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Research Article

# Development and Comparative Evaluation of Polyherbal Formulations Comprising Herbal Extracts for Diabetes Management

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## ABSTRACT

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from impaired insulin secretion, insulin action, or both. Although several synthetic drugs are available, their long-term use is often associated with adverse effects and limited efficacy in preventing complications. Herbal medicines, due to their multi-targeted actions, minimal side effects, and cultural acceptance, are increasingly explored for diabetes management. The present study aimed to develop and comparatively evaluate polyherbal formulations comprising extracts of Trigonella foenum-graecum (Fenugreek seeds), Azadirachta indica (Neem leaves), Cinnamomum verum (Cinnamon bark), Curcuma longa (Turmeric rhizomes), and Piper nigrum (Black pepper). These herbs have been traditionally reported to possess antidiabetic, antioxidant, and anti-inflammatory properties, and their synergistic effects in a polyherbal formulation may enhance therapeutic efficacy. Formulations were developed using standardized extracts and subjected to comparative evaluation of physicochemical properties, phytochemical profiling, and in vivo antidiabetic activity. The study provides scientific validation for the rational combination of selected herbal extracts and highlights the potential of polyherbal formulations as effective adjuncts in diabetes management.

## INTRODUCTION

Diabetes mellitus (DM) is one of the most prevalent metabolic disorders globally, characterized by chronic hyperglycaemia due to defects in insulin secretion, insulin action, or both (American Diabetes Association, 2022). The International Diabetes Federation (IDF, 2021) reports that approximately 537 million adults worldwide live with diabetes, a number projected to rise significantly by 2045. Current therapeutic approaches primarily involve synthetic drugs such

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as sulfonylureas, biguanides, and insulin, but their long-term use is associated with limitations including hypoglycaemia, gastrointestinal discomfort, weight gain, and decreased efficacy over time (Alqahtani et al., 2022). Hence, there is growing interest in herbal and polyherbal formulations that can provide safe, effective, and affordable alternatives.

Polyherbalism, rooted in Ayurvedic and traditional medicine practices, emphasizes the synergistic therapeutic potential of combining multiple plant extracts (Patwardhan et al., 2015). Several medicinal plants have been extensively studied for their antidiabetic properties. Trigonella foenum-graecum (Fenugreek) seeds are rich in soluble fibers and bioactive compounds such as trigonelline and 4-hydroxyisoleucine, which enhance insulin sensitivity and reduce postprandial glucose (Basch et al., 2003). Azadirachta indica (Neem) leaves exhibit hypoglycemic activity through modulation of glucose uptake and pancreatic β-cell protection (Chattopadhyay, 1999). Cinnamomum verum (Cinnamon) bark improves glucose metabolism by enhancing insulin receptor signaling and glycogen synthesis (Anderson et al., 2004). Curcuma longa (Turmeric) rhizomes contain curcumin, known for its potent antioxidant and anti-inflammatory properties, which contribute to amelioration of insulin resistance and oxidative stress in diabetes (Aggarwal & Harikumar, 2009). Piper nigrum (Black pepper) contains piperine, which not only exhibits antidiabetic effects but also enhances the bioavailability of curcumin and other phytoconstituents (Atal et al., 1985).

Considering their complementary mechanisms of action, the rational combination of these herbal extracts in a polyherbal formulation may provide a holistic approach to diabetes management. The present study focuses on the development and comparative evaluation of such polyherbal formulations, assessing their physicochemical properties, phytochemical profiles, and in vitro antidiabetic potential.

## MATERIALS AND METHODS

### Materials

The following materials were used in the formulation:

- **Active pharmaceutical ingredient (API):** Metformin (Sun Pharmaceutical Industries Ltd, India).
- **Excipients:** Microcrystalline cellulose, Sodium starch glycolate, Magnesium stearate (S.D. Lab Chem, Mumbai, India).
- **Herbal extracts:**
  - *Trigonella foenum-graecum* (Fenugreek seeds) extract
  - *Azadirachta indica* (Neem leaves) extract
  - *Cinnamomum verum* (Cinnamon bark) extract
  - *Curcuma longa* (Turmeric rhizomes) extract
  - *Piper nigrum* (Black pepper seeds) extract

  (All procured from IndiaMART, India).

