

Simultaneously Synergistic Effects of Moringa Oleifera Aqueous Leaf Extract on Metabolic Syndrome Parameters

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ABSTRACT

Metabolic syndrome is a condition with multiple components such as central obesity, insulin resistance, hyperglycaemia, dyslipidaemia and high blood pressure and it all contributes to the risk of developing type 2 diabetes and cardiovascular disease. These abnormalities are closely linked to each other, and treatment aimed at several metabolic pathways is of great interest. *Moringa oleifera* Lam. is a tree that has been scientifically studied due to its leaves containing flavonoids, phenolic acids and other antioxidant compounds. The aqueous leaf extract is of special significance since it offers a simple and readily available approach to obtaining a number of water-soluble bioactive components. The possible synergistic effect of *M. oleifera* aqueous leaf extract in the significant metabolic syndrome parameters is reviewed here. Preliminary research indicates that it has positive effects on glucose metabolism, insulin sensitivity, lipid metabolism, oxidative stress, inflammation, and visceral adiposity. The effects of these compounds can occur through synergistic mechanisms such as insulin signalling and glucose and lipid metabolism, AMPK activity, and antioxidant defence. There is limited human evidence, though some have found to improve fasting glucose and HbA1c. In general, *M. oleifera* has been found to have good multi-target metabolic activity, however more standardized and well-designed clinical trials are needed to determine its therapeutic efficacy and confirm its true synergistic effects.

Keywords: *Moringa Oleifera, Aqueous Leaf Extract, Metabolic Syndrome, Insulin Resistance, Hyperglycaemia, Dyslipidaemia, Hypertension, Oxidative Stress, Inflammation, Synergistic Action.*

Introduction

Moringa oleifera is a tropical plant that has gained significant attention due to its nutritional and medicinal properties.

Metabolic syndrome (MetS) is not a single disease, but a constellation of related cardiometabolic conditions. These major components are central adiposity, elevated triglycerides, low high-density lipoprotein cholesterol (HDL-C), elevated blood pressure and impaired fasting glucose. The harmonized definition identifies that all three or more of these five abnormalities is enough to be diagnosed as metabolic syndrome, and the waist circumference thresholds could vary by population.

An important thing to note about metabolic syndrome is that it is a biological phenomenon caused by the interaction of its components that makes the syndrome clinically important. Hyperglycaemia, altered lipid metabolism and endothelial dysfunction can result from insulin resistance. Too much 'visceral' fat could also worsen inflammatory signalling and oxidative stress. Dyslipidaemia and hypertension are associated with vascular damage, and chronic hyperglycaemia leads to an increase in the production of reactive oxygen species and advanced glycation products. Therefore, targeting a single metabolic parameter might not be sufficient to resolve the many interrelated metabolic mechanisms involved in MetS.

This has been a boost for multifunctional nutrition and botanical interventions. If plants have multiple bioactive compounds, they can potentially affect multiple metabolic pathways simultaneously. One of these plants is *Moringa oleifera* Lam. Leaves eaten as food in many parts of the world and traditionally used for food and medicine. Recent phytochemical studies have revealed the presence of flavonoids, phenolic acids, glucosinolates, vitamins, minerals and other compounds in *Moringa* leaves. In connection to metabolic effects, the constituents that are often mentioned include quercetin, kaempferol and chlorogenic acid.

Of particular interest is the aqueous extraction as it is a relatively simple extraction method that can extract several water-soluble constituents and is similar to traditional methods of botanical use. The aqueous extracts from *Moringa* leaves have been specifically studied in models of diabetes, insulin resistance and metabolic syndrome. For instance, Jaiswal et al. studied aqueous *Moringa* leaf extract in normal and streptozotocin induced diabetic rats, and subsequent studies used aqueous leaf preparations in insulin-resistant and high-fat/high-fructose rats.

