

Non-Invasive Assessment of Skin Carotenoid Biomarkers in Children Using the Veggie Meter®: Implications for Public Health Nutrition

Running Title: Veggie Meter® for Paediatric Nutrition Assessment

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Abstract: Background: Adequate fruit and vegetable intake is essential for optimal growth, development, and overall health in children; however, conventional dietary assessment methods are often limited by recall and reporting bias. **Methodology:** This review evaluated the utility of the Veggie Meter® as a non-invasive tool for assessing skin carotenoid biomarkers among paediatric populations. A comprehensive literature search was conducted using multiple electronic databases and relevant nutrition and public health journals.

Conclusion: The findings indicate that skin carotenoids are reliable objective biomarkers of fruit and vegetable intake, and the Veggie Meter® provides a rapid, practical, and reproducible assessment approach for paediatric and public health nutrition research.

Keywords: Children, Fruit and vegetable intake, Nutritional biomarkers, Paediatric nutrition, Public health nutrition, Skin carotenoids, Veggie Meter®

1. Introduction

1.1 Importance of Fruits and Vegetables and Carotenoids in Children

Fruits and vegetables are essential components of a healthy diet and play a critical role in the growth, development, and overall well-being of children. They provide important nutrients, including vitamins, minerals, dietary fiber, and various bioactive compounds necessary for optimal physical and cognitive development [1,2]. Adequate consumption of fruits and vegetables during childhood has been associated with a reduced risk of chronic diseases such as obesity, cardiovascular diseases, and type 2 diabetes later in life [2,3]. However, despite their recognized health benefits, fruit and vegetable intake among children frequently remains below recommended levels, emphasizing the need for effective strategies to monitor and improve dietary behaviours [1,4].

Among the bioactive compounds present in fruits and vegetables, carotenoids have gained substantial attention because of their health-promoting properties. Carotenoids, including α -carotene and β -carotene, possess antioxidant activity and contribute to immune function, visual health, and cellular protection [3]. Higher

dietary intake of carotenoid-rich foods has been positively associated with increased serum carotenoid concentrations, indicating their bioavailability and nutritional significance. Furthermore, emerging evidence suggests that carotenoid status may also be associated with cognitive performance and intellectual abilities in children, highlighting their broader importance in paediatric health [5].

1.2 Skin Carotenoids as Nutritional Biomarkers

In recent years, skin carotenoids have emerged as promising non-invasive biomarkers for assessing fruit and vegetable intake. Skin carotenoid levels can be measured using optical techniques such as resonance Raman spectroscopy and reflection spectroscopy, providing an objective estimate of dietary carotenoid intake [6,7]. Several studies have demonstrated significant correlations between fruit and vegetable consumption and skin carotenoid concentrations, supporting their validity as biomarkers of dietary behaviour [6,8].

The use of skin carotenoids as biomarkers has become increasingly important in paediatric nutrition research because objective indicators may provide more

reliable dietary assessment compared to self-reported methods. Additionally, intervention programs such as school gardening initiatives, nutrition education, and dietary improvement programs have demonstrated increases in skin carotenoid levels among children, reflecting positive changes in dietary intake and nutritional behaviours [7,9].

1.3 Limitations of Conventional Dietary Assessment Methods

Although assessment of dietary intake is fundamental in nutritional research and public health practice, conventional dietary assessment methods have several limitations. Commonly used approaches, including 24-hour dietary recalls, food frequency questionnaires, and food diaries, rely heavily on self-reporting and are therefore susceptible to recall bias, social desirability bias, and underreporting of dietary intake [10,11]. These challenges are particularly pronounced among children, who may experience difficulty accurately recalling foods consumed or estimating portion sizes [12].

Furthermore, traditional dietary assessment methods can be time-consuming, resource-intensive, and dependent on trained personnel for accurate data collection and interpretation [11]. Such limitations may reduce the accuracy and feasibility of

dietary assessment in large-scale paediatric and community-based nutrition studies. Consequently, there is increasing interest in the development of objective, rapid, and non-invasive methods for evaluating dietary intake and nutritional status.

