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Phytochemical profiling and structural elucidation of active compounds in *Momordica charantia* L.

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Abstract
Momordica charantia L. (bitter gourd) is a well-known medicinal plant consumed as both a vegetable and a therapeutic agent in many parts of the world. Its distinctive bitterness reflects a unique reservoir of bioactive compounds, ranging from cucurbitane-type triterpenoids and saponins to phenolics, flavonoids, and bioactive peptides. These compounds have been linked to diverse pharmacological activities, including antidiabetic, anticancer, antioxidant, and antimicrobial effects. Phytochemical profiling provides a systematic framework for identifying and quantifying these constituents, while structural elucidation offers insights into their molecular architecture, stereochemistry, and functional groups that determine biological activity. This paper reviews the methodologies for phytochemical profiling of *M. charantia* using modern chromatographic and spectroscopic techniques, summarizes the major classes of bioactive constituents, and highlights structural elucidation studies that have clarified the chemistry of compounds such as charantin, momordicosides, karavilagenins, and polypeptide-p. By integrating traditional knowledge with advanced phytochemical analysis, bitter gourd emerges as a plant of continuing importance in nutraceutical and pharmaceutical research.

Keywords: *Momordica charantia*, phytochemical profiling, charantin, cucurbitane triterpenoids, NMR, LC-MS

Introduction
Medicinal plants have long been integral to the treatment of human diseases, serving as a primary source of remedies in traditional healthcare systems and as the foundation for many modern drugs. Among these, *Momordica charantia* L., commonly known as bitter gourd, karela, or balsam pear, has attracted wide attention because of its culinary use, cultural significance, and therapeutic versatility. Bitter gourd belongs to the family Cucurbitaceae and is cultivated extensively in tropical and subtropical regions of Asia, Africa, and Latin America. The plant is recognized for its fruit, which is characteristically bitter due to a complex array of secondary metabolites.

In Ayurveda, bitter gourd is recommended for conditions associated with *Prameha* (diabetes-like syndromes), digestive imbalances, and infections. In Traditional Chinese Medicine, it is prescribed to clear internal heat, detoxify the body, and regulate blood sugar. These ethnomedical uses point toward the bioactive potential of the plant. Modern phytochemical investigations have confirmed that bitter gourd contains structurally diverse metabolites that underlie its pharmacological activities.

Phytochemical profiling involves the systematic identification, isolation, and quantification of plant constituents. This process has evolved from classical solvent extraction and thin-layer chromatography (TLC) to advanced analytical technologies such as high-performance liquid chromatography (HPLC), liquid chromatography coupled with mass spectrometry (LC-MS), nuclear magnetic resonance (NMR), and Fourier-transform infrared spectroscopy (FTIR). Structural elucidation builds upon profiling by determining the exact molecular structures of compounds, including their stereochemistry, which is critical to understanding biological activity.

This paper examines the phytochemical profile of *M. charantia*, focusing on major classes of active constituents, and describes the analytical strategies used to elucidate their structures. The aim is to provide an integrated account of the chemistry of bitter gourd, bridging traditional use with contemporary phytopharmaceutical research.

Phytochemical Constituents of *M. charantia*
Bitter gourd contains a wide variety of phytochemicals that can be grouped into

triterpenoids, saponins, steroids, flavonoids, phenolics, alkaloids, and proteins. Each of these contributes to the plant's bitterness and therapeutic potential.

Cucurbitane-type triterpenoids are the most characteristic compounds of *M. charantia*. They include charantin, momordicosides, and karavilagenins. These compounds are strongly associated with antidiabetic and anticancer activities.

Steroidal glycosides contribute to hypoglycaemic effects and are often co-isolated with triterpenoids.

Phenolic compounds and flavonoids, including quercetin, gallic acid, and chlorogenic acid, are responsible for antioxidant properties and for protecting tissues from oxidative damage.

Alkaloids and saponins are linked to antimicrobial and cytotoxic effects, while peptides such as polypeptide-p exhibit insulin-like activity.

The phytochemical composition is influenced by factors such as cultivar, stage of ripening, part of the plant (fruit, seed, leaf, or root), and extraction method.

Analytical Approaches for Phytochemical Profiling

Extraction Strategies

Traditional methods such as maceration, decoction, and Soxhlet extraction are still employed, but modern profiling often uses sequential extraction with solvents of increasing polarity (hexane, chloroform, ethanol, methanol, and water). This ensures a comprehensive capture of compounds with diverse solubilities.

Chromatographic Methods

High-performance liquid chromatography (HPLC) is widely used for quantifying marker compounds like charantin. Thin-layer chromatography (TLC) provides rapid preliminary screening, while gas chromatography (GC) coupled with mass spectrometry (GC-MS) is applied to volatile and semi-volatile constituents.

