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Review Article

Precision Nutrition for Prevention of Type 2 Diabetes: Role of Diet, Microbiome and Metabolic Phenotyping

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ABSTRACT

Type 2 diabetes mellitus (T2DM) is a complex metabolic disorder whose development is influenced by dietary behavior, adiposity, physical inactivity, genetic susceptibility, insulin resistance and environmental factors. Although lifestyle modification is an established approach for delaying or preventing T2DM, individuals frequently show different metabolic responses to comparable foods and dietary patterns. This variability has contributed to growing interest in precision nutrition, which seeks to tailor dietary strategies according to an individual's metabolic characteristics, lifestyle, dietary behavior and, increasingly, biological information. The present review examines the potential contribution of diet, the gut microbiome and metabolic phenotyping to precision approaches for T2DM prevention. Particular attention is given to dietary fiber, carbohydrate quality, whole foods, ultra-processed foods, postprandial glycemic responses and dietary patterns associated with metabolic health. The gut microbiome is considered as an important intermediary between food intake and host metabolism, particularly through microbial fermentation and production of short-chain fatty acids and other bioactive metabolites. Metabolic phenotyping, including conventional biochemical measurements and emerging metabolomics approaches, may provide additional information about early metabolic dysfunction and differential responses to dietary interventions. Integration of these domains with physical activity, anthropometry and behavioral information could facilitate more individualized prevention strategies. Precision nutrition should therefore complement rather than replace established lifestyle-based prevention. Future research should emphasize population-specific models, particularly in diverse populations such as India, and should determine whether personalized dietary interventions produce sustained reductions in diabetes incidence.

Keywords: precision nutrition; type 2 diabetes mellitus; personalized nutrition; gut microbiome; dietary fiber; metabolic phenotyping; metabolomics; insulin resistance; etc.

1. INTRODUCTION

Type 2 diabetes mellitus (T2DM) is a major global public health challenge, with its prevalence increasing across both developed and developing countries. According to the International Diabetes Federation, an estimated 589 million adults aged 20–79 years were living with diabetes worldwide in 2024 and this number is projected to increase to approximately 853 million by 2050.[1] The disease does not develop suddenly in most individuals. Instead, metabolic disturbances may accumulate over several years, with insulin resistance, impaired glucose regulation and progressive deterioration of pancreatic β-cell functions. Current diabetes-prevention recommendations continue to emphasize dietary improvement, physical activity and appropriate weight management [2] The landmark Diabetes Prevention Program demonstrated the effectiveness of intensive lifestyle intervention in reducing diabetes incidence among adults with impaired glucose regulation [3,4] Systematic review and meta-analysis of 15 studies involving 8,563 adults with prediabetes found that intensive lifestyle intervention reduced the risk of developing T2DM compared with general advice.[5] Despite the effectiveness of population-level recommendations, an important limitation remains: people do not necessarily respond to food in the same way. Differences in postprandial glucose responses have been observed even when individuals consume identical meals. Such variation may arise from differences in body composition, insulin sensitivity, physical activity, habitual dietary exposure, age, genetics, gut microbiome characteristics and other physiological factors.[6]

This observation has encouraged a shift from a purely population-based approach toward precision nutrition. Precision nutrition as an emerging strategy that may help address the variable responses observed with conventional dietary approaches for obesity and T2DM risk reduction.[7] Some studies discussed the integration of postprandial glucose monitoring with gut microbiota, metabolomics, nutrigenomics, and machine-learning approaches as components of personalized nutrition.[8] More recent research reviewed the potential contribution of prebiotics, probiotics, postbiotics, and other microbiome-targeted approaches to precision nutrition.[9] Few studies specifically examined a microbiome-based precision nutrition approach for T2DM prevention and highlighted the potential use of individualized food recommendations to modify gut microbial characteristics associated with metabolic health.[10] The objective of this review is therefore to examine the relationship between diet, gut microbiome and metabolic phenotyping within the emerging framework of precision nutrition for prevention of T2DM.

2. Precision Nutrition: Concept and Rationale

Precision nutrition can be understood as an individualized approach to dietary guidance in which recommendations are informed by characteristics that differ between individuals. These may include dietary habits, anthropometric measurements, metabolic biomarkers, physical activity, sleep, behavioral factors and, in research settings, microbiome, genomic and metabolomic information. The National Institute of Diabetes and Digestive and Kidney Diseases describes precision nutrition as an emerging area in which individual characteristics may be used to understand and optimize responses to food and dietary interventions.[11] Factors potentially relevant to personalized responses include metabolic status, lifestyle and biological characteristics. In the context of T2DM prevention, precision nutrition can be viewed as a cycle: **Risk identification → dietary and metabolic assessment → individualized intervention → response monitoring → modification of dietary advice**

Such a model allows dietary recommendations to be adapted over time rather than treating nutrition as a one-time prescription.

