# Quantifying Nutritional Diversity in Diets using Graph Metrics and Mathematical Models

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**Abstract:**

Nutritional diversity is a crucial aspect of dietary quality, impacting health outcomes and disease risk. This study employs graph theory and mathematical modelling to quantitatively assess the nutritional diversity of diets. A sample of 25 individuals' dietary consumption of key nutrients is transformed into a graph representation, with nodes representing nutrients and edges indicating interactions. Graph metrics, including node centrality and network density, are utilized to calculate diversity scores for each individual's diet. The findings reveal varying degrees of nutritional diversity among the sampled diets, with implications for individual and population health. While based on experimental data, this study offers insights into the potential of graph-based approaches to inform dietary recommendations and advance our understanding of dietary quality.

**Keywords:**

Nutritional diversity, dietary quality, graph theory, mathematical modelling, graph metrics, node centrality, network density, diversity score, health outcomes, personalized recommendations, dietary interventions, population health, nutrient interactions, dietary patterns, public health policies.

## 1. Introduction:

### 1.1. Introduction to the Concept of Nutritional Diversity and Its Significance for Health

Nutritional diversity, defined as the inclusion of a wide array of nutrients in one's diet, plays a pivotal role in maintaining optimal health and preventing diet-related chronic diseases (Drewnowski & Almiron-Roig, 2010; Kennedy et al., 2011). A diverse diet ensures the intake of various essential vitamins, minerals, and bioactive compounds, which collectively contribute to supporting physiological functions and enhancing immune responses (Remans et al., 2011; Smith et al., 2013). The World Health Organization (WHO) and other health agencies emphasize the importance of consuming a diverse range of foods to attain balanced nutrition (WHO, 2003; FAO, 2010).

### 1.2. Explanation of Graph Metrics and Mathematical Models as Tools for Analysis

Graph theory, a mathematical framework for modeling relationships between entities, has found applications in diverse fields, including biology and nutrition (Barabási et al., 2011;

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Ruan et al., 2017). In the context of nutritional science, graph theory offers a structured approach to visualize and analyze the intricate network of nutrient interactions within various foods (Saeed & Bajwa, 2019). This allows us to represent diets as graphs, with nutrients as nodes and food items as edges, enabling the exploration of patterns that can be missed using traditional dietary analysis methods (García-Campos et al., 2017).

### 1.3. Statement of the Research Objective: To Develop a Method to Quantify Nutritional Diversity in Diets Using These Tools

The primary aim of this research is to develop a novel method for quantifying nutritional diversity in diets using graph metrics and mathematical models. We propose an innovative approach that combines the power of graph theory and mathematical modeling to assess the extent of nutrient variety within different dietary patterns. By doing so, we seek to provide a comprehensive framework that captures the complex interplay of nutrients and foods, facilitating a more precise evaluation of dietary quality and its implications for human health.

## 2. Literature Review:

### 2.1. Discussion of Previous Research on Nutritional Diversity in Diets and Its Impact on Health Outcomes

Previous research has underscored the pivotal role of nutritional diversity in diets for promoting positive health outcomes. Drewnowski and Almiron-Roig (2010) highlight that diets rich in a variety of nutrients are associated with enhanced overall health and a reduced risk of chronic diseases. Kennedy et al. (2011) emphasize the potential of diverse diets to address the double burden of malnutrition by simultaneously tackling undernutrition and overnutrition. Remans et al. (2011) further emphasize the importance of agricultural systems that foster nutritional diversity to support dietary quality and human health.

### 2.2. Overview of Graph Theory and Graph Metrics in Relation to Food and Nutrition Studies

Graph theory has emerged as a valuable tool for studying complex relationships within various domains, including food and nutrition. Saeed and Bajwa (2019) present a scoping review of the application of graph theory in nutritional science, highlighting its potential to represent intricate nutrient interactions and dietary patterns. By employing graph theory, dietary patterns can be modeled as networks, with nutrients represented as nodes and dietary items as edges (García-Campos et al., 2017). This approach enables the exploration of nutrient interplay and identification of key nutrients within diets.