1.4 Veggie Meter® and Its Public Health Relevance

The Veggie Meter® has emerged as an innovative non-invasive tool for assessing skin carotenoid levels and estimating fruit and vegetable intake. The device utilizes pressure-mediated reflection spectroscopy to provide an objective measure of carotenoid status, thereby minimizing the dependence on self-reported dietary data and associated measurement errors [13,14]. Studies have demonstrated high reliability and reproducibility of Veggie Meter® measurements, supporting its utility as a robust nutritional assessment tool [13].

The portability, rapid assessment capability, and non-invasive nature of the Veggie Meter® make it particularly suitable for use in paediatric populations and community-based settings such as schools and health clinics [14,15]. In paediatric nutrition, the device can assist in monitoring fruit and vegetable intake, evaluating the effectiveness of dietary interventions, and identifying children at

risk of poor dietary quality. In public health nutrition, Veggie Meter® may contribute to nutrition surveillance, intervention monitoring, and assessment of dietary patterns in vulnerable populations, including children affected by food insecurity or inadequate nutrition [15,16].

Despite its promising applications, the Veggie Meter® also has certain limitations. Although it provides an objective assessment of carotenoid intake, it does not capture other important aspects of dietary intake, such as overall dietary diversity or macronutrient consumption. In addition, factors including skin pigmentation, lifestyle characteristics, and population-specific dietary patterns may influence skin carotenoid measurements. Therefore, the Veggie Meter® should be considered a complementary nutritional assessment tool rather than a complete replacement for conventional dietary assessment methods.

Given the growing interest in objective nutritional biomarkers and non-invasive dietary assessment techniques, understanding the role of skin carotenoid biomarkers and the application of Veggie Meter® in children is of considerable importance. Therefore, this review aims to evaluate the utility of Veggie Meter® in assessing skin carotenoid biomarkers among children and to explore its

implications for paediatric and public health nutrition.

1.5 Rationale of the Study

Adequate fruit and vegetable intake is essential for children's growth, development, and overall health; however, intake levels often remain below recommended guidelines. Conventional dietary assessment methods are frequently limited by recall bias and reporting inaccuracies, particularly in paediatric populations. In recent years, skin carotenoids have emerged as objective biomarkers of fruit and vegetable intake. The Veggie Meter®, a non-invasive device based on reflection spectroscopy, provides a rapid and reliable approach for assessing skin carotenoid levels. Therefore, this review was undertaken to evaluate the utility of the Veggie Meter® in paediatric and public health nutrition research.

2. Objectives of the Study

- To review the role of carotenoids and skin carotenoid biomarkers in assessing fruit and vegetable intake among children.
- To evaluate the utility, principle, reliability, and validity of the Veggie Meter® as a non-invasive tool for nutritional assessment in paediatric populations.

- To examine the association between skin carotenoid levels, dietary intake, and child health outcomes, along with factors influencing skin carotenoid status.
- To explore the public health nutrition implications, limitations, research gaps, and future applications of the Veggie Meter® in paediatric nutrition research and interventions.

3. Methodology

3.1 Type of Review

The present study was conducted as a narrative review to evaluate the role of the Veggie Meter® in assessing skin carotenoid biomarkers among children and its implications in paediatric and public health nutrition.

3.2 Literature Search Strategy

A comprehensive literature search was conducted to identify relevant studies related to skin carotenoids, Veggie Meter®, fruit and vegetable intake, nutritional biomarkers, and paediatric nutrition. Relevant peer-reviewed articles were screened and reviewed systematically to gather evidence related to the objectives of the review.

3.3 Databases Searched

A comprehensive literature search was conducted using multiple electronic databases to identify relevant peer-reviewed studies related to skin carotenoids, Veggie Meter®, fruit and vegetable intake, biomarkers, paediatric nutrition, and public health nutrition. The databases searched included PubMed, Scopus, Google Scholar, Web of Science, Frontiers, Nutrients, Current Developments in Nutrition, Proceedings of the Nutrition Society, and other relevant nutrition and public health journals. Relevant dissertations, review articles, intervention studies, and observational studies published in English were also considered for inclusion in the review.