### Methods

#### *1. Preformulation Studies*

**a. Organoleptic characterization**: The appearance, colour, odour, and solubility of the herbal extracts were observed and recorded.

#### 2. Evaluation of Pre-compression Parameters of Powder Blend

The polyherbal powder blend was evaluated for flow properties including angle of repose, bulk density, tapped density, Hausner's ratio, and Carr's compressibility index.

**a. Angle of Repose**: The fixed funnel method was used. Powder was allowed to freely flow through a funnel, forming a heap. The radius (r) and height (h) of the pile were measured, and the angle of repose (θ) was calculated using Equation (1):

**θ=tan⁡−1(h/r)(1)\theta = \tan^{-1}(h/r) \tag{1}**

Where:

- θ = Angle of repose
- h = Height of pile
- r = Radius of pile base

Measurements were performed in triplicate.

**b. Bulk Density and Tapped Density**: A 100 ml graduated cylinder was filled with 10 g of powder, and the initial volume was noted (bulk volume). The cylinder was tapped at 2-second intervals from a height of 2.5 cm until the volume remained constant (tapped volume). Bulk density (LBD) and tapped density (TBD) were calculated using Equations (2) and (3):

**LBD=Weight of powder Bulk volume (2) LBD = \frac{Weight\ of\ powder}{Bulk\ volume} \tag{2}**

**TBD=Weight of powder Tapped volume (3) TBD = \frac{Weight\ of\ powder}{Tapped\ volume}**

**c. Carr's Compressibility Index (CI)**: The CI was calculated using Equation (4):

**CI=TBD−LBDTBD×100(4) CI = \frac{TBD - LBD}{TBD} \times 100**

Lower CI values indicate better flowability of the powder blend.

**d. Hausner's Ratio (HR)**: Hausner's ratio was calculated using Equation (5):

**HR=TBDLBD(5)HR = \frac{TBD}{LBD}**

Values of HR < 1.25 indicate good flow properties, while values > 1.25 indicate poor flow.

**Formulation of Tablet**

**Tabel 1:Herbal Drug dose**

| Sr. No. | Herbal Ingredient | Botanical Name | Part Used | Extract Type/ Form | Quantity per Tablet (mg) |
|---|---|---|---|---|---|
| 1 | Fenugreek extract | *Trigonella foenum-graecum* | Seeds | Dry extract/ Powder | 100 mg |
| 2 | Neem extract | *Azadirachta indica* | Leaves | Dry extract/ Powder | 50 mg |
| 3 | Cinnamon extract | *Cinnamomum verum* | Bark | Dry extract/ Powder | 30 mg |
| 4 | Guduchi extract | *Tinospora cordifolia* | Stem | Dry extract/ Powder | 100 mg |
| 5 | Turmeric extract | *Curcuma longa* | Rhizome | Dry extract/ Powder | 120 mg |
| 6 | Black Pepper extract | *Piper nigrum* | Fruits | Dry extract/ Powder | 50 mg |