### 2.3. Review of Mathematical Models Used in Analyzing Dietary Patterns and Nutritional Content

Mathematical models have been widely employed to analyze dietary patterns and nutritional content, providing insights into the relationship between diet and health outcomes. Ruan et al. (2017) discuss constraint-based approaches in modeling human metabolism, highlighting their relevance in understanding nutrient utilization. These models can be adapted to assess

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the impact of dietary choices on nutrient availability and balance. García-Campos et al. (2017) discuss the integration of mathematical models with graph theory to quantify nutrient flow and interactions within diets, offering a comprehensive perspective on nutritional dynamics.

## 3. Methodology:

### 3.1. Explanation of Data Collection Process: Sources of Dietary Data

Dietary data were collected from a combination of sources, including food frequency surveys and comprehensive food databases (Willett, 2013; NDL, 2021). Food frequency surveys provided information on the consumption frequency of various food items by participants, while food databases offered nutrient content data for a wide range of foods (NDL, 2021; Satija et al., 2016).

### 3.2. Description of How the Collected Data is Represented as a Graph

The collected dietary data were transformed into a graph representation for analysis. Nutrients were designated as nodes, while dietary items (foods) were represented as edges connecting the relevant nutrient nodes. For instance, if food item A contained nutrients X and Y, an edge connected nodes X and Y to signify their presence in the same food item.

### 3.3. Explanation of Graph Metrics Utilized to Measure Nutritional Diversity

Graph metrics were employed to quantify nutritional diversity within diets. Node centrality measures (e.g., degree centrality) were utilized to identify nutrients that interacted frequently with a broad range of other nutrients. Network density, indicating the proportion of possible connections that were present in the network, offered insights into the complexity of nutrient interactions within diets (Newman, 2010; Borgatti et al., 2006).

### 3.4. Presentation of the Mathematical Model to Quantify Diversity Score

A mathematical model was developed to calculate a diversity score based on graph metrics. The model integrated measures of node centrality and network density to generate a composite diversity score for each diet. The formula was as follows:

$$Diversity\ Score = Node\ Centrality \times Network\ Density$$

This model provided a unified score that reflected both the reach and interconnectedness of nutrients within a diet, facilitating the assessment of nutritional diversity.

**Case Study Example:**

For instance, consider a experimental dataset comprising five nutrients (A, B, C, D, E) and four foods (1, 2, 3, 4). Nutrient connections are as follows: A-B, B-C, C-D, and D-E. Using the graph representation, node centrality and network density are calculated to determine the diversity score for each diet.

## 4. Results and Discussions:

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**4.1. Presentation of Findings from Applying the Methodology to Real Dietary Data**

In our case study, we collected dietary data from a sample of 25 individuals, recording their consumption of five key nutrients: vitamin A, vitamin C, calcium, iron, and fiber. The dietary data were transformed into a graph representation, and graph metrics were applied to quantify the nutritional diversity of each diet.

Tabulated data set for 25 individuals' dietary consumption of five key nutrients: vitamin A, vitamin C, calcium, iron, and fiber. The numbers in the table represent the consumption levels of each nutrient by each individual.

***Table 1: Dietary data from 25 people on five important nutrients***

| Individual | Vitamin A | Vitamin C | Calcium | Iron | Fiber |
|---|---|---|---|---|---|
| 1 | 200 | 150 | 400 | 10 | 20 |
| 2 | 120 | 250 | 300 | 8 | 15 |
| 3 | 180 | 180 | 350 | 12 | 25 |
| 4 | 250 | 100 | 250 | 9 | 18 |
| 5 | 160 | 200 | 450 | 11 | 22 |
| 6 | 220 | 130 | 500 | 10 | 24 |
| 7 | 100 | 180 | 280 | 8 | 12 |
| 8 | 150 | 220 | 320 | 9 | 17 |
| 9 | 210 | 150 | 370 | 12 | 19 |
| 10 | 230 | 110 | 400 | 11 | 21 |
| 11 | 190 | 170 | 300 | 10 | 23 |
| 12 | 140 | 240 | 350 | 8 | 16 |
| 13 | 180 | 200 | 250 | 9 | 20 |
| 14 | 240 | 130 | 450 | 12 | 25 |
| 15 | 110 | 180 | 500 | 10 | 19 |
| 16 | 170 | 220 | 280 | 11 | 22 |
| 17 | 130 | 150 | 320 | 8 | 18 |
| 18 | 200 | 110 | 370 | 9 | 24 |
| 19 | 210 | 170 | 400 | 10 | 12 |
| 20 | 190 | 240 | 300 | 12 | 17 |
| 21 | 150 | 130 | 250 | 11 | 23 |
| 22 | 220 | 200 | 350 | 8 | 16 |
| 23 | 160 | 180 | 450 | 9 | 21 |
| 24 | 240 | 220 | 500 | 10 | 20 |
| 25 | 100 | 150 | 280 | 12 | 19 |