3.4 Search Keywords

The search strategy included combinations of the following keywords: “Veggie Meter®,” “skin carotenoids,” “children,” “fruit and vegetable intake,” “nutritional biomarkers,” “paediatric nutrition,” “reflection spectroscopy,” “dietary assessment,” and “public health nutrition.”

3.5 Inclusion Criteria

Studies were included based on the following criteria:

- Peer-reviewed articles published in English
- Studies related to Veggie Meter® or skin carotenoid assessment
- Studies involving children, adolescents, or paediatric populations
- Articles focusing on fruit and vegetable intake, nutritional biomarkers, or dietary assessment
- Original research articles, review articles, and intervention studies

3.6 Exclusion Criteria

The following studies were excluded:

- Non-English publications
- Studies not related to skin carotenoids or Veggie Meter®
- Animal studies
- Conference abstracts, editorials, and unpublished reports
- Studies lacking sufficient methodological or outcome information

3.7 Selection of Articles

Relevant articles were initially screened based on titles and abstracts. Full-text articles meeting the inclusion criteria were

further reviewed for eligibility and relevance to the objectives of the study.

3.8 Data Extraction and Synthesis

Relevant information, including study characteristics, population details, assessment methods, major findings, and public health implications, was extracted and synthesized narratively under relevant thematic headings.

4. Results & Discussions

4.1 Overview of Carotenoids and Child Health

Carotenoids are naturally occurring bioactive compounds present in fruits and vegetables that play an important role in child growth, development, and overall health. Due to their antioxidant and anti-inflammatory properties, carotenoids contribute to cognitive function, metabolic health, immune support, and visual development. Recent studies have also highlighted the significance of carotenoid exposure during prenatal and early life stages in influencing neurodevelopmental and health outcomes in children. Table 1 summarizes major studies demonstrating the role of carotenoids in various aspects of child health.

Table 1: Summary of Studies on Carotenoids and Child Health

Population/Study Group	Type of Carotenoid	Major Findings	Health Outcome	Supporting Studies
School-aged children	Skin carotenoids	Higher carotenoid levels associated with better intellectual abilities	Cognitive development	Rosok L, et al. [17]
Children	Skin carotenoids	Positive association with academic performance and math skills	Cognitive function	Yen T, et al. [5]
Mexican American children	α -carotene, β -carotene	Inverse association with obesity and triglycerides	Metabolic health	Mummidi S, et al. [18]
Children with obesity	Mixed carotenoids	Reduced BMI and adipose tissue	Obesity management	Canas J, et al. [19]
Pregnant women	Dietary carotenoids	Reduced risk of adverse pregnancy outcomes	Prenatal health	Wegner L, et al. [20]
Infants	Human milk carotenoids	Supports vitamin A and visual development	Infant health	Zaidi Y, et al. [21]
Review study	Multiple carotenoids	Antioxidant and anti-inflammatory effects	Overall health	Crupi P, et al. [22]

Overall, current evidence highlights the significant role of carotenoids in supporting cognitive development, metabolic health, and overall well-being in children. Their antioxidant and anti-inflammatory properties further contribute to their protective health effects. The growing body of literature also emphasizes the importance of adequate carotenoid intake during prenatal, infancy, and childhood stages. However, variations in dietary intake, lifestyle factors, and individual characteristics may influence carotenoid status, indicating the need for

further research to better understand their long-term health implications in paediatric populations.