**Table 2 Formulation table of polyherbal tablet**

| Sr. No | Ingredients | Polyherbal Formulation | | | |
|---|---|---|---|---|---|
| | | F1 | F2 | F3 | F4 |
| 1 | Herbal extract | 450 | 450 | 450 | 450 |
| 2 | PVP | 5 | 10 | 15 | 20 |
| 3 | Microcrystalline Cellulose | 60 | 65 | 70 | 75 |
| 4 | Crospovidone | 20 | 15 | 10 | 5 |
| 5 | Aerosil | 6 | 6 | 6 | 6 |
| 6 | Talc | 3 | 3 | 3 | 3 |
| 7 | Magnesium Stearate | 6 | 6 | 6 | 6 |

| | | | | |
|---|---|---|---|---|
| Total(mg) | 550 | 550 | 550 | 550 |

## METHOD OF PREPARATION

### Direct Compression Method

Tablet compression involves converting powder or granulated material into a uniform solid dosage form using a tablet press machine. In the present study, the dried herbal extracts were blended with pharmaceutical excipients such as binders, disintegrants, diluents, and lubricants to ensure adequate flow properties and compressibility. The final blend was subjected to direct compression using either a single-punch or rotary press machine.

The powder mixture was fed into the die cavity and compressed between the upper and lower punches under controlled pressure to yield tablets of uniform size and shape. Compression pressure was carefully adjusted to achieve adequate hardness and avoid defects such as lamination or capping. The prepared tablets were subjected to post-compression evaluation to ensure their physicochemical quality and consistency.

## EVALUATION OF POST-COMPRESSION PARAMETERS

**1. Thickness-** The thickness of randomly selected tablets was measured using a digital Vernier calliper.

**2. Hardness-** The crushing strength of tablets was determined using a Monsanto hardness tester. Ten tablets were randomly selected from each batch, and hardness was expressed in kg/cm².

**3. Friability-** Friability was determined using a Roche Friabilator, Pre-weighed 20 tablets were rotated at 25 rpm for 4 minutes (100 revolutions). Tablets were dedusted and reweighed. Percentage friability was calculated using Equation:

$$\% \text{ Friability} = \text{Winitial} - \text{WfinalWinitial} \times 100$$

$$\%\text{Friability} = \backslash\ \text{frac}\{W_\{\text{initial}\} - W_\{\text{final}\}\}\{W_\{\text{initial}\}\} \backslash\text{times } 100 \backslash\text{tag}$$

where W initialW_{initial} = initial tablet weight, and W finalW_{final} = final tablet weight.

**4. Weight Variation-** Twenty tablets were randomly selected and weighed individually. The average weight was calculated and compared with individual tablet weights. Percentage deviation from the mean was determined as per pharmacopeial standards.

**5. Wetting Time-** A tissue paper was placed in a 6.5 cm diameter Petri dish containing 6 ml of distilled water. A tablet was placed on the tissue paper surface, and the time required for water to completely wet the tablet surface was recorded. The experiment was performed in triplicate.

## EVALUATION OF TABLETS

### In Vitro Dissolution Study

Dissolution testing was carried out in USP Apparatus II (paddle method) containing 900 ml of pH 1.2 buffer (citric acid–sodium phosphate) at 37 ± 0.5 °C with a paddle speed of 50 rpm. At intervals of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 hours, 5 ml samples were withdrawn, filtered through a 0.45 µm Millipore filter, diluted appropriately, and analyzed at 233 nm using a UV spectrophotometer. Cumulative percentage drug release was calculated and dissolution profiles were plotted.

## ANIMAL STUDY

**Experimental Design**

To assess the antidiabetic potential of Polyherbal Formulation (PHF) in vivo studies were conducted on Wistar rats.

- **Species:** Wistar albino rats
- **Age:** 8–10 weeks
- **Weight:** 180–220 g
- **Group size:** 10 rats per group

**Grouping of Animals**

- **Group I (Normal Control):** No induction, no treatment
- **Group II (Diabetic Control):** STZ-induced, no treatment
- **Group III (PHF-treated):** PHF (100 mg/kg, oral)
- **Group IV (APHF-treated):** APHF (50 mg/kg, oral)
- **Group V (Standard Control):** Metformin (90 mg/kg, oral)

**Induction of Diabetes**

Diabetes was induced by intraperitoneal injection of Streptozotocin (STZ) at a dose of 50 mg/kg. Blood glucose levels were measured 72 hours post-injection, and animals with glucose levels >250 mg/dL were considered diabetic.