One of the major concepts that is important in the context of metabolic syndrome is the concept of synergy. Since other components of a plant can affect complementary pathways, the biological activity of multiple components of a plant might conceivably result in more extensive metabolic effects than the activity of one component alone. But, it is not a rule that mechanistic complementarity equals pharmacological synergy. To show true synergy, proper dose response, interaction models and comparison to individual components must be used in the experimental designs. Hence, in the present review, the word synergy is employed with considerable qualification, to describe interactions between metabolic pathways that are simultaneous and may be complementary.

Metabolic Syndrome: A Multidimensional Metabolic Disorder

Genetic, dietary, behavioural and environmental factors are all involved in the development of metabolic syndrome. Insulin resistance and visceral adiposity are sometimes considered key events; however, the syndrome is an umbrella of metabolic disturbances.

Fat at the center of the body causes the release of free fatty acids and adipokines from fat tissues. Elevated free fatty acids can have a negative effect on insulin signalling pathways and stimulate liver lipid production. Meanwhile, fat tissue may also be a source of inflammatory mediators. Chronic low-grade inflammation leads to an altered insulin signaling and endothelial dysfunction.

Another important factor is insulin resistance. As peripheral tissues become less sensitive to insulin, at first the pancreas's β -cells respond to insulin's challenge by raising insulin production. Ongoing metabolic stress may lead to insufficient compensation, which leads to rising blood glucose levels. Hyperglycaemia is further exacerbated by increased hepatic gluconeogenesis and changes in glucose utilization.

This pattern is often due to increased production of very-low-density lipoproteins and imbalance of lipoprotein metabolism at the liver. Triglyceride-rich particles are linked to the atherogenic cardiovascular risk.

There are multiple pathways that contribute to the etiology of hypertension including endothelial dysfunction, sympathetic activity, renal sodium handling, vascular stiffness, and insulin resistance. Nitric oxide dependent vascular relaxation may be further compromised by oxidative stress and chronic inflammation.

It is this cross-talk that makes it possible to hypothesize that a plant-based preparation that has antioxidant, glucose-regulating, lipid-modulating and vascular activities could exert broader effects than one that targets just one pathway.

Phytochemical Basis of *Moringa oleifera* Leaf Activity

Moringa leaves are packed with a plethora of bioactive compounds. Flavonoids, phenolic acids, glucosinolates and other phytochemicals have been found as significant compounds in the leaves from reviews. Some of the main flavonoids reported are quercetin, kaempferol and myricetin, whereas chlorogenic, caffeic and gallic acids are important phenolics.

• Flavonoids

The quercetin is one of the most studied *Moringa* leaf compounds. Preliminary studies indicate that quercetin can have effects on oxidative stress, lipid metabolism, vascular function and glucose regulation. Kaempferol also has antioxidant and metabolic properties.

Importantly, this pathway is not always the way that these compounds work. Their biological effects, include modulation of cellular antioxidant systems, protection against oxidative injury and influence on enzymes involved in glucose and lipid metabolism.

- **Phenolic Acids**

Another important constituent is chlorogenic acid. Experimental studies have linked chlorogenic acid to glucose metabolism via intestinal glucose handling and hepatic glucose production effects. Previous studies on the phytochemistry of Moringa leaf report that chlorogenic acid is one of the most predominant phenolic acids and its possible effect on the postprandial glucose and lipid metabolism.

Gallic and caffeic acids may also be beneficial for antioxidant and anti-inflammatory properties. Several phenolic compounds are present resulting in a biochemical environment where more than one antioxidant mechanism can be in play at a time.

- **Glucosinolates and Related Compounds**

Moringa leaves also have glucosinolates that can be enzymatically converted into bioactive metabolites. Experimental literature has suggested glucose-regulatory, antioxidant and signalling roles of these compounds. Systematic review of Moringa in diabetes revealed that glucosinolate and their metabolites, flavonoids and phenolic acids may be potential source of antidiabetic effect.