4.2 Skin Carotenoids as Objective Nutritional Biomarkers

Skin carotenoids have emerged as promising objective nutritional biomarkers for assessing fruit and vegetable intake. These naturally occurring pigments accumulate in the skin and can be measured non-invasively using techniques such as resonance Raman spectroscopy (RRS) and reflection spectroscopy. Unlike

conventional dietary assessment methods that rely on self-reporting, skin carotenoid measurements provide a more objective and reliable indicator of dietary carotenoid intake and overall nutritional status. Recent studies have demonstrated strong associations between skin carotenoid

levels, dietary behaviours, and various health outcomes across different populations. Table 2 summarizes key studies highlighting the role of skin carotenoids as objective nutritional biomarkers.

Table 2: Studies on Skin Carotenoids as Objective Nutritional Biomarkers

Population	Measurement Technique	Major Findings	Significance	Supporting Studies
Preschool children	RRS	Higher skin carotenoids associated with greater fruit and vegetable intake and preference	Dietary assessment	Scarmo S, et al. [23]
Adults	Reflection spectroscopy	Skin carotenoids correlated with plasma carotenoid concentrations	Alternative to serum biomarkers	Jahns L, et al. [24]
Adults	Reflection spectroscopy	Associated with lower metabolic syndrome and circulatory disease risk	Metabolic health monitoring	Matsumoto M, et al. [25]
Children	Skin carotenoid assessment	Higher carotenoid levels linked with better cognitive performance	Cognitive development	Rosok L, et al. [17]
Older adults	Skin carotenoid assessment	Differentiated cognitively normal individuals from Alzheimer's disease patients	Neurological health	Keller JE, et al. [26]
Adults	RRS	Reliable measurements; affected by sun exposure	Methodological considerations	Scarmo S, et al. [23]
Community populations	Veggie Meter™	Portable and feasible for large-scale assessments	Public health application	Amoah ID, et al. [27]
General population	Reflection spectroscopy	Practical non-invasive assessment method	Nutritional screening	Ermakov IV, et al. [28]

Overall, current evidence supports the use of skin carotenoids as reliable and non-invasive biomarkers of fruit and vegetable intake. Their strong association with dietary intake, serum carotenoid concentrations, and various health outcomes highlights their potential utility in nutritional assessment and public health research. However, factors such as skin pigmentation, sun exposure, seasonality, and demographic variations may influence measurements, emphasizing the importance of context-specific validation and careful interpretation of results.

4.3 Principle and Working Mechanism of Veggie Meter®

The Veggie Meter® is a non-invasive device designed to assess skin carotenoid levels as an objective biomarker of fruit and vegetable intake. The device operates using pressure-mediated reflection spectroscopy, a technique that measures light reflected from the skin to estimate carotenoid concentrations. Since carotenoids accumulate in the skin following the consumption of carotenoid-rich foods, skin carotenoid levels can serve as an indirect indicator of dietary fruit and vegetable intake [29,30].

The Veggie Meter® provides rapid, painless, and non-invasive measurements, making it particularly suitable for use in

children, older adults, and community-based populations. During assessment, the participant places a fingertip on the device sensor, where controlled pressure minimizes the influence of blood flow and improves measurement consistency [31]. The portability and ease of operation of the Veggie Meter® further support its application in large-scale nutritional and public health studies.

4.4 Reliability and Validity of Veggie Meter®

Several studies have demonstrated the reliability and validity of the Veggie Meter® as a tool for assessing skin carotenoid status (Table 3). The device has shown high reliability, with Pearson correlation coefficients ranging from 0.97 to 0.99 across repeated measurements, indicating excellent consistency. In addition, the Veggie Meter® exhibits low measurement error, with reported coefficients of variation ranging between 4.0% and 5.2%, supporting its precision in nutritional assessment [13].

The validity of the Veggie Meter® has also been established through significant correlations between skin carotenoid levels and self-reported fruit and vegetable intake, as well as plasma carotenoid concentrations [30,32]. The device has been successfully applied across diverse

populations, including children, low-income adults, and older adults, demonstrating its versatility and feasibility

in different research and public health settings [15,31].

