from a combination of bilimbi and lemon basil leaves. The first comparator group consumed a decoction prepared from bilimbi leaves only, while the second comparator group was given a decoction made solely from lemon basil leaves.

Preparation of plant decoction

The combined decoction was prepared by boiling 2.5 g of bilimbi leaves and 2.5 g of lemon basil leaves, sourced from verified organic farms to ensure consistency, in 300 mL of distilled water for 15 minutes at 90°C. For the single decoctions, 5 g of bilimbi leaves or 5 g of lemon basil leaves were processed similarly, with all leaves thoroughly cleaned and dried to a uniform moisture content before use. After boiling, the decoctions were filtered using sterile gauze, cooled to room temperature, and measured to yield precisely 150 mL per serving for each respondent. Quality control processes were applied to standardize the bioactive compound content by conducting preliminary phytochemical screening. Additional quality control measures, including precise weight measurements using calibrated scales and sterile handling during preparation, were implemented.

Phytochemical analysis of decoction

Phytochemical analysis was conducted at the Makassar Health Laboratory Center, South Sulawesi, Indonesia, under registration number 24021134-24021136/LHU/BBLK-MKS/VIII/2024, to identify active compounds such as flavonoids, alkaloids, and tannins in each intervention decoction. The presence and concentration of these compounds were determined using a spectrophotometric method. This approach involves measuring the absorbance of light at specific wavelengths corresponding to the compounds of interest. Each decoction was subjected to standard spectrophotometric procedures to detect and quantify flavonoids, alkaloids, and tannins based on their characteristic absorbance profiles. This method ensures accurate identification and provides quantitative data to support the evaluation of the decoctions' active phytochemical content.

Experimental procedures

Before the intervention, fasting blood glucose levels were measured using the EasyTouch General Check-Up (GCU) glucometer by competent nurses at the three health centers. Interviews were also conducted to collect data on respondents' characteristics. Researchers prepared fresh decoctions of the intervention ingredients every morning, distributed daily at 4 pm. For 14 days, the researcher and enumerator team administered 150 mL of decoction once daily to respondents under standardized conditions, instructing them to consume it on an empty stomach to ensure consistent absorption. The interventions included a combination of bilimbi and lemon basil leaves at Lumpue Health Center, bilimbi leaf decoction at Lakessi Health Center, and lemon basil leaf decoction at Madising Health Center. On the seventh day, fasting blood glucose levels were measured again (post-test 1) after overnight fasting. The intervention continued until day 14, and on day 15, a final fasting blood glucose measurement (post-test 2) was conducted, marking the end of data collection.

Ethical considerations

This study obtained permission from the Research Ethics Commission of the Faculty of Public Health, Hasanuddin University, with number 1788/UN4.14.1/TP.01.02/2024. All respondents were informed of the intervention's purpose and procedures, and their identities and privacy were kept confidential. They signed a consent form before the study began.

Data analysis

Data were analyzed using STATA software version 14. Univariate analysis was performed to describe participants' baseline characteristics, while bivariate analysis tested the effects of interventions on fasting blood glucose (FBG) levels. The Friedman test was chosen to assess within-group changes in FBG across three-time points (pre-test, post-test 1, and post-test 2) because it is suitable for non-parametric repeated measures data. A One-Way ANOVA was applied to compare the mean FBG reductions among the three intervention groups, as the data met assumptions for parametric testing, including normal distribution and homogeneity of variance. All statistical tests were conducted at a significant level of α=0.05.

RESULTS

Phytochemical analysis

As shown in Table 1, the combined decoction of basil leaves and bilimbi leaf decoction, flavonoids were found at 12.31 μg/mL, alkaloids at 15.52 μg/mL, and tannins with the highest concentration of 60.21 μg/mL. Meanwhile, in the decoction of bilimbi leaf decoction, the flavonoid content identified reached 26.04 μg/mL, higher than in combination with basil leaves, followed by alkaloids at 11.11 μg/mL, and tannins at 58.53 μg/mL. On the other hand, the decoction of basil leaves independently only contained flavonoids of 2.81 μg/mL, showing a lower concentration than the combination and decoction of star fruit leaves.

Sample characteristics

Table 2 shows that most respondents were in the age group of 56-60 years, with the highest number in comparator group 1 (65 %), followed by the main group and comparator group 2,

Table 1. Phytochemical Testing Results

No.	Tested Materials	Phytochemical Compounds	Unit	Test Results
1.	Combination decoction of bilimbi and lemon basil leaves	Flavonoids	μg/mL	12.31
		Alkaloids	μg/mL	15.52
		Tannins	μg/mL	60.21
2.	Bilimbi leaf decoction	Flavonoids	μg/mL	26.04
		Alkaloids	μg/mL	11.11
		Tannins	μg/mL	58.53
3.	Lemon basil leaf decoction	Flavonoids	μg/mL	2.81

with 40 % each. In terms of education, most respondents had a junior high school education background. Comparator group 1 had the highest proportion (55 %), while the main and comparator group 2 had 35 % each. Based on occupation, most respondents were housewives. The highest proportion was in the main group and the comparator group 2 (70 %), followed by the comparator group 1 (65 %). For marital status, most respondents in all three intervention groups were married. Comparator group 2 had the highest proportion (95 %), followed by the main group and comparator group 1 with 85 % each.