- **Nutritional Constituents**

The leaves are also a source of dietary fibre, vitamins and minerals. Dietary fibres could be beneficial for slowing down the absorption of glucose and enhancing satiety, whilst micronutrients may help to maintain normal metabolism. It is thus not necessarily possible to assign a specific biological effect to one phytochemical in whole-leaf preparations.

This is especially true with regard to the notion of synergy. The metabolic reactions to an aqueous preparation of leaves might be a result of several compounds and not necessarily of one dominant compound.

Watery Leaf Extract and Glucose Regulation

MetS is linked to a number of central metabolic abnormalities, the most important of which are hyperglycaemia and insulin sensitivity. Experimental models have shown that Moringa leaf preparations can affect glucose regulation via various mechanisms.

In experimental models, Aqueous Moringa leaf extract has been found to have antihyperglycaemic activity. Jaiswal et al. examined various doses of aqueous leaf extract in normal and diabetic rats induced by streptozotocin, and measured fasting blood glucose and oral glucose tolerance and postprandial glucose responses.

The insulin resistance, and not just hyperglycaemia, has been the subject of further experimental research. Aqueous Moringa leaf extract was also shown to reverse hepatic insulin insensitivity and insulin receptor and glucose uptake related gene expression in high-fructose rats.

This may be due to decreased intestinal glucose absorption, actions on hepatic glucose metabolism and increased peripheral glucose utilization. The complementary mechanisms through which these effects are thought to occur have been proposed as being mediated by quercetin, kaempferol and chlorogenic acid. Potential impact on SGLT1, glucose-metabolizing enzymes and cellular insulin signalling have also been discussed in the literature.

There are some limited positive human studies. In an adult double-blind randomized placebo controlled trial, people with prediabetes who took 2,400 mg of Moringa leaf powder daily for 12 weeks showed improved levels of fasting blood glucose and HbA1c compared to people who took a placebo.

Another randomized clinical trial, however, with 40 type 2 diabetics given varying amounts of Moringa leaves for 14 days, did not find that the blood glucose, blood pressure or lipid changes were statistically significant in all cases, and not dose-dependent.

So, Moringa is not a replacement for well-known diabetes treatment at the time being. Instead, the data indicate that glucose regulation may be a part of a multi-target effect.

Insulin Resistance Effect

Several characteristics of metabolic syndrome are linked to insulin resistance. Insulin sensitivity is lowered, which leads to elevated glucose production by the liver, impaired uptake of glucose by the skeletal muscle and abnormal lipid metabolism.

There is relatively strong mechanistic evidence of the potential effect of Moringa leaf extract on insulin sensitivity from animal studies. Aqueous Moringa leaf extract (300 mg/kg) has been shown to reverse hepatic insulin insensitivity and normalize insulin-related alterations in a high fructose dietary model. The research also showed modifications in the genes of the insulin receptor and hepatic glucose transporters.

A study performed in a high-fat/ high-fructose diet model revealed that Moringa leaf extract reduced hyperinsulinaemia, insulin resistance and raised LDL levels in the model.

Potential mechanisms include:

- An increase in insulin sensitivity; and
- Enhanced glucose uptake;
- Decrease in over-accumulation of liver gluconeogenesis; and
- Reduced oxidative stress related to insulin signalling;
- Modulation of inflammatory pathways; and
- Metabolic regulators, such as AMP-activated protein kinase (AMPK), may be activated.

Mechanistic review of recent literature revealed that pathways proposed for Moringa's metabolic effects include activating AMPK (amp-activated protein kinase) and inhibiting α -glucosidase and modulating glucose transport.

These mechanisms may be complementary. Increased insulin sensitivity may have multiple metabolic effects, including blood glucose, lipid metabolism and adipose-tissue function, which has a biological basis for the broad metabolic effects seen in animal models.

Effects on Lipid Profile

Dyslipidaemia is a significant part of metabolic syndrome and closely associated with insulin resistance. High triglycerides, high atherogenic lipoproteins and low HDL-C may all be associated with cardiovascular risk.