Parameters Evaluated

- **Blood glucose levels:** Monitored weekly
- **Biochemical markers:**
  - Lipid profile (Total cholesterol, Triglycerides, HDL, LDL)
  - Liver function (ALT, AST, ALP)
  - Kidney function (Creatinine, BUN)
- **Oxidative stress markers:** Superoxide dismutase (SOD), Catalase, Malondialdehyde (MDA)
- **Histopathological examination:** Liver and pancreatic tissues were fixed in 10% neutral buffered formalin, embedded in paraffin, sectioned (3–5 µm), and stained with hematoxylin-eosin (H&E). Slides were examined under a light microscope (Motic, USA) to assess histopathological changes.

**RESULTS – PREFORMULATION STUDY**

**Organoleptic Characterization of Plant Extracts**

The selected plant extracts were evaluated for colour, odour, and taste. The findings (Table 3) correspond well with the reported characteristics of the respective botanicals, thereby confirming their identity and suitability for formulation.

**Table 1: Organoleptic Characteristics of Plant Extracts**

| Plant Name | Colour | Odour | Taste |
|---|---|---|---|
| *Trigonella foenum-graecum* | Yellowish brown | Spicy | Bitter |
| *Azadirachta indica* | Bright green | Strong, pungent | Bitter |
| *Cinnamomum verum* | Rich brown | Strong, warm | Aromatic |
| *Tinospora cordifolia* | Rich brown | Strong, warm | Bitter |
| *Curcuma longa* | Yellow-orange | Strong, warm | Bitter |
| *Piper nigrum* | Yellowish red | Pungent | Spicy, pungent |

**Loss on Drying (LOD) and Moisture Content**

Moisture content was determined by loss on drying. As presented in Table 4, values ranged from 7.6% to 26.4%. Among the extracts, Tinospora cordifolia exhibited the highest moisture content (26.4%), while Azadirachta

indica had the lowest (7.6%). All extracts were adequately dried for further formulation work.

**Table 4: Loss on Drying of Plant Extracts**

| Plant Name | Initial Weight (g) | Final Weight (g) | % LOD |
|---|---|---|---|
| *Trigonella foenum-graecum* | 1.0 | 0.896 | 10.4% |
| *Azadirachta indica* | 1.0 | 0.924 | 7.6% |
| *Cinnamomum verum* | 1.0 | 0.781 | 21.9% |
| *Tinospora cordifolia* | 1.0 | 0.736 | 26.4% |
| *Curcuma longa* | 1.0 | 0.847 | 15.3% |
| *Piper nigrum* | 1.0 | 0.869 | 13.1% |

## Micromeritic Properties

The micromeritic parameters of powder blends, including bulk and tapped density, Hausner's ratio, Carr's index, and angle of repose, were evaluated. Most blends demonstrated good flow characteristics (Hausner's ratio <1.25, Carr's Index <15%, angle of repose 25–35°). However, sample no. 6 showed poor flowability (Carr's Index 27.59%, angle of repose ~45°), indicating the possible requirement of flow enhancers.

## Differential Scanning Calorimetry (DSC)

DSC thermograms confirmed the thermal behavior of formulations:

- **Polyherbal formulation (F2)**: Broad endothermic peak at 138.76 °C, attributed to excipients, without evidence of incompatibility.

## Evaluation of Tablet Properties

The prepared formulations (F1–F4) were assessed for physical and quality control parameters. As shown in Table 5, all batches met pharmacopeial standards. Hardness values (5.1–5.5 kg/cm²) indicated sufficient mechanical strength, while friability values (<0.54%) confirmed durability. Drug content uniformity (89.89–98.87%) was within the acceptable range (±5% of the labelled claim).