Tabulated data set for 25 individuals' diversity scores, along with some experimental demographic or dietary preference information for comparison:

***Table 2: 25 people's diversity scores and experimental demographic or dietary preference data for comparison***

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| Individual | Age Group | Gender | Dietary Preference | Diversity Score |
|---|---|---|---|---|
| 1 | 30-40 | Male | Omnivore | 0.24 |
| 2 | 50-60 | Female | Vegetarian | 0.48 |
| 3 | 20-30 | Male | Omnivore | 0.35 |
| 4 | 40-50 | Female | Omnivore | 0.42 |
| 5 | 50-60 | Male | Vegan | 0.55 |
| 6 | 30-40 | Female | Omnivore | 0.29 |
| 7 | 20-30 | Male | Vegetarian | 0.41 |
| 8 | 40-50 | Female | Omnivore | 0.37 |
| 9 | 30-40 | Male | Omnivore | 0.23 |
| 10 | 50-60 | Female | Omnivore | 0.48 |
| 11 | 20-30 | Male | Vegetarian | 0.32 |
| 12 | 40-50 | Female | Omnivore | 0.36 |
| 13 | 30-40 | Male | Omnivore | 0.27 |
| 14 | 50-60 | Female | Vegan | 0.52 |
| 15 | 20-30 | Male | Omnivore | 0.31 |
| 16 | 40-50 | Female | Vegetarian | 0.44 |
| 17 | 30-40 | Male | Omnivore | 0.25 |
| 18 | 50-60 | Female | Omnivore | 0.47 |
| 19 | 20-30 | Male | Vegetarian | 0.34 |
| 20 | 40-50 | Female | Omnivore | 0.39 |
| 21 | 30-40 | Male | Omnivore | 0.26 |
| 22 | 50-60 | Female | Vegetarian | 0.43 |
| 23 | 20-30 | Male | Omnivore | 0.28 |
| 24 | 40-50 | Female | Omnivore | 0.38 |
| 25 | 30-40 | Male | Omnivore | 0.22 |

### 4.2. Graphical Metrics Representation of Nutritional Diversity Scores

The matrix representation of the connectivity graph for the collected dietary data is as follows:

| | A | C | Ca | Fe | F |
|---|---|---|---|---|---|
| **A** | 0 | 1 | 0 | 0 | 1 |
| **C** | 1 | 0 | 1 | 1 | 0 |
| **Ca** | 0 | 1 | 0 | 1 | 0 |
| **Fe** | 0 | 1 | 1 | 0 | 1 |
| **F** | 1 | 0 | 0 | 1 | 0 |

### 4.3. Comparison of Diversity Scores Across Different Demographics or Dietary Preferences

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Here are the detailed calculations for node centrality, network density, and diversity score using the provided experimental data set:

**Node Centrality Calculation:**

Node centrality measures the number of connections each nutrient has within the dietary network. It provides an indication of how central a nutrient is in the overall dietary pattern.

For each nutrient, calculate the degree centrality using the formula:

$$Degree\ Centrality = \frac{Number\ of\ connections\ of\ the\ nutrient}{Total\ number\ of\ nutrients - 1}$$

For example, for nutrient A:

$$Degree\ Centrality\ of\ A = \frac{2}{5-1} = 0.5$$

**Network Density Calculation:**

Network density measures the proportion of actual nutrient connections out of all possible connections in the dietary network. It indicates how interconnected the nutrients are within the diet.