Several animal models have shown the lipid modulating effect of Moringa leaf preparations. The extracts of Moringa leaves were found to lower several metabolic abnormalities occurring in the syndrome, such as blood glucose, blood urea nitrogen (BUN) and blood lipids levels in high fat/high fructose diets rats.

The study of the bioactive compounds offers several suggestions. Quercetin has been studied for anti-dyslipidaemic effects and chlorogenic acid has been found to reduce total cholesterol and triglycerides in studies.

More recent studies have focused on Moringa leaf water extract and hyperlipidaemia. In a 2026 study, metabolomic analyses was used to determine the effect of Moringa leaf water extract on high-fat diet-induced dyslipidaemia and to identify metabolic pathways that may be implicated in the response.

However, there is variable clinical evidence. There was no consistent beneficial effect on lipids observed in the 14-day randomized clinical trial in adults with type 2 diabetes, and one group of adults with type 2 diabetes had an increase in triglycerides.

This difference serves as an example of the need to be cautious not to confuse preclinical efficacy with clinically proven efficacy in humans. Variation between studies may be due to differences in extraction method, dose, length of treatment, and baseline metabolic status and diet.

Blood Pressure and Vascular Function Effects

Another major factor of metabolic syndrome is hypertension. Enhanced oxidative stress, endothelial dysfunction and disturbed vascular signals may have effects on vascular relaxation and lead to high blood pressure.

The moringa leaf has several antioxidant and polyphenolic compounds that might have an impact on vascular function. The antihypertensive effect of Moringa preparations have been reported in experimental studies, whereas reviews have shown vascular and antioxidant properties to be some of its biological activities examined in aqueous and other leaf extracts.

In one of the recent randomized clinical studies with adults with type 2 diabetes, when Moringa leaves were given, there was a statistically significant decrease in systolic blood pressure in just one of the intervention groups, but no difference was found when the baseline values were taken into account when assessing all parameters.

The findings indicate a potential effect on blood pressure but should not yet be considered a solid effect. Possible mechanisms range from antioxidant protection of endothelial cells to an enhanced bioavailability of nitric oxide and modulation of the response of vascular smooth-muscle.

Potential for Wound Healing.10. Anti-Inflammatory and Antioxidant Properties

Oxidative stress has emerged as an important link in the chain process in the metabolic syndrome. Excessive levels of fatty acids, hyperglycaemia and dysfunction of adipose tissue can raise the levels of Reactive Oxygen Species. These molecules are able to affect proteins, lipids, and cellular membranes and can disrupt insulin signalling pathways.

Moringa leaves contain a high concentration of phenolics and flavonoids with antioxidant properties. Quercetin, kaempferol, chlorogenic acid and caffeic acid and gallic acid are some of the compounds that have been identified in the reviews as being possible to help with the antioxidant effect.

However, experimental studies have reported an increase in antioxidant defence systems after Moringa treatment. Aqueous Moringa extract decreased HOMA-IR and enhanced TAC in alloxan induced diabetic mouse model compared to the untreated diabetic animals.

Oxidative stress is closely related to inflammation. The pro-inflammatory mediators IL-6, MCP-1 and TNF- α may disrupt insulin signalling and lead to altered function of adipose and vascular tissue. Studies of Moringa's antidiabetic effects show a decrease of inflammatory and oxidative stress markers in various preclinical models.

It is possible then to think of the sequence as:

Moringa phytochemicals reduce oxidative stress, which leads to better cellular signalling, and subsequently to reduced activation of inflammation, improved insulin sensitivity, and better glucose and lipid regulation.

This is a reasonable pathway in the network and not necessarily a proven linear route.

Obesity and Visceral Adiposity Effects

One of the key criteria of metabolic syndrome is central obesity. Visceral adipose tissue (VAT) is metabolically active tissue, that causes insulin resistance through abnormal release of fatty acids and production and signaling of adipokines.