Spectroscopic Methods

- UV-Visible Spectroscopy is used to quantify total phenolics and flavonoids.
- Fourier Transform Infrared Spectroscopy (FTIR) identifies functional groups and provides a chemical fingerprint of extracts.
- Nuclear Magnetic Resonance (NMR) is essential for structure elucidation, offering detailed information on hydrogen and carbon environments.
- Mass Spectrometry (MS), especially LC-MS/MS, provides molecular weight, fragmentation patterns, and structural information.

Structural Elucidation of Active Compounds

The structural complexity of bitter gourd constituents necessitates advanced analytical tools. Charantin, for example, was structurally elucidated as a mixture of stigmasteryl and β-sitosteryl glucosides. NMR spectroscopy confirmed its steroidal backbone, while MS data provided molecular weight and fragmentation patterns.

Momordicosides, a series of cucurbitane glycosides, were characterized using HPLC-MS and ^{1}H and ^{13}C NMR. These compounds show structural variations in glycosidic linkages and hydroxylation patterns that affect biological activity.

Karavilagenins, triterpenoid derivatives, were also elucidated by detailed NMR analysis, which identified their ring structures and substitution patterns.

Polypeptide-p was isolated and sequenced using chromatographic separation followed by amino acid analysis. Structural studies revealed that it mimics some of the functions of insulin, explaining its hypoglycaemic activity in experimental models.

Table 1: Major bioactive compounds of *Momordica charantia* and their structural characteristics

Compound	Chemical Class	Structural Features	Reported Activity
Charantin	Steroidal saponin mixture	Sitosterol and stigmasterol glucosides	Antidiabetic, hypolipidaemic
Momordicosides	Cucurbitane-type triterpenes	Diverse glycosidic linkages, hydroxyl groups	Antidiabetic, anti-inflammatory
Karavilagenins	Triterpenoids	Modified cucurbitane skeleton	Anticancer, antimicrobial
Polypeptide-p	Bioactive peptide	Amino acid chain with insulin-like activity	Hypoglycaemic
Quercetin, rutin	Flavonoids	Polyphenolic ring structures	Antioxidant, cardioprotective
Gallic acid	Phenolic acid	Trihydroxybenzoic acid structure	Antioxidant, antimicrobial

Therapeutic Relevance of Structural Elucidation

The structural elucidation of bitter gourd compounds is not merely an academic exercise; it directly informs therapeutic applications. By identifying functional groups and stereochemistry, researchers can predict biological activity, optimize extraction, and design analogues with improved pharmacological profiles. For example, understanding the structure of momordicosides has led to insights into their role as AMPK activators, linking chemistry to antidiabetic mechanisms. Similarly, the structure of karavilagenins explains their cytotoxic activity against cancer cells, providing a basis for further drug development.

Challenges in Phytochemical Profiling

Despite significant advances, challenges remain. The variability of phytochemical composition across cultivars and regions complicates standardization. Structural similarity among cucurbitane triterpenoids can lead to overlapping signals in NMR and MS, requiring sophisticated multidimensional techniques. Bioavailability is another concern, as many compounds are poorly absorbed or rapidly metabolized in the human body. Safety considerations also need attention, as seeds containing vicine can pose risks for individuals with G6PD deficiency.

Future Perspectives

Future research should prioritize integrating metabolomics, proteomics, and transcriptomics with phytochemical profiling to better understand the plant's holistic activity. Nanotechnology-based delivery systems could enhance bioavailability of poorly absorbed compounds. Collaborative projects combining ethnobotany with cutting-edge chemistry can help preserve traditional knowledge while generating novel pharmacological insights. Clinical studies that employ standardized extracts characterized by known marker compounds such as charantin and momordicosides are essential to move from laboratory to therapeutic use.

Conclusion

Momordica charantia represents a rich source of structurally diverse phytochemicals with wide-ranging therapeutic potential. Phytochemical profiling and structural elucidation have uncovered the complexity of its active constituents, from cucurbitane-type triterpenoids like charantin and momordicosides to peptides, flavonoids, and phenolics. These compounds provide the scientific basis for its traditional use and modern applications in managing diabetes, oxidative stress, infections, and even cancer. While challenges remain in standardization, bioavailability, and safety, the integration of advanced analytical methods with clinical validation holds promise for developing bitter gourd-derived nutraceuticals and pharmaceuticals. By combining traditional knowledge with modern phytochemistry, *M. charantia* continues to emerge as a plant of remarkable scientific and therapeutic significance.

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