Table 2. Socio-Demographic Characteristics of the Sample

General Characteristics of Respondents	Main Group		Comparator Group 1		Comparator Group 2		Total	
	n	%	n	%	n	%	n	%
Age Group								
36-45 Years	0	0.00	1	5.00	5	25.00	6	10.00
46-55 Years	12	60.00	6	30.00	7	35.00	25	41.67
56-60 Years	8	40.00	13	65.00	8	40.00	29	48.33
Education								
Completed elementary school	4	20.00	5	25.00	3	15.00	12	20.00
Completed middle school	7	35.00	11	55.00	7	35.00	25	41.67
Completed high school	6	30.00	4	20.00	7	35.00	17	28.33
Completed bachelor's degree	3	15.00	0	0.00	3	15.00	6	10.00
Jobs								
Housewife	14	70.00	13	65.00	14	70.00	41	68.33
Merchant	2	10.00	4	20.00	3	15.00	9	15.00
Civil Servants	4	20.00	1	5.00	3	15.00	8	13.33
Retired	0	0.00	2	10.00	0	0.00	2	3.33
Marriage Status								
Unmarried	0	0.00	1	5.00	0	0.00	1	1.67
Marry	17	85.00	17	85.00	19	95.00	53	88.33
Divorce Life/Death	3	15.00	2	10.00	1	5.00	6	10.00

Based on Table 3, most respondents had a normal BMI category, especially in comparator group 2 (70 %), while comparator group 1 was dominated by obesity I (55 %). Most respondents had no family history of diabetes mellitus, especially in comparator group 1 (70 %). Most respondents had a paternal history of diabetes, with the highest proportion in comparator group

1 (30 %). Most respondents have had diabetes for 1-3 years, with the highest percentage in comparator group 1 (60 %). Most respondents did not engage in physical activity, with the highest percentage in the main group (85 %). Most respondents received medication supervision from their children, with the highest percentage in the comparator group 2 (40 %).

Table 3. Clinical Characteristics of the Sample

General Characteristics of Respondents	Main Group n	Main Group %	Comparator Group 1 n	Comparator Group 1 %	Comparator Group 2 n	Comparator Group 2 %	Total n	Total %
Body Mass Index (BMI)								
Underweight	0	0.00	0	0.00	1	5.00	1	1.67
Normal	7	35.00	5	25.00	14	70.00	26	43.33
Overweight	7	35.00	2	10.00	3	15.00	12	20.00
Obesity I	4	20.00	11	55.00	2	10.00	17	28.33
Obesity II	2	10.00	2	10.00	0	0.00	4	6.67
Family History								
Yes	9	45.00	6	30.00	8	40.00	23	38.33
No	11	55.00	14	70.00	12	60.00	37	61.67
Family with DM								
Mother	4	20.00	0	0.00	3	15.00	7	11.67
Father	5	25.00	6	30.00	5	25.00	16	26.67
None	11	55.00	14	70.00	12	60.00	37	61.67
Duration of Suffering								
<1 Year	4	20.00	1	5.00	3	15.00	8	13.33
1-3 Years	10	50.00	12	60.00	9	45.00	31	51.67
>3 Years	6	30.00	7	35.00	8	40.00	21	35.00
Physical Activity								
Yes	3	15.00	7	35.00	4	20.00	14	23.33
No	17	85.00	13	65.00	16	80.00	46	76.67
Medication Supervisor								
Husband/Wife	6	30.00	6	30.00	8	40.00	20	33.33
Children	7	35.00	7	35.00	8	40.00	22	36.67
Brother	3	15.00	5	25.00	2	10.00	10	16.67
Other families	4	20.00	2	10.00	2	10.00	8	13.33

Blood sugar levels before and after intervention

Table 4 shows that all three intervention groups significantly reduced blood sugar levels after treatment. In the main group, blood sugar levels decreased from an average pre-test of 234.95 mg/dL to 149.25 mg/dL in post-test 2, with a p-value = 0.0001, indicating this change was statistically significant. The comparator group 1 also showed a decrease in blood sugar levels, from 229.35 mg/dL in the pre-test to 181.65 mg/dL in post-test 2, with a p-value = 0.0001, which means this decrease is significant. Similarly, with the comparator group 2, blood sugar levels fell from 249.60 mg/dL in the pre-test to 189.70 mg/dL in post-test 2, and the p-value = 0.0001 indicating a significant decrease. The significant reduction in each group suggests that all interventions reduce fasting blood sugar levels in patients with diabetes mellitus.