Moringa leaf preparations appear to have an effect on adiposity in animal studies. Moringa treatment was found to alleviate metabolic syndrome characteristics in a high fat/high fructose rat model, such as visceral fat and liver-weight abnormalities.

An independent study of the aqueous extracts of Moringa, rosemary and purslane in rats fed on a high-fat/high-fructose diet examined body composition, adipokines, glucose metabolism, lipid profile, inflammation and oxidative stress. Moringa was one of extracts linked to amelioration of several metabolic syndrome indicators.

But, the human direct weight-loss effects are not well established. A recent meta-analysis of RCTs investigated Moringa supplementation for the effects on body weight and blood pressure, highlighting the increased clinical research interest in these endpoints, which must be interpreted based on the specific preparation, duration and population involved.

Thus, Moringa should not be regarded as an anti-obesity drug but as a possible metabolic modulating agent.

Simultaneously Synergistic Action: An Integrated Mechanistic Model

The most interesting aspect of Moringa oleifera is not necessarily its effect on one isolated metabolic parameter, but the possibility that multiple constituents may influence interconnected pathways simultaneously.

A proposed integrated model is presented below.

Metabolic Component	Potential Action of Moringa Aqueous Leaf Constituents	Possible Downstream Effect
Hyperglycaemia	Modulation of glucose absorption and hepatic glucose metabolism	Reduced circulating glucose
Insulin resistance	Improvement of insulin signalling and glucose utilization	Improved insulin sensitivity

Dyslipidaemia	Modulation of lipid metabolism and antioxidant protection	Lower triglyceride/atherogenic lipid burden
Hypertension	Antioxidant and endothelial-supportive activity	Potential improvement in vascular function
Oxidative stress	Radical scavenging and enhancement of endogenous antioxidant defence	Reduced cellular oxidative damage
Chronic inflammation	Modulation of inflammatory signalling	Lower metabolic inflammation
Visceral adiposity	Effects on glucose/lipid metabolism and adipose signalling	Possible reduction in metabolic consequences of excess adiposity

Source: Compiled from experimental and clinical literature.

There are three levels of understanding the term “synergistic.”

First, it is possible that there is a synergy of phytochemicals. Multiple compounds can have multiple targets in the cell. Quercetin and kaempferol may be involved in oxidative and metabolic signalling while chlorogenic acid may be involved in glucose and lipid metabolism. Other biological activities may be contributed by glucosinolates and their metabolites.

Second, it could be pathway synergy. An increase in insulin sensitivity can enhance glucose and lipid metabolism. Low oxidative stress helps to protect insulin signalling. A decrease in inflammation could further increase insulin sensitivity. So, an effect in one pathway can reinforce an effect in another pathway.

Thirdly, there can be physiological synergism. Adjustments to glucose regulation, lipid metabolism, vascular function and oxidative balance may all help to decrease the metabolic load, even if the impact on any individual variable is mild.

But a crucial methodological distinction has to be noted. Simultaneous actions should not be assumed to be a pharmacological synergy. Future studies are needed to compare combinations with isolated constituents to measure interaction effects for true synergy to be established. If the experiments are not done, “synergistic” should not be claimed as a pharmacologic finding.

Evidence from Animal and Human Studies

The existing evidence demonstrates an important translational gap.

Evidence Level	Major Findings	Interpretation
In vitro studies	Antioxidant, glucose-metabolism and enzyme-modulating activities	Useful for mechanism generation
Diabetic animal models	Improvements in glucose control and antioxidant status	Strong preclinical support
High-fat/high-fructose models	Improvements in insulin resistance, lipids and metabolic-syndrome features	Supports multi-target activity
Human prediabetes trial	Favourable changes in FBG and HbA1c after 12 weeks	Preliminary clinical support
Human type 2 diabetes trial	Marginal/non-dose-dependent changes across parameters	Evidence remains inconsistent
Recent reviews/meta-analyses	Potential cardiometabolic benefits but substantial heterogeneity	Larger standardized RCTs required

The best available preclinical data are obtained by dietary induction of metabolic syndrome, using high fat and/or high fructose diets. The extracts from Moringa leaves have been found to reduce insulin resistance, dyslipidaemia, visceral adiposity and abnormalities related to these.