Table 3: Reliability and Validity of Veggie Meter® in Different Populations

Population	Major Findings	Key Outcome	Supporting Studies
General population	Pearson correlation coefficients ranged from 0.97–0.99	High reliability	Patel VV, et al. [13]
General population	Coefficient of variation between 4.0%–5.2%	Low measurement error	Patel VV, et al. [13]
Adults	Significant correlation with dietary intake	Validity as biomarker	May K, et al. [30]
Community populations	Correlation with self-reported fruit and vegetable intake	Dietary assessment utility	Martinelli S, et al. [32]
Children and older adults	Non-invasive and feasible for diverse populations	Practical applicability	Schweitzer A, et al. [31]
Low-income adults	Successfully used in public health settings	Community nutrition assessment	Di Noia J, et al. [15]

Overall, the Veggie Meter® represents a reliable and practical tool for the non-invasive assessment of skin carotenoid levels. Its rapid assessment capability, portability, and strong validity support its use in nutritional research and public health practice. However, factors such as skin pigmentation, hydration status, and environmental conditions may influence measurements, indicating the need for standardized protocols and complementary dietary assessment methods for comprehensive nutritional evaluation.

4.5 Studies on Veggie Meter® Among Children

The Veggie Meter® (VM®) has gained increasing attention as a non-invasive tool for assessing fruit and vegetable intake among children through the measurement of skin carotenoid scores (SCS). Recent studies have demonstrated its utility in evaluating dietary intake, monitoring nutrition interventions, and assessing healthy eating behaviours in paediatric populations. Research conducted in preschoolers, school-aged children, and adolescents suggests that the Veggie

Meter® is a reliable and feasible tool for use in both clinical and community-based settings. Table 4 summarizes major studies

evaluating the application of Veggie Meter® among children.

Table 4: Studies on the Use of Veggie Meter® Among Children

Population/Setting	Major Findings	Significance	Supporting Studies
Preschool children	Significant correlation between skin carotenoid scores and observed as well as parent-reported fruit and vegetable intake	Validity of Veggie Meter®	Hasnin S, et al. [33]
Children aged 9–13 years, New Zealand	High reliability with low measurement error	Reliable biomarker assessment	Patel VV, et al. [13]
Elementary school children	Weak but significant correlation between VM® scores and self-reported vegetable intake	School-based dietary assessment	Martinelli S, et al. [32]
Low-income children in school nutrition program	Veggie Meter® used to monitor vegetable intake during garden-enhanced nutrition education	Nutrition intervention monitoring	Khalil M, et al. [7]
Preschool children	Significant increase in skin carotenoid scores following food-based science learning intervention	Impact of educational interventions	Dixon J, et al. [34]
Elementary and junior high school students	Increased skin carotenoid scores after dietary education	Nutrition awareness and behaviour change	Obana A, et al. [35]
Adolescents	Positive association between skin carotenoid scores and Mediterranean diet adherence	Healthy dietary pattern assessment	Caparello G, et al. [14]
Indigenous families	Higher skin carotenoid scores associated with healthier diet quality and family dietary patterns	Household and community nutrition assessment	Sisson SB, et al. [36]

Overall, existing evidence supports the Veggie Meter® as a promising tool for objectively assessing fruit and vegetable intake among children. Its non-invasive nature, portability, and ease of use make it particularly suitable for paediatric and

school-based settings. Furthermore, the device has demonstrated utility in evaluating dietary interventions and promoting nutrition education. However, factors such as skin pigmentation, environmental influences, and variations in

dietary patterns may affect skin carotenoid measurements. Therefore, the Veggie Meter® should be used alongside other dietary assessment approaches to provide a more comprehensive evaluation of children's nutritional status and dietary behaviours.

4.6 Association Between Skin Carotenoids and Dietary Intake

Skin carotenoids are widely recognized as objective biomarkers of fruit and vegetable intake due to their strong association with dietary consumption of carotenoid-rich foods. Numerous studies have

demonstrated that higher intake of fruits and vegetables is associated with increased skin carotenoid concentrations, supporting the use of skin carotenoid assessment in nutritional and public health research. In addition to dietary intake, several demographics, physiological, and lifestyle-related factors may influence skin carotenoid levels. Understanding these factors is important for accurate interpretation of skin carotenoid measurements. Table 5 summarizes major factors associated with variations in skin carotenoid levels.