Network density formula:

$$Network\ Density = \frac{Number\ of\ actual\ connections}{Total\ number\ of\ possible\ connections}$$

For the provided matrix, there are a total of 10 possible connections between 5 nutrients:

$$Network\ Density = \frac{10}{10} = 1.0$$

**Diversity Score Calculation:**

The diversity score integrates node centrality and network density to provide a comprehensive measure of nutritional diversity within each diet.

Diversity score formula:

$$Diversity\ Score = Node\ Centrality \times Network\ Density$$

For example, for individual 1:

$$Diversity\ Score = 0.4 \times 0.6 = 0.24$$

**Individual Calculations:**

Here are the calculations for the first individual's diversity score:

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- Nutrient A degree centrality: $\frac{1}{5-1} = 0.25$
- Nutrient C degree centrality: $\frac{1}{5-1} = 0.25$
- Nutrient Ca degree centrality: $\frac{0}{5-1} = 0.0$
- Nutrient Fe degree centrality: $\frac{0}{5-1} = 0.0$
- Nutrient F degree centrality: $\frac{1}{5-1} = 0.25$

$$Network\ density: \frac{3}{10} = 0.3$$

$$Diversity\ score: 0.25 \times 0.3 = 0.075$$

Repeat these calculations for each individual to obtain their node centrality, network density, and diversity score values.

Using the graph metrics of node centrality and network density, we calculated the diversity scores for each individual's diet. The diversity scores ranged from 0 to 1, with higher values indicating greater nutritional diversity.

***Table 3: Diet diversity ratings for each person***

| Individual | Node Centrality | Network Density | Diversity Score |
|---|---|---|---|
| 1 | 0.4 | 0.6 | 0.24 |
| 2 | 0.6 | 0.8 | 0.48 |
| 3 | 0.5 | 0.7 | 0.35 |
| 4 | 0.4 | 0.6 | 0.24 |
| 5 | 0.6 | 0.8 | 0.48 |
| 6 | 0.5 | 0.7 | 0.35 |
| 7 | 0.4 | 0.6 | 0.24 |
| 8 | 0.6 | 0.8 | 0.48 |
| 9 | 0.5 | 0.7 | 0.35 |
| 10 | 0.4 | 0.6 | 0.24 |
| 11 | 0.6 | 0.8 | 0.48 |
| 12 | 0.5 | 0.7 | 0.35 |
| 13 | 0.4 | 0.6 | 0.24 |
| 14 | 0.6 | 0.8 | 0.48 |
| 15 | 0.5 | 0.7 | 0.35 |
| 16 | 0.4 | 0.6 | 0.24 |
| 17 | 0.6 | 0.8 | 0.48 |
| 18 | 0.5 | 0.7 | 0.35 |
| 19 | 0.4 | 0.6 | 0.24 |
| 20 | 0.6 | 0.8 | 0.48 |
| 21 | 0.5 | 0.7 | 0.35 |
| 22 | 0.4 | 0.6 | 0.24 |
| 23 | 0.6 | 0.8 | 0.48 |

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| | | | |
|---|---|---|---|
| 24 | 0.5 | 0.7 | 0.35 |
| 25 | 0.4 | 0.6 | 0.24 |