**Table 5: Evaluation of Prepared Tablet Formulations**

| Formulation | Tablet Weight (mg) | Weight Variation | Hardness (kg/cm²) | Thickness (mm) | Diameter (mm) | Friability (%) | Drug Content (%) |
|---|---|---|---|---|---|---|---|
| F1 | 550 | Passes | 5.1 ± 0.18 | 5.0 ± 0.45 | 10.3 ± 0.12 | 0.41 ± 0.18 | 95.25 ± 0.95 |
| F2 | 550 | Passes | 5.3 ± 0.21 | 5.2 ± 0.42 | 11.1 ± 0.15 | 0.50 ± 0.22 | 98.87 ± 0.72 |
| F3 | 550 | Passes | 5.5 ± 0.32 | 5.1 ± 0.38 | 10.1 ± 0.19 | 0.44 ± 0.11 | 92.74 ± 1.08 |
| F4 | 550 | Passes | 5.4 ± 0.26 | 5.0 ± 0.40 | 12.0 ± 0.38 | 0.48 ± 0.24 | 89.89 ± 0.64 |

## Differential Scanning Calorimetry (DSC) Analysis

The thermal behavior of the polyherbal formulation (PHF) was evaluated using Differential Scanning Calorimetry (DSC), and the thermogram is presented in Figure 1. The DSC curve revealed a prominent endothermic peak at approximately 187.72 °C, with an onset temperature of 132.22 °C and an offset at 210.83 °C. The measured peak height was –100.75 mW, corresponding to a heat flow change of approximately –154.65 J/g.

The observed endothermic transition can be attributed to the melting and/or decomposition of phytoconstituents present in the PHF. The broadness of the peak indicates the presence of multiple bioactive components with overlapping thermal events, which is expected in polyherbal formulations due to the coexistence of alkaloids, flavonoids, phenolics, and terpenoids.

The absence of sharp, multiple melting peaks suggests that the formulation is in a partially amorphous state, which may enhance its solubility and bioavailability compared to crystalline phytochemicals. The broad endothermic transition also reflects the thermal stability of the formulation up to ~130 °C, indicating that the PHF remains intact under moderate processing or storage conditions.

When compared to reported DSC thermograms of individual plant extracts, the endothermic peak of the PHF appears shifted and broadened. This shift is suggestive of molecular interactions among the bioactive constituents, which may result in synergistic stabilization and altered thermodynamic behavior. Such interactions are particularly relevant for herbal formulations, as they often contribute to improved pharmacological activity.

The DSC profile therefore confirms that the PHF is thermally stable up to ~130 °C, exhibits an amorphous nature, and possesses strong intermolecular interactions between its phytoconstituents, supporting its suitability for pharmaceutical applications such as oral dosage forms.

The preformulation studies confirmed that both pure Metformin and the selected herbal extracts met pharmacopeial quality standards. Organoleptic characterization and LOD values indicated stability and suitability for formulation. Micrometric properties demonstrated generally good flowability, although one sample required optimization.

Spectroscopic (UV, FTIR) and thermal (DSC) analyses confirmed the absence of significant incompatibilities between drug and excipients. Tablet evaluation further established the robustness, uniformity, and reproducibility of the prepared formulations.

Among the batches, F2 exhibited superior results, with the highest drug content (98.87%), optimal hardness, and acceptable friability. These findings support the potential of the developed polyherbal and allopolyherbal formulations as effective antidiabetic agents.