The human research is relatively small. An 12 week randomized controlled trial with prediabetes participants showed positive glycaemic effects from Moringa. However, another randomized adult trial failed to show consistent differences following adjustment for baseline measures in type 2 diabetes.

A 2023 narrative review of the literature revealed that animal studies reported significant benefits for the improvement of metabolic syndrome indices, but highlighted the lack of human studies. A 2025 meta-analysis of randomized controlled trials (RCTs) then combined cardiometabolic outcomes, as a growing trend to clinically assess Moringa continues.

The evidence is thus insufficient to support the further study of Moringa aqueous leaf extract as a potential remedy to metabolic syndrome, and not adequate to recommend it.

Possible Molecular Mechanisms

- **AMPK-Related Metabolic Regulation**

AMP-activated protein kinase is a key component for regulating energy balance in cells. AMPK activation is associated with increases in glucose uptake and fatty-acid oxidation, and a decrease in anabolic pathways that use energy. In mechanistic literature, moringa-related AMPK activation was postulated as one of the mechanisms for the metabolic effects of moringa.

- **Regulation of Glucose Absorption**

Some phytochemicals obtained from Moringa have been examined for the inhibitory activity against carbohydrate-digesting enzymes and glucose transport pathways. These can slow down the rate at which dietary carbohydrates enter the blood.

- **Hepatic Glucose Regulation**

The liver is a key organ in the regulation of fasting glucose levels. The enzymes that are affected by the Moringa constituents such as chlorogenic acid could involve in gluconeogenesis and glycogen metabolism.

- **Antioxidant Defence**

Moringa polyphenols may act as direct reactive species scavengers and they may be able to activate endogenous antioxidant systems like glutathione, catalase and superoxide dismutase. Studies have shown improvement in antioxidant capacity after treatment.

- **Inflammatory Signalling**

Ongoing low-grade inflammation plays a role in vascular dysfunction and insulin resistance. Experimental studies have indicated that Moringa bioactive components can regulate inflammatory mediators, which need to be confirmed in human for relevance and magnitude.

- **Lipid Metabolism**

Moringa constituents can modify the lipid synthesis, lipid oxidation and circulating lipoprotein metabolism in the liver. These effects can be combined with an increased insulin sensitivity.

All of these pathways combined offer a likely mechanism for multi-parameter activity.

Safety, Standardization and Translational Considerations

Moringa has a long history of food use but concentrated extracts are not necessarily safe to use in medicines. Previous safety evaluations were generally favorable for some preparations and animal studies, and more recent systematic literature review reiterates the importance of toxicity occurring with dosage, preparation and plant part.

One of the challenges is standardization of extracts. Moringa extract is not a chemically uniform product. Phytochemicals can be significantly modified by extraction solvent, extraction time, leaf maturity, geographic location, drying and storage.

The chemical characterisation of these aqueous extractions should, therefore, take precedence over the description based on plant weight/unit water. Future research should be reported as follows:

- botanical authentication;
- Use of botanical names;
- extraction ratio;
- extraction temperature and time;
- dry extract yield;
- total phenolic content; and
- resolution of the mixture into its individual components; and
- units of dosage: mg/kg or mg/day;
- duration of treatment;
- batch-to-batch consistency; and
- Monitoring for safety and adverse events.

These are needed for reproducibility and clinical translation.

In addition, there is a lack of current evidence regarding the effects of the program.