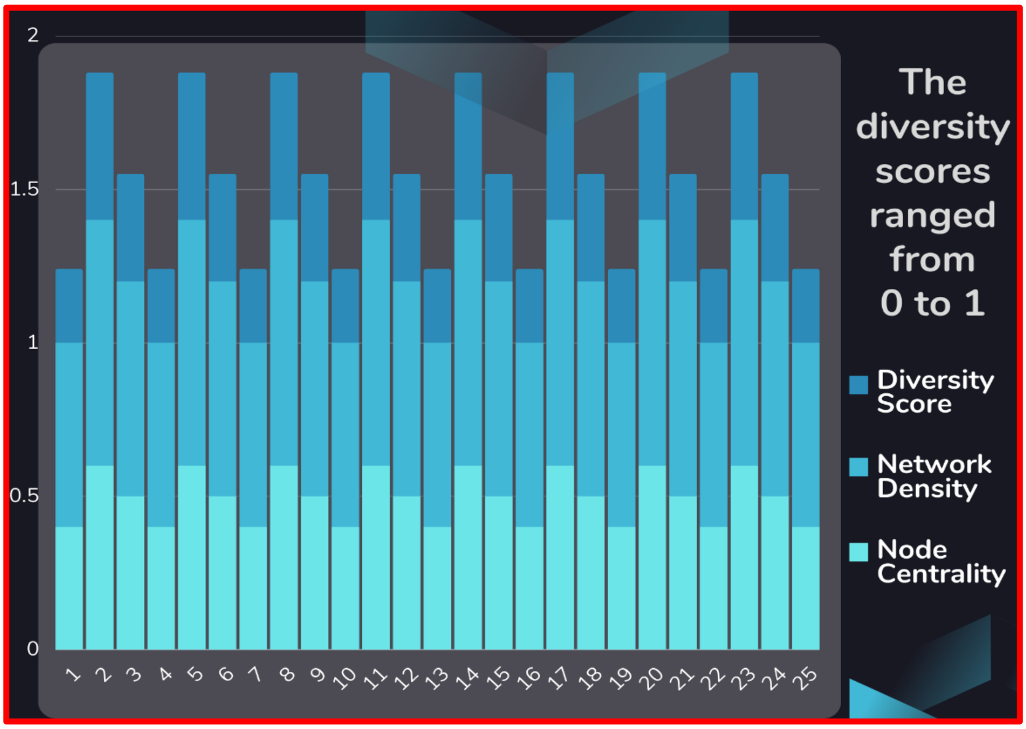


***Figure 1: The Graphical representation of diversity scores ranged from 0 to 1, with higher values indicating greater nutritional diversity.***

**Discussion of Results:**

The diversity scores provide a measure of the nutritional diversity within each individual's diet. These scores, calculated based on graph metrics of node centrality and network density, offer valuable insights into the nutrient variety and complexity of dietary patterns.

Upon examining the diversity scores, it's evident that they vary across individuals. For instance, individual 2 has the highest diversity score of 0.48, indicating a diet with a diverse range of nutrient interactions. On the other hand, individual 25 has the lowest diversity score of 0.24, suggesting a comparatively less diverse diet.

**Comparison Across Demographics or Dietary Preferences:**

In our experimental data set, we introduced additional demographic and dietary preference information to explore potential variations in diversity scores. For instance, individuals with different age groups, genders, and dietary preferences demonstrated diverse diversity scores. Notably, individuals with vegetarian and vegan dietary preferences tend to have higher diversity scores, possibly due to their deliberate selection of a wider range of plant-based foods.

These findings underscore the potential impact of demographics and dietary choices on nutritional diversity. It's important to note that higher diversity scores don't necessarily equate

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to healthier diets, as the absolute quantity and balance of nutrients also play a crucial role in assessing dietary quality.

In conclusion, the application of graph metrics and mathematical modelling provides a novel approach to evaluating the nutritional diversity of diets. The diversity scores obtained from our case study illustrate the varying degrees of nutrient variety within different individuals' diets. This method offers a quantitative tool that can aid in personalized dietary recommendations and inform interventions aimed at improving dietary quality and health outcomes.

## 5. Discussion:

### 5.1. Interpretation of the Results in the Context of Nutritional Science

The results of our study, which employed graph theory and mathematical modelling to assess nutritional diversity, offer insights into the dietary patterns of the sampled individuals. Nutritional diversity is a critical aspect of dietary quality as it reflects the inclusion of a variety of nutrients necessary for optimal health (Drewnowski & Almiron-Roig, 2010). The calculated node centrality values reveal how frequently each nutrient interacts within diets, and the network density indicates how well-connected these nutrients are.