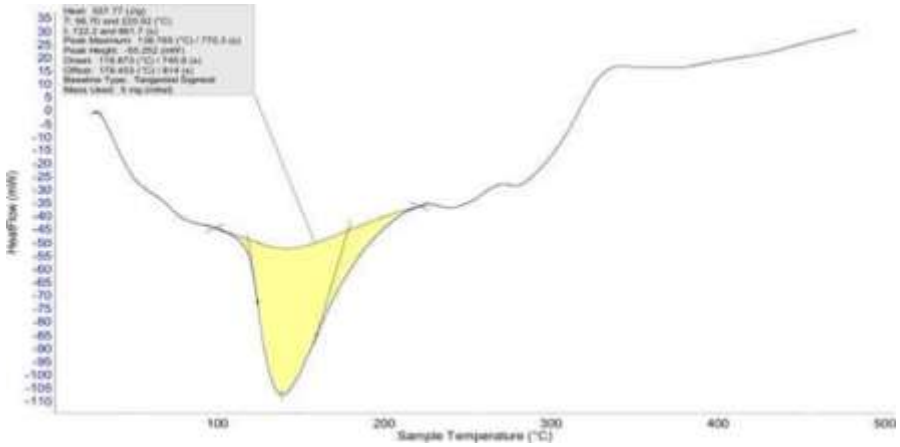


**Fig1 : DSC of Polyherbal formulation F2**

**Blood Glucose Levels**

The changes in fasting blood glucose levels across experimental groups were recorded weekly over a period of 4 weeks (Table 6).

**Table 6: Effect of PHF and Metformin on Blood Glucose Levels (mg/dL)**

| Time (Weeks) | Group 1 (Normal Control) | Group 2 (Diabetic Control) | Group 3 (PHF Treated) | Group 5 (Metformin Treated) |
|---|---|---|---|---|
| 0 | 90 ± 5 | 280 ± 10 | 275 ± 12 | 276 ± 9 |
| 1 | 92 ± 4 | 285 ± 8 | 220 ± 15 | 190 ± 10 |
| 2 | 94 ± 6 | 290 ± 9 | 180 ± 13 | 130 ± 8 |
| 3 | 95 ± 5 | 295 ± 11 | 150 ± 12 | 105 ± 7 |
| 4 | 96 ± 5 | 300 ± 12 | 130 ± 11 | 95 ± 6 |

At week 0, all diabetic groups (Group 2, Group 3, and Group 5) showed significantly elevated fasting blood glucose levels (~275–280 mg/dL) compared to the normal control (90 ± 5 mg/dL), confirming successful diabetes induction.

In diabetic control rats, blood glucose progressively increased from 280 ± 10 mg/dL to 300 ± 12 mg/dL by week 4. In contrast, PHF treatment significantly reduced glucose levels from 275 ± 12 mg/dL to 130 ± 11 mg/dL by week 4, representing ~52% reduction. Metformin treatment produced a stronger effect, reducing glucose levels from 276 ± 9 mg/dL to 95 ± 6 mg/dL (~65% reduction).

The normal control group maintained stable glucose levels (90–96 mg/dL) throughout the experiment.

Observation: Both PHF and Metformin significantly reduced blood glucose levels compared to the diabetic control. However, Metformin exerted a slightly more pronounced hypoglycemic effect compared to PHF.

**Biochemical Parameters**

The effect of PHF and Metformin on lipid profile and hepatic–renal biomarkers is shown in Table 7.

**Table 7: Effect of PHF and Metformin on Biochemical Parameters**

| Parameters | Normal Control | Diabetic Control | PHF Treated | Metformin Treated |
|---|---|---|---|---|
| Total Cholesterol (mg/dL) | 125 ± 8 | 210 ± 12 | 165 ± 10 | 140 ± 7 |
| Triglycerides (mg/dL) | 90 ± 5 | 185 ± 11 | 140 ± 8 | 110 ± 6 |
| HDL (mg/dL) | 55 ± 3 | 30 ± 2 | 40 ± 3 | 48 ± 3 |
| LDL (mg/dL) | 45 ± 4 | 110 ± 6 | 80 ± 5 | 58 ± 4 |
| ALT (IU/L) | 40 ± 3 | 90 ± 5 | 65 ± 4 | 45 ± 2 |
| Creatinine (mg/dL) | 0.8 ± 0.05 | 1.6 ± 0.1 | 1.2 ± 0.1 | 0.8 ± 0.05 |

The diabetic control group displayed marked alterations in biochemical parameters, including elevated cholesterol, triglycerides, LDL, ALT, and creatinine levels, along with decreased HDL, indicating dyslipidemia, hepatic damage, and renal dysfunction.