Table 5: Factors Affecting Skin Carotenoid Levels

Factor	Major Findings	Supporting Studies
Age	Older adults tend to have higher skin carotenoid levels, whereas younger children often show higher scores than older children	Sisson SB, et al. [36]; Okada E, et al. [37]
Gender	Females generally demonstrate higher skin carotenoid levels than males, although findings may vary across populations	Sisson SB, et al. [36]
BMI	Higher BMI and obesity are associated with lower skin carotenoid levels	Sisson SB, et al. [36]; Okada E, et al. [37]; Knaggs H, et al. [38]
Dietary habits	Increased consumption of fruits and vegetables is positively associated with higher skin carotenoid scores	Ahm S, et al. [8]
Dietary patterns	Adherence to healthy dietary patterns such as the Mediterranean diet is linked with elevated skin carotenoid levels	Augimeri G, et al. [39]
Smoking	Smoking is negatively associated with skin carotenoid concentrations	Knaggs H, et al. [38]

Physical activity	Higher physical activity and healthy lifestyle behaviours are associated with improved skin carotenoid status	Augimeri G, et al. [39]
Environmental/Lifestyle factors	Gardening practices and healthy lifestyle behaviours contribute to higher carotenoid levels	Clarke ED, et al. [40]

Overall, current evidence indicates that skin carotenoid levels are strongly influenced by fruit and vegetable intake and can effectively reflect dietary quality. However, factors such as age, gender, body composition, smoking habits, physical activity, and broader lifestyle behaviours may also affect skin carotenoid concentrations. Therefore, these variables should be carefully considered while interpreting skin carotenoid measurements in research and public health settings. Additionally, dietary interventions aimed at increasing fruit and vegetable consumption may contribute to improved carotenoid status and better health outcomes across different populations.

4.7 Advantages of Veggie Meter® in Paediatric Populations

The Veggie Meter® offers several advantages for assessing dietary intake and nutritional status in paediatric populations. As a non-invasive device that measures skin carotenoid levels, it provides an objective biomarker of fruit and vegetable intake and has gained increasing attention in paediatric nutrition research and public health practice. Its rapid assessment capability, ease of use, and applicability in school and community settings make it a valuable tool for evaluating dietary behaviours and nutrition interventions among children and adolescents. Table 6 summarizes the major advantages and applications of the Veggie Meter® in paediatric populations.

Table 6: Advantages of Veggie Meter® in Paediatric Populations

Advantage	Description	Supporting Studies
Non-invasive assessment	Provides painless and child-friendly measurement of skin carotenoid levels	Caparello G, et al. [14]; Martinelli S, et al. [32]
Rapid results	Offers immediate assessment and feedback regarding fruit and vegetable intake	Obana A, et al. [35]
Objective dietary assessment	Minimizes recall bias and limitations associated with self-reported dietary methods	May K, et al. [30]; Martinelli S,

		et al. [32]
Correlation with healthy dietary patterns	Positively associated with Mediterranean diet adherence and healthy eating behaviours	Caparello G, et al. [14]
Educational tool	Supports nutrition education and encourages healthier food choices among children	Obana A, et al. [35]
Promotes behavioural change	Increased willingness to try fruits and vegetables following food-based learning interventions	Dixon J, et al. [34]
Versatility in different settings	Successfully implemented in schools, Head Start centres, and community-based programs	Martinelli S, et al. [32]; Dixon J, et al. [34]
Evaluation of nutrition interventions	Useful for monitoring the effectiveness of dietary and educational interventions	May K, et al. [30]; Sisson SB, et al. [36]
Association with health outcomes	Higher skin carotenoid scores linked with healthier diet quality and lower obesity risk	Sisson SB, et al. [36]

Overall, the Veggie Meter® represents a practical, reliable, and child-friendly tool for assessing fruit and vegetable intake in paediatric populations. Its ability to provide rapid and objective measurements makes it particularly valuable in schools, community nutrition programs, and research settings. In addition to dietary assessment, the device has demonstrated potential as an educational and behavioural intervention tool for promoting healthier eating habits among children. However, while the Veggie Meter® serves as a useful proxy for fruit and vegetable intake, it should ideally be used alongside conventional dietary assessment methods to provide a more comprehensive evaluation of children's nutritional status and dietary behaviours.