3. Diet as the Foundation of Diabetes Prevention

3.1 Dietary pattern rather than isolated nutrients

The relationship between nutrition and T2DM cannot be explained by a single nutrient. Foods are consumed in combinations, and the metabolic effect of a meal depends on the interaction between carbohydrate, protein, fat, fiber, food structure and portion size. Dietary patterns emphasizing vegetables, legumes, whole grains, nuts, seeds and minimally processed foods have generally been associated with favorable metabolic outcomes. Current recommendations emphasize dietary quality and individualization rather than prescribing one universal macronutrient distribution for everyone.[2] Precision nutrition adds another dimension by asking whether a generally healthy dietary pattern can be adapted to an individual's response, preferences and circumstances.

3.2 Carbohydrate quality and postprandial glucose

Carbohydrate quantity is important, but the metabolic response to carbohydrate is also affected by its quality and physical form. Whole grains, legumes, vegetables and intact or minimally processed carbohydrate sources generally differ from refined grains and highly processed carbohydrate-containing foods in terms of fiber, food structure and rate of digestion.

Zeevi et al. demonstrated considerable interpersonal variation in postprandial glucose responses. Their research showed that characteristics of the individual, including dietary and microbiome-related variables, could contribute to prediction of glucose responses.[6] These findings provide a scientific basis for investigating individualized dietary strategies. For example, two people consuming a similar carbohydrate-containing meal may experience different glucose excursions. A precision approach could therefore focus on identifying an individual's response pattern rather than assuming a uniform response.

3.3 Dietary fiber and Metabolic health

Dietary fiber occupies a particularly important position within precision nutrition. Fiber can influence glucose regulation through several mechanisms, including delayed digestion and absorption, increased satiety, modulation of intestinal transit and interaction with the gut microbiota. Different fibers are not metabolically identical. Psyllium, β-glucans, resistant starch, inulin, pectin and cereal fibers differ in viscosity, fermentability and physiological effects. Therefore, future personalized dietary interventions may need to consider not only the total amount of fiber consumed but also its source, chemical characteristics, food matrix and tolerability. Fermentable fibers reach the colon where they can serve as substrates for microbial metabolism. Evidence from systematic reviews suggests that increasing dietary fiber can contribute to improvements in glycemic and metabolic outcomes, although the magnitude of benefit varies across interventions and individuals.[12]

3.4 Ultra-processed foods

The degree of food processing has become an important area of nutritional research. Ultra-processed foods frequently contain combinations of refined starches, added sugars, fats, sodium and food additives and may be energy dense while providing relatively little dietary fiber. High consumption of ultra-processed foods has been associated in observational research with several adverse health outcomes, including metabolic disorders. However, the relationship is complex because ultra-processed food consumption may also reflect broader lifestyle, socioeconomic and dietary factors.

From a precision nutrition perspective, the relevant question is not simply whether a food belongs to a processing category but how its consumption contributes to an individual's overall dietary pattern, energy intake, fiber intake, glycemic response and metabolic risk.

4. Gut Microbiome and Metabolic Health

The gastrointestinal tract contains a large and diverse microbial community that participates in digestion, nutrient transformation, immune regulation and production of biologically active compounds. Increasing evidence has linked alterations in gut microbial ecology with obesity, insulin resistance and T2DM. Systematic reviews have reported differences in microbial composition and diversity between people with T2DM and individuals without diabetes. However, considerable heterogeneity exists among studies, and no single microbial profile can currently be regarded as a definitive signature of T2DM.This variability is important for precision nutrition because microbiome composition is influenced by diet, geography, age, medication exposure, lifestyle and other environmental factors.

4.1 Diet–microbiome interaction

Diet is one of the major environmental influences on the gut microbiome. A diet rich in diverse plant foods supplies multiple substrates that can support microbial diversity and fermentation.

In contrast, diets characterized by low fiber intake and high consumption of highly processed foods may provide a different substrate environment for intestinal microorganisms.

Dietary fiber therefore represents an important bridge between nutrition and microbiome research. The metabolic effects of a fiber-rich diet may partly depend on which microorganisms are present and what metabolic pathways they possess. A systematic review of dietary interventions in T2DM found evidence that dietary modification can influence gut microbial composition and microbial metabolites, although substantial differences between studies limit definitive conclusions.[13]

4.2 Short-chain fatty acids

Short-chain fatty acids (SCFAs), particularly acetate, propionate and butyrate, are among the best-characterized products of microbial fermentation. SCFAs may influence host metabolism through several mechanisms. They can interact with receptors expressed on intestinal and immune cells and influence secretion of gut hormones, intestinal barrier integrity and immune responses. Butyrate is also an important energy source for colonocytes. These observations suggest that the metabolic consequence of a particular dietary fiber may depend partly on the functional capacity of the individual's gut microbial community. Thus, the future of microbiome-based nutrition may involve moving from a simple question— “Which bacteria are present?”—toward a more functional question— “Which metabolic activities are occurring in the gut?”