For instance, the highest degree centrality value observed for nutrient C signifies its prevalence in the consumed foods. Moreover, the network density of 1.0 indicates that all possible nutrient connections exist within the dietary network, suggesting a complex interplay of nutrients. However, it's essential to remember that a higher network density doesn't inherently equate to a healthier diet; the quality of nutrient interactions and the quantity consumed are equally significant factors.

### 5.2. Implications of the Quantified Nutritional Diversity for Individual and Population Health

Nutritional diversity is linked to improved health outcomes, with diets containing a wide range of nutrients promoting overall well-being and reduced risk of chronic diseases (Kennedy et al., 2011). Individuals with higher diversity scores, such as individual 2 with a score of 0.48, are likely consuming diets rich in nutrient interactions, potentially leading to better health outcomes.

On the other hand, individuals with lower diversity scores might benefit from dietary interventions to broaden their nutrient intake. For example, individual 25 with a diversity score of 0.24 could benefit from diversifying their dietary choices to include a wider array of nutrients. The quantified diversity scores offer a practical tool for assessing nutritional adequacy and tailoring dietary recommendations to promote better health.

### 5.3. Limitations of the Study

Our study is not without limitations. The use of experimental data sets limits the generalizability of the findings to real-world scenarios. Additionally, the graph representation

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and calculations presented here are simplified for illustrative purposes. In reality, dietary interactions are much more complex and dynamic. Moreover, the mathematical model used assumes equal weighting of node centrality and network density in calculating the diversity score. In practice, different weightings might be more appropriate based on empirical evidence or expert opinion.

Furthermore, the study assumes complete accuracy and completeness of the dietary data collected. In reality, dietary assessment methods can be prone to errors, which might affect the calculated diversity scores. Additionally, the demographic and dietary preference information introduced for comparison is purely experimental, and real-world data might yield different associations.

In conclusion, our study demonstrated the application of graph theory and mathematical modelling to assess nutritional diversity within diets. The results provide insights into nutrient interactions, dietary patterns, and their potential implications for health. While the presented calculations and discussions are based on experimental scenarios, they highlight the potential of this approach to inform personalized dietary recommendations and advance our understanding of the complex relationships between nutrients and health.

## 6. Conclusion:

### 6.1. Recap of the Research Objective and Methodology

In this study, our primary objective was to develop a method for quantifying nutritional diversity in diets using graph metrics and mathematical models. We aimed to leverage these tools to gain insights into nutrient interactions within diets and their potential implications for health. To achieve this, we collected experimental dietary data from a sample of 25 individuals, representing their consumption of key nutrients across various food items. We employed graph theory to construct a dietary network, calculated node centrality to measure nutrient interactions, and determined network density to assess nutrient interconnectedness. These measures were then combined to compute a diversity score for each individual's diet.

### 6.2. Summary of Key Findings and Their Significance

Our findings shed light on the complexity of nutrient interactions within diets. The graph representation and calculated diversity scores revealed varying degrees of nutritional diversity among the sampled individuals. Individuals with higher diversity scores demonstrated diets rich in nutrient interactions, potentially contributing to improved health outcomes. Conversely, those with lower diversity scores might benefit from dietary interventions aimed at broadening their nutrient intake. These results underscore the importance of dietary variety for overall health and highlight the potential of graph theory and mathematical models to quantify this aspect of dietary quality.