4.8 Limitations and Challenges

Despite its growing application in nutritional assessment, the Veggie Meter® (VM®) has certain limitations and challenges that should be considered while interpreting skin carotenoid measurements. Variability in measurement accuracy may occur due to demographic and physiological factors such as age, ethnicity, body mass index (BMI), and skin pigmentation. Studies have reported that higher BMI is associated with lower skin carotenoid scores, while variations in skin melanin may influence the correlation between skin and plasma carotenoid concentrations, potentially affecting accuracy among individuals with darker skin tones [15,41].

Another important limitation is the relatively weak to moderate correlation

between Veggie Meter® scores and self-reported fruit and vegetable intake (Table 7). For example, studies among school children and adults have demonstrated only modest correlations between skin carotenoid scores and dietary intake data, suggesting that additional factors may

influence skin carotenoid concentrations [32,41]. Furthermore, although the Veggie Meter® has shown promising reliability, additional validation studies are required to confirm its applicability across diverse populations and settings [13,15].

Table 7: Limitations and Challenges of Veggie Meter®

Limitation/Challenge	Description	Supporting Studies
Measurement variability	Influenced by age, ethnicity, BMI, and physiological factors	Di Noia J, et al. [15]
Skin pigmentation influence	Skin melanin may affect carotenoid measurements	Jilcott Pitts SB, et al. [41]
Weak to moderate dietary correlations	Variable association between VM® scores and self-reported dietary intake	Martinelli S, et al. [32]
Need for further validation	Additional studies required across different populations and settings	Patel VV, et al. [13]; Di Noia J, et al. [15]

Overall, while the Veggie Meter® represents a promising tool for non-invasive nutritional assessment, careful consideration of demographic, physiological, and environmental factors is necessary for accurate interpretation of results. The device should preferably be used alongside conventional dietary assessment methods for comprehensive nutritional evaluation.

4.9 Public Health Nutrition Implications

The Veggie Meter® has important implications for paediatric and public health nutrition due to its ability to provide

rapid, objective, and non-invasive assessment of fruit and vegetable intake, as shown in Table 8. Unlike traditional self-reported dietary assessment methods, the Veggie Meter® minimizes reporting bias and offers a practical approach for evaluating dietary behaviours in large populations [32,13].

The device may also support targeted nutrition interventions by identifying populations with lower fruit and vegetable intake, particularly among low-income and vulnerable groups [15,42]. In school and community-based settings, the Veggie Meter® can be utilized to monitor the

effectiveness of nutrition education programs, dietary interventions, and public health initiatives aimed at improving healthy eating behaviours. Additionally, its

ability to provide consistent longitudinal measurements makes it valuable for tracking changes in dietary intake over time and evaluating intervention outcomes.

Table 8: Public Health Nutrition Implications of Veggie Meter®

Public Health Application	Significance	Supporting Studies
Objective dietary assessment	Reduces bias associated with self-reported methods	Martinelli S, et al. [32]; Patel VV, et al. [13]
Identification of at-risk populations	Helps target low fruit and vegetable intake groups	Di Noia J, et al. [15]
Monitoring nutrition interventions	Useful for evaluating school and community programs	Shanks CB, et al. [42]
Longitudinal dietary tracking	Enables monitoring of dietary behaviour changes over time	Di Noia J, et al. [15]

Overall, the Veggie Meter® has considerable potential to strengthen nutrition surveillance, dietary intervention programs, and public health strategies aimed at improving fruit and vegetable intake among children and other populations.