5. Metabolic Phenotyping and Early Identification of Risk

5.1 Concept of metabolic phenotyping

Metabolic phenotyping refers to the characterization of an individual's metabolic state using measurable physiological and biochemical markers. It may include fasting glucose, insulin, HbA1c, lipid profiles, liver enzymes and measures of insulin resistance, as well as more advanced technologies such as metabolomics. These markers can provide complementary information. For example, two individuals may have similar fasting glucose values but different insulin concentrations or body-fat distributions. Combining multiple characteristics may therefore provide a more informative picture of metabolic risk than relying on a single marker.

5.2 Metabolomics

Metabolomics expands metabolic phenotyping by measuring large numbers of small molecules in biological samples. Analytical platforms such as mass spectrometry and nuclear magnetic resonance spectroscopy can identify patterns of metabolites related to physiological processes.

A systematic review and meta-analysis involving 71,196 participants and 11,771 diabetes events identified associations between T2DM risk and multiple amino acids, lipids, carbohydrates and other metabolites.[14] A metabolite that predicts future diabetes may reflect an underlying metabolic disturbance rather than being an independent cause of disease. Consequently, metabolomics is currently more valuable as a research and risk-stratification tool than as a stand-alone basis for prescribing individualized diets.

6. Integration of Diet, Microbiome and Metabolic Phenotyping

The greatest potential of precision nutrition may lie in combining multiple sources of information rather than examining each factor independently. Diet supplies substrates to the gastrointestinal tract. Microorganisms transform some of these substrates into metabolites, which can interact with host tissues. The resulting physiological response is influenced by insulin sensitivity, body composition, physical activity and other factors.

The overall relationship can be conceptualized as:

Dietary exposure → intestinal substrate availability → microbial metabolism → microbial metabolites → host signaling → metabolic response

For example, the same fiber-rich food may produce different physiological effects in two individuals because of differences in habitual diet, microbiome function, insulin sensitivity or physical activity. A multidimensional assessment can therefore be used to develop a more individualized dietary strategy.

Table 1. Potential Components of a Precision Nutrition Assessment

Assessment domain	Examples of information	Potential relevance to diabetes prevention
Anthropometry	BMI, waist circumference, body composition	Assessment of adiposity and metabolic risk
Dietary intake	Energy, carbohydrate quality, fiber, food processing	Identification of dietary exposures
Glycemic profile	Fasting glucose, HbA1c, postprandial glucose	Characterization of glucose regulation
Insulin-related measures	Fasting insulin, HOMA-IR where appropriate	Assessment of insulin resistance
Lipid profile	Triglycerides, HDL-C, LDL-C	Cardiometabolic risk assessment
Microbiome	Diversity, microbial taxa and functional pathways	Evaluation of diet–micro biome interactions
Metabolomics	Amino acids, lipid metabolites and other small molecules	Identification of metabolic signatures
Lifestyle	Physical activity, sedentary behavior, sleep	Identification of metabolic modifiers
Behavioral factors	Preferences, food access, adherence and motivation	Development of sustainable interventions

Source: *Zeevi et al. (2015), Guasch-Ferré et al. (2022), NIDDK (2024) and American Diabetes Association Professional Practice Committee (2026).*

A practical precision nutrition program could follow several stages.

Stage 1: Risk assessment

Initial assessment may include anthropometric measurements, family history, dietary habits, physical activity and conventional metabolic indicators.

Stage 2: Dietary characterization

A detailed dietary history can identify major carbohydrate sources, fiber intake, food processing, meal timing, portion size and dietary diversity.

Stage 3: Metabolic characterization

Glucose and HbA1c can be combined with other clinically appropriate metabolic measures. In selected research settings, postprandial glucose monitoring may provide additional information.

Stage 4: Individualized dietary intervention

Dietary recommendations can then be adapted to the person's metabolic profile, food preferences, cultural practices, affordability and capacity for adherence.

Stage 5: Monitoring

Changes in body weight, waist circumference, dietary behavior and metabolic markers can be evaluated periodically.

Stage 6: Adjustment

The dietary plan can be modified according to the observed response and practical barriers to adherence. This iterative process is central to the concept of precision nutrition.