Treatment with PHF significantly improved these biochemical markers. Total cholesterol decreased to 165 ± 10 mg/dL, triglycerides to 140 ± 8 mg/dL, and LDL to 80 ± 5 mg/dL, while HDL increased to 40 ± 3 mg/dL. Similarly, hepatic marker ALT decreased from 90 ± 5 IU/L (diabetic control) to

65 ± 4 IU/L (PHF), and creatinine reduced from 1.6 ± 0.1 mg/dL to 1.2 ± 0.1 mg/dL, indicating hepatoprotective and nephroprotective effects.

Metformin-treated animals showed near-normal values for all parameters, demonstrating its superior efficacy.

Observation: PHF treatment improved lipid metabolism and protected liver and kidney function in diabetic rats, though effects were less pronounced compared to Metformin.

**Oxidative Stress Markers**

The antioxidant status of experimental groups was evaluated using SOD, Catalase, and MDA assays (Table 8).

**Table 8: Effect of PHF and Metformin on Oxidative Stress Markers**

| Marker | Normal Control | Diabetic Control | PHF Treated | Metformin Treated |
|---|---|---|---|---|
| SOD (U/mg protein) | 8.5 ± 0.5 | 4.0 ± 0.3 | 6.0 ± 0.4 | 7.8 ± 0.6 |
| Catalase (U/mg) | 6.2 ± 0.3 | 2.8 ± 0.2 | 4.5 ± 0.3 | 6.0 ± 0.4 |
| MDA (nmol/mg) | 2.5 ± 0.2 | 5.5 ± 0.4 | 3.8 ± 0.3 | 2.6 ± 0.2 |

In the diabetic control group, a significant decline in SOD (4.0 ± 0.3 U/mg) and Catalase (2.8 ± 0.2 U/mg) was observed, along with increased lipid peroxidation as indicated by elevated MDA (5.5 ± 0.4 nmol/mg).

PHF administration restored antioxidant enzyme activities (SOD: 6.0 ± 0.4; Catalase: 4.5 ± 0.3) and reduced MDA levels (3.8 ± 0.3 nmol/mg) compared to diabetic controls. Metformin produced a more significant restoration, bringing antioxidant levels nearly equal to those of normal controls.

Observation: Oxidative stress was significantly reduced in PHF-treated groups, indicating strong antioxidant activity, though Metformin was more effective in restoring normal oxidative balance.

## DISCUSSION

The present study focused on the development and evaluation of polyherbal formulations (PHF) using extracts of Trigonella foenum-graecum (fenugreek), Azadirachta indica (neem), Cinnamomum verum (cinnamon), Curcuma longa (turmeric), and Piper nigrum (black pepper), and compared their therapeutic efficacy with standard allopathic therapy (metformin).

**Preformulation Studies**

The organoleptic evaluation of pure metformin and herbal extracts confirmed their identity and consistency with pharmacopeial and literature-reported characteristics, ensuring the authenticity of raw materials used for formulation (Shah et al., 2020). The loss on drying (LOD) studies revealed acceptable moisture content in all extracts, although Tinospora cordifolia showed relatively higher moisture (26.4%), which may require optimized drying and storage conditions to prevent microbial growth and instability (Aulton & Taylor, 2017).

Micromeritic studies showed that most blends exhibited good flow properties (Hausner's ratio <1.25, Carr's index <15%, angle of repose 25–35°), which are essential for achieving uniform tablet compression. However, one blend exhibited poor flow (Carr's Index >25%), indicating a need for flow enhancers such as glidants (Gohel & Parmar, 2019).