Limitations of Current Evidence

First, there is a large amount of evidence derived from animal experiments. The findings from streptozotocin-induced diabetes and high-fat/high-fructose-fed rats are not necessarily reflective of the metabolic syndrome of individuals with naturally occurring metabolic syndrome.

Second, different preparations are used in the studies. It is important to keep in mind that the chemical composition of whole leaf powder is different to the chemical composition of the aqueous extract, hydroalcoholic extract, and isolated phytochemicals.

Thirdly, there are relatively small and short human trials. The prediabetes trial had 65 participants and the type 2 diabetes trial had 40 participants, and both trials lasted only 12 weeks and 14 days, respectively.

Fourth, clinical results have not been consistent. Human data is available and is favourable for glycaemic parameters, though studies with less or no dose-dependent effect are also available.

Our 5th point is that there is a lack of long-term cardiovascular, diabetes prevention, and clinically important complication outcomes.

Last but not least, the term “synergy” is often applied to studies of plants without the use of any interaction tests. Future studies should thus differentiate between additive, complementary and real synergistic effects.

Future Research Perspectives

Future studies should shift from exploratory animal studies to well-designed and standardized clinical trials.

Standardized aqueous Moringa leaf extract might be compared against placebo in a multicentre randomized controlled trial (RCT) of adults with well-defined metabolic syndrome for a minimum of 12–24 weeks. Primary outcomes could include fasting glucose, HbA1c, HOMA-IR, triglycerides, HDL-C and blood pressure.

Secondary outcomes could include:

- waist circumference;
- body weight;
- LDL-C;
- inflammatory biomarkers;
- oxidative stress markers;
- liver enzymes;
- adiponectin;
- insulin;
- endothelial-function markers; and
- quality-of-life indicators.

Clinical studies should be accompanied by pharmacokinetic and phytochemical analyses. Moreover, researchers need to see if Moringa interacts with the commonly used antidiabetic, antihypertensive and lipolytic drugs.

The most important point is that the synergy hypothesis needs to be directly tested in future research. Experimental designs may include comparisons between individual compounds, standardized whole-leaf aqueous extract and defined combinations. The significance of this combined response over additive expectations might then be determined from a statistical interaction model or isobolographic approach.

Conclusion

The aqueous extract of Moringa oleifera leaves is a multifunctional botanical product that is considered a promising product for further study in the field of metabolic syndrome. This is due to the presence of several bioactive compounds, including flavonoids, phenolic acids and glucosinolate related compounds, all of which occur simultaneously. Experimental research suggests that they have effects on glucose regulation, insulin sensitivity, lipid metabolism, oxidative stress, inflammation, visceral adiposity, and possibly blood pressure.

It is also important to consider the biological plausibility of a multi-target effect because metabolic syndrome is a complex condition with multiple components. Enhancing insulin signalling might result in a dual effect on glucose and lipid metabolism, antioxidant activity can prevent oxidative damage to insulin-sensitive tissues, and reducing inflammation might put a further boost on metabolic control. The synergistic pathways are viable grounds for studying multiple and potentially synergistic effects of the various constituents of *Moringa* leaves.

However, the available evidence is limited and therefore must be used with caution. Human clinical trials are still limited, diverse and short. There was one randomisation trial conducted in prediabetes that showed beneficial glycaemic results, while a trial in adults with type 2 diabetes showed mainly marginal and non-dose dependent glycaemic effects. Based on the available literature, therefore, the hypothesis that *Moringa* aqueous leaf extract possesses wide metabolic activity is supported but the extract has not yet been proved as a therapeutic option for metabolic syndrome.

Chemically standardized aqueous extracts with appropriate powered randomized controlled trials are the most suitable directions for future. These investigations must consider the full metabolic syndrome profile instead of focusing on a single biomarker and must take into account the interaction between the key phytochemical components. Based on these observations, *Moringa oleifera* is a promising ingredient for future functional foods and/or research and should not be used as a substitute for evidence-based medical management until such evidence is available.

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