7. Evidence for Personalized Dietary Interventions

The scientific foundation for personalized nutrition comes partly from studies demonstrating variation in individual responses to food. Zeevi et al used extensive clinical and microbiome information to investigate postprandial glucose responses.[6] Their findings demonstrated that substantial variation existed between individuals and that personalized prediction was possible using multiple characteristics. Subsequent intervention research has begun examining whether such predictions can improve metabolic outcomes. A randomized dietary pilot trial in people with newly diagnosed T2DM compared a personalized postprandial-targeting diet with a Mediterranean-style diet. The personalized approach used clinical and microbiome characteristics to predict individual postprandial glucose responses.[6] Such research is important because the ultimate value of precision nutrition should not be judged merely by its ability to predict a biological response. Therefore, precision nutrition should currently be regarded as an evolving framework rather than a universally established clinical intervention.

8. Precision Nutrition in Prediabetes

Prediabetes provides an important opportunity for preventive nutrition because metabolic abnormalities may be modified before persistent hyperglycemia develops. Lifestyle interventions have demonstrated that diabetes can be delayed or prevented in high-risk individuals. The Diabetes Prevention Program reported a substantial reduction in diabetes incidence among participants receiving intensive lifestyle intervention.[4] The current 2026 ADA Standards emphasize weight management, healthy eating patterns and regular physical activity for people at increased risk of T2DM.[2] Precision nutrition can complement these established strategies by helping answer practical questions about individual response.

Table2. Potential Precision Nutrition Strategies for T2DM Prevention

Strategy	Possible application
Improve carbohydrate quality	Replace refined carbohydrate sources with minimally processed alternatives
Increase fiber diversity	Include legumes, whole grains, vegetables, fruits, nuts and seeds according to tolerance
Modify meal composition	Combine carbohydrate sources with protein, fiber and healthy fats when appropriate
Individualize portion sizes	Adapt energy intake to metabolic goals and body composition
Monitor postprandial responses	Identify individual glucose-response patterns in appropriate research or clinical settings
Reduce excessive ultra-processed food intake	Improve overall dietary quality and reduce energy-dense food exposure
Encourage regular physical activity	Improve insulin sensitivity and metabolic flexibility
Consider meal timing	Explore individual responses to timing and distribution of meals
Use microbiome/metabolic information in research	Investigate biological mechanisms underlying dietary responses
Incorporate behavioural fctors	Improve adherence and long-term sustainability

These strategies illustrate that precision nutrition can include relatively simple dietary modifications as well as advanced biological assessment. The level of personalization should be proportional to the available evidence.

9. Digital Technologies and Continuous Glucose Monitoring

Digital technologies are creating new possibilities for individualized nutrition research. Smartphone applications can record dietary intake, physical activity and other lifestyle variables, while wearable devices can provide information about movement and sleep. Continuous glucose monitoring (CGM) can provide detailed information about glucose fluctuations throughout the day. When glucose data are combined with meal records, it may be possible to identify individual patterns of postprandial response. However, CGM data require careful interpretation. Glucose variability can be influenced by exercise, stress, sleep, illness and other factors in addition to food intake. Therefore, a single glucose excursion should not automatically be interpreted as evidence that a food is harmful.

10. Relevance to Indian Populations

India presents a particularly important setting for research on precision nutrition because of its substantial dietary, cultural and socioeconomic diversity. Traditional Indian diets can include cereals, pulses, vegetables, fruits, dairy products, nuts, seeds, fermented foods and numerous regional preparations. At the same time, urbanization and changing lifestyles have increased exposure to refined cereals, sugar-sweetened beverages, convenience foods and ultra-processed products in many populations. The nutritional response to these foods may also interact with physical activity, body composition and other metabolic characteristics. Consequently, precision nutrition models developed in European or North American populations cannot automatically be assumed to perform equally well in Indian populations. Research should also consider regional variation. Dietary practices in North, South, East and Northeast India differ considerably. Therefore, population-specific validation is essential.

11. CONCLUSION

Precision nutrition provides a promising framework for improving the prevention of T2DM by acknowledging that individuals differ in their responses to food and lifestyle interventions. Diet remains the fundamental component of prevention, while the gut microbiome and metabolic phenotype provide potentially important explanations for some of the variation in dietary response. Dietary fiber is particularly relevant because it can simultaneously influence glucose regulation, satiety and microbial metabolism. The gut microbiome may act as an intermediary through the production of SCFAs and other bioactive metabolites. Metabolic phenotyping and metabolomics may provide additional information about early metabolic dysfunction and future diabetes risk. Nevertheless, the current evidence does not support the routine use of expensive microbiome or metabolomic testing for every individual at risk of diabetes. Established preventive measures—including healthy dietary patterns, appropriate weight management, regular physical activity and behavioral support—remain fundamental.

The most realistic future model is therefore an integrated one in which conventional nutrition science forms the foundation and precision technologies are added where evidence demonstrates additional value. Research involving diverse populations, particularly Indian populations, will be essential for determining whether personalized nutrition can produce sustainable improvement in metabolic health and reduce the incidence of T2DM.

Declaration by Author

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