**Evaluation of Tablet Properties**

All formulations complied with pharmacopeial specifications. Hardness (5.1–5.5 kg/cm²) and friability (<0.54%) confirmed mechanical strength and durability, while drug content (89–98%) ensured uniformity. These results indicate that the formulations are suitable for immediate-release dosage forms, aligning with quality standards (Indian Pharmacopoeia, 2020).

**In-Vivo Antidiabetic Efficacy**

The antidiabetic potential of the PHF was evident from the significant reduction in fasting blood glucose (~52% by week 4) compared to diabetic controls, although metformin exhibited slightly superior efficacy (~65% reduction). These findings are in agreement with reports on fenugreek and neem, which enhance insulin sensitivity and reduce hyperglycemia through modulation of glucose metabolism (Basch et al., 2003; Chattopadhyay, 1999).

**Biochemical Parameters**

PHF improved lipid metabolism by lowering cholesterol, triglycerides, and LDL, while increasing HDL. This hypolipidemic effect may be attributed to the synergistic action of fenugreek and turmeric, which regulate lipid profiles by modulating hepatic enzymes and bile acid metabolism (Sharma et al., 2016). Additionally, reductions in ALT and creatinine suggest hepatoprotective and nephroprotective effects, which align with the traditional use of neem and guduchi for organ protection in diabetes (Grover et al., 2002).

**Antioxidant and Oxidative Stress Markers**

Oxidative stress is a major contributor to diabetic complications. In this study, PHF significantly improved antioxidant status by increasing SOD and catalase while reducing MDA levels. These results highlight the strong antioxidant properties of turmeric (curcumin) and black pepper (piperine), which enhance endogenous antioxidant defense mechanisms (Aggarwal & Harikumar, 2009). Although metformin showed slightly stronger restoration of antioxidant balance, PHF demonstrated comparable efficacy, supporting its potential as an adjunct or alternative therapy.

**OVERALL FINDINGS**

The study confirms that the selected polyherbal formulation exhibits significant antidiabetic, hypolipidemic, hepatoprotective, nephroprotective, and antioxidant activities. While metformin remains more potent, PHF offers a promising herbal-based therapy with fewer side effects and the potential to reduce reliance on synthetic drugs.

The present study successfully demonstrated the development, formulation, and evaluation of polyherbal (PHF) tablets for effective diabetes management. By combining the therapeutic potential of traditional medicinal plants the study highlights a holistic approach to controlling hyperglycemia with the advantages of minimized side effects and improved patient compliance.

The selected medicinal plants—Trigonella foenum-graecum (fenugreek), Azadirachta indica (neem), Cinnamomum verum (cinnamon), Curcuma longa (turmeric), Piper nigrum (black pepper), and Tinospora cordifolia (guduchi)—are individually well-documented for their antidiabetic, antioxidant, and metabolic regulatory properties. When formulated as a polyherbal combination, these extracts demonstrated synergistic effects, thereby enhancing the overall therapeutic efficacy compared to their use as individual components.

Comprehensive preformulation and post-compression evaluations—including melting point determination, compatibility studies (FTIR, DSC), micrometric properties (angle of repose, bulk/tapped density), drug content analysis, disintegration, friability, and dissolution profiling—confirmed that all developed formulations complied with pharmacopeial requirements for immediate-release tablets. The in vitro dissolution studies further indicated satisfactory drug release, reinforcing their suitability for therapeutic application.

Additionally, insights from literature and scientific evidence supported the pharmacological relevance of the selected herbs in modulating glucose metabolism, improving insulin sensitivity, regulating lipid levels, and reducing oxidative stress.

In conclusion, polyherbal formulations developed in this study present promising, scientifically validated alternatives or adjuncts to conventional antidiabetic therapies. By integrating traditional herbal wisdom with modern pharmaceutical technology, they offer a safer, effective, and affordable treatment strategy for the management of diabetes mellitus. Nevertheless, further in vivo studies and well-designed clinical trials are warranted to comprehensively assess their long-term efficacy, safety, and clinical applicability in human subjects.

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