Table 4. Analysis of Blood Sugar Level Reduction Before and After Intervention

Group	Category	Mean	SD	P-value*
Main group (combination)	Pre-test	234.95	55.34	0.0001
	Post-test 1	204.15	52.24	
	Post-test 2	149.25	43.47	
Comparator group 1 (bilimbi leaf)	Pre-test	229.35	77.08	0.0001
	Post-test 1	211.60	74.34	
	Post-test 2	181.65	63.06	
Comparator group 2 (lemon basil leaf)	Pre-test	249.60	73.64	0.0001
	Post-test 1	213.75	71.99	
	Post-test 2	189.70	62.67	

Notes: *Friedman test,

The difference in blood sugar level reduction between the three groups

Based on the results of the One-Way ANOVA test shown in Table 5, a p=0.0001 value was obtained, which means there is a difference in the change in fasting blood glucose levels between the three intervention groups. Further tests can be carried out to determine which intervention most affects changes in blood sugar levels. Due to normal data distribution and the significance of the one-way ANOVA test, the Tukey Test was used.

Table 5. Analysis of Differences in Blood Sugar Levels Between the Main Intervention, Intervention Comparator I, and Intervention Comparator II

Group	n	Δ Mean (post-test two minus pre-test)		P-value*
		Mean	SD	
Main group (combination)	20	-85.70	21.092	0.0001
Comparator group 1 (bilimbi leaf)	20	-47.70	21.728	
Comparator group 2 (lemon basil leaf)	20	-59.90	30.199	

Notes: *One Way ANOVA test

Table 6 shows the results of the Tukey test when comparing the three groups regarding reducing fasting blood glucose levels. The comparison between the comparator group 1 and the main group showed a p-value of 0.0001, which indicates a statistically significant difference between the two groups' fasting blood glucose level changes. Comparing the comparator group 2 and the main group showed a statistically significant difference in fasting blood glucose levels between the two groups, with a p-value of 0.005. When comparing comparator group 2 and comparator group 1, no significant difference in the fasting blood glucose levels change between these two groups was observed with a p-value of 0.270. Thus, the main intervention was more effective in reducing fasting blood glucose levels than the two comparator groups in this study.

Table 6. Post Hoc Test

Group	Standard Error	P-value*
Comparator group 1 (bilimbi) *vs* main intervention (combination)	7.808	0.0001
Comparator group 2 (lemon basil) *vs* main intervention (combination)	7.808	0.005
Comparator group 2 (lemon basil) *vs* comparator group 1 (bilimbi)	7.808	0.270

Notes: * Tukey test

DISCUSSION

The study results demonstrated a significant reduction in fasting blood glucose (FBG) levels in all intervention groups. However, the combination of bilimbi and lemon basil leaf decoctions showed superior effectiveness compared to single-ingredient interventions. This enhanced efficacy likely stems from the synergistic interaction of the bioactive compounds present in the two plants. Synergism theory suggests that combining multiple bioactive compounds can amplify their therapeutic effects, as each compound contributes through distinct yet complementary mechanisms (25).

The bioactive compounds in bilimbi and lemon basil leaves are particularly noteworthy in their ability to lower FBG levels. *Averrhoa bilimbi* leaves and fruits contain phytochemicals, such as alkaloids, saponins, tannins, flavonoids, phenols, and triterpenoids. Flavonoids are a group of natural substances with variable phenolic structures and have low-molecular-weight phenolic compounds, potent antioxidants as free radical scavengers, chelating metals, and inhibitors of fat oxidation. These actions reduce oxidative stress and enhance insulin receptor sensitivity. These compounds are pivotal in reducing insulin resistance and enhancing glucose metabolism. Flavonoids act through various mechanisms, including inhibiting carbohydrate digestion and glucose production by blocking α-amylase and α-glucosidase enzymes, thereby reducing the conversion of complex carbohydrates into glucose (26). They also prevent glucose absorption in the intestines by inhibiting glucose transporters and modulating the activity of dipeptidyl peptidase-4 (DPP-4), which prolongs incretin hormone activity. This prolongation promotes insulin secretion and suppresses hepatic glucose production, contributing to better glycemic control (15,27).