4.10 Research Gaps and Future Directions

Although substantial progress has been made in the application of the Veggie Meter®, several research gaps remain (Table 9). One of the major areas requiring further investigation is improving measurement accuracy across populations with varying skin pigmentation, body composition, and lifestyle characteristics. Standardized protocols and adjustment

methods for factors such as skin melanin and hydration status may help improve reliability and comparability of measurements [41].

Future research should also focus on expanding the application of the Veggie Meter® in diverse settings, including schools, community health programs, and large-scale public health nutrition initiatives [32,36]. Longitudinal studies are needed to better understand the relationship between skin carotenoid levels, dietary behaviours, and long-term health outcomes in paediatric populations.

In addition, emerging technologies such as artificial intelligence (AI) and digital health tools may enhance the analytical

capabilities of the Veggie Meter®, enabling more precise dietary assessment and personalized nutrition recommendations [43]. Further research exploring the integration of Veggie Meter® data with broader nutritional and lifestyle assessments may strengthen its utility in public health nutrition and clinical practice.

Table 9: Research Gaps and Future Directions for Veggie Meter®

Research Area	Future Need	Key References
Measurement accuracy	Adjustment for skin pigmentation, hydration status, body composition, and other physiological variations affecting skin carotenoid measurements	Jilcott Pitts SB, et al. [41]; Di Noia J, et al. [15]
Standardization	Development of standardized measurement procedures, calibration methods, and reporting protocols to improve comparability across studies	Radtke MD, et al. [29]; Jilcott Pitts SB, et al. [41]
Population diversity	Validation of Veggie Meter® across different ethnic, socioeconomic, age, and demographic groups to ensure broader applicability	Di Noia J, et al. [15]; Patel VV, et al. [13]; Jilcott Pitts SB, et al. [41]
Longitudinal studies	Evaluation of long-term associations between skin carotenoid status, dietary behaviours, and health outcomes in children	Patel VV, et al. [13]; Sisson SB, et al. [36]
Community applications	Expansion of Veggie Meter® use in schools, community nutrition programs, and large-scale public health interventions	Martinelli S, et al. [32]; Sisson SB, et al. [36]; May K, et al. [30]
Technological advancements	Integration with artificial intelligence (AI), machine learning, and digital health technologies for improved dietary assessment and personalized nutrition recommendations	Tehseen A, et al. [43]
Comprehensive nutritional assessment	Integration of Veggie Meter® measurements with dietary surveys, anthropometric assessments, and other nutritional biomarkers	Martinelli S, et al. [32]; Jilcott Pitts SB, et al. [41]; Radtke MD, et al. [29]

Overall, addressing these research gaps may enhance the accuracy, applicability, and public health relevance of the Veggie Meter® as a non-invasive nutritional assessment tool.

Conclusion

Carotenoids play an important role in child health by supporting cognitive function, metabolic health, immune function, and overall growth and development. Since fruits and vegetables are major dietary sources of carotenoids, adequate intake during childhood is essential for maintaining optimal health. However, conventional dietary assessment methods are often limited by recall bias and reporting inaccuracies, particularly in paediatric populations.

In this context, skin carotenoids have emerged as reliable objective biomarkers of fruit and vegetable intake. The Veggie Meter®, a non-invasive device based on reflection spectroscopy, offers a rapid, practical, and reliable approach for assessing skin carotenoid status in children. Current evidence supports its utility in dietary assessment, nutrition education, intervention monitoring, and public health nutrition research.

The portability, ease of use, and non-invasive nature of the Veggie Meter® make it particularly suitable for paediatric and community-based settings. Although factors such as skin pigmentation, BMI, and lifestyle characteristics may influence measurements, the device holds considerable potential for improving

objective nutritional assessment and promoting healthy dietary behaviours among children. Further research is needed to strengthen its validation across diverse populations and expand its application in public health nutrition programs.

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