Lemon basil leaves are abundant in eugenol, a bioactive compound known for its hypoglycemic properties. Eugenol enhances insulin sensitivity, stimulates insulin secretion by pancreatic β-cells, and reduces glucose absorption during digestion (28,29). It also possesses anti-inflammatory properties, which can help mitigate the chronic inflammation commonly associated with type 2 diabetes. Studies have reported eugenol concentrations in lemon basil leaves ranging from 16.23 % to 36.17 % (30), with some findings suggesting concentrations as high as 2.44 ± 0.26 µg/mL (31) or 2.80 ± 0.15 g/kg of dry weight (32). Eugenol inhibits α-glucosidase activity, reducing carbohydrate breakdown and stabilizing postprandial glucose levels, making it a valuable compound for diabetes management (19).

The combined effects of flavonoids and eugenol create a synergistic mechanism that significantly enhances glycemic control. Flavonoids and eugenols operate through different pathways, yet their interactions amplify the hypoglycemic impact. Previous studies demonstrated that flavonoids, such as quercetin, reduce FBG by 37.29 % at a dose of 25 mg/kg over 28 days (33), while eugenol has been shown to decrease blood glucose levels by up to 70 % at a dose of 10 mg/kg over 30 days (34). Including other bioactive compounds, such as alkaloids and tannins, in the decoction further enhances its effectiveness. Alkaloids reduce hepatic glucose production (gluconeogenesis) and increase glucose uptake by muscle cells (35,36). Tannins, meanwhile, influence glucose metabolism by modulating key enzymes, reducing intestinal glucose absorption, and promoting pancreatic β-cell regeneration (37,38)

Furthermore, the potential of bilimbi and lemon basil leaves extends beyond glycemic control. Their antioxidant properties may also play a crucial role in mitigating oxidative stress associated with diabetes. Oxidative stress is known to contribute significantly to the pathophysiology of diabetic complications, including cardiovascular diseases and neuropathy (39). The rich flavonoid content in bilimbi can scavenge free radicals, thereby reducing cellular damage and inflammation, while eugenol has been shown to enhance endogenous antioxidant enzyme activity (29,40). This dual action supports blood glucose regulation and fosters overall metabolic health, suggesting that these herbal interventions could serve as complementary strategies in managing diabetes-related complications. As such, integrating these plants into dietary practices may yield multifaceted benefits, promoting both immediate glycemic improvements and long-term protection against chronic disease progression.

Synergistic interactions are not limited to bilimbi and lemon basil but extend to various combinations of herbal remedies traditionally used in different cultures. For instance, ethnopharmacological practices in Nigeria utilize a blend of plants like *Vernonia amygdalina* and *Ocimum gratissimum* to achieve significant reductions in blood glucose levels, showcasing the potential for culturally rooted remedies to inform modern diabetes management strategies (41). Such findings underscore the importance of exploring these multi-component formulations further, as they may offer a more effective therapeutic strategy for managing conditions like diabetes than isolated compounds alone. Additionally, understanding the mechanisms behind these synergies could pave the way for developing novel nutraceuticals that harness the full potential of nature's pharmacy.

These bioactive compounds act together, creating a multifaceted approach to lowering FBG levels. This interaction explains why the combined decoction of bilimbi and lemon basil leaves outperforms the single-ingredient interventions. These findings support the potential of plant-based synergies in enhancing glycemic control and contribute to the growing research on herbal therapies for diabetes management. While promising, this study has several limitations. The intervention lasted only 14 days, providing limited insight into the long-term effects of the combined decoction on blood glucose levels. The study's modest sample size and focus on a specific population also limits the generalizability of the findings. Future research should address these limitations by conducting studies with more diverse populations and more extended intervention periods.

Additionally, exploring other plant combinations with potential synergistic effects could expand the range of natural, cost-effective therapies for type 2 diabetes mellitus. This study highlights the potential of herbal medicine as a complementary approach to diabetes management, offering an accessible and culturally relevant alternative for resource-limited settings. By demonstrating the effectiveness of combining bilimbi and lemon basil leaves, this research paves the way for further investigation into plant-based synergies and their role in diabetes treatment.

CONCLUSION

In this study, the combined decoction of *Averrhoa bilimbi* and *Ocimum basilicum* demonstrated a significant reduction in fasting blood glucose levels among patients with type 2 diabetes mellitus, surpassing the effects observed with single-plant treatments. These findings suggest a potential synergistic effect, highlighting the promise of herbal combinations in enhancing glycemic control. As an accessible and culturally accepted intervention, this bilimbi-lemon basil decoction could serve as a low-cost adjunct therapy for diabetes management, particularly in resource-limited settings. However, the study's short duration and modest sample size indicate that further research is needed to confirm these results and evaluate long-term efficacy. Future studies should focus on larger, more diverse populations and explore additional plant combinations to broaden the scope of effective, natural diabetes treatments. This research underscores the potential of plant-based synergies as an alternative therapeutic approach, offering new insights into accessible, complementary strategies for managing diabetes in diverse populations.

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