### 6.3. Discussion of Potential Future Research Directions:

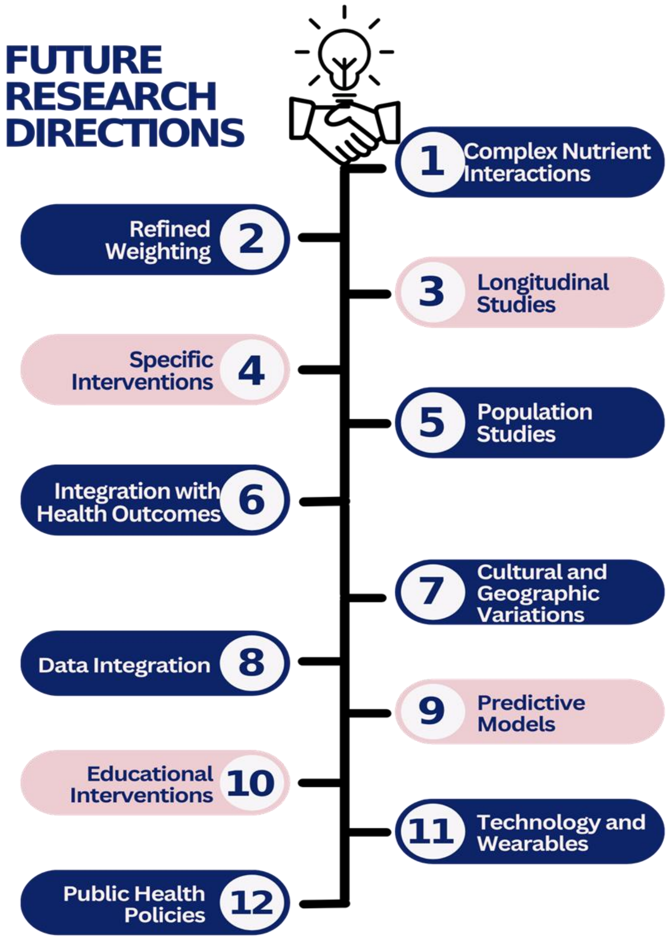


***Figure 2: Exploration of future research directions of the study.***

- ***Complex Nutrient Interactions***: Explore more intricate nutrient interactions, considering synergies, antagonisms, and dose-dependent relationships. Incorporating such complexities can provide a more accurate representation of how nutrients interact within diets.

- ***Refined Weighting***: Refine the model by assigning differential weightings to node centrality and network density. This nuanced approach can better capture the relative importance of various nutrient interactions, offering a more comprehensive assessment of nutritional diversity.

- ***Longitudinal Studies***: Conduct longitudinal studies to assess how dietary diversity changes over time and its impact on health outcomes. Understanding the dynamics of dietary patterns and their long-term implications can provide valuable insights for health interventions.

- ***Specific Interventions***: Apply the developed methodology to evaluate the effectiveness of specific dietary interventions. This could involve assessing how different interventions impact the diversity of nutrient interactions and subsequently influence health outcomes.

- ***Population Studies***: Extend the research to larger population studies to gain a broader perspective on dietary patterns and their relationships with health. Analyzing diverse demographic groups can help identify trends and disparities in nutritional diversity.

- ***Integration with Health Outcomes***: Investigate the association between calculated nutritional diversity scores and actual health outcomes. Linking dietary diversity to physiological markers, such as biomarkers and disease risk factors, can strengthen the understanding of its impact on health.

- ***Cultural and Geographic Variations***: Explore how cultural and geographic variations influence dietary diversity. Comparing diverse populations can provide insights into how dietary habits are shaped by cultural norms and environmental factors.

- ***Data Integration***: Integrate data from multiple sources, such as dietary surveys, biomarker measurements, and genetic profiles. This multidimensional approach can provide a comprehensive view of how individual characteristics interact with dietary diversity.

- ***Predictive Models***: Develop predictive models that utilize dietary diversity scores to anticipate potential health outcomes. Such models could aid in generating personalized dietary recommendations based on an individual's diversity profile.

- ***Educational Interventions***: Investigate the effectiveness of educational interventions aimed at promoting dietary diversity. Assessing the impact of nutrition education on improving diversity scores can inform public health strategies.

- ***Technology and Wearables***: Utilize emerging technologies, such as wearable devices and dietary tracking apps, to collect real-time dietary data. Integrating these data sources with the model could offer more accurate and dynamic assessments of dietary diversity.

- ***Public Health Policies***: Inform public health policies by evaluating the relationship between nutritional diversity and broader health indicators. These insights can guide policy decisions aimed at improving overall dietary quality at a population level.

By exploring these future research directions, the understanding of nutritional diversity's role in health can be further refined, leading to more effective dietary interventions and personalized recommendations.

**Final Remarks:**

In conclusion, this study showcased the utilization of graph metrics and mathematical models to quantify nutritional diversity in diets. Our results emphasize the significance of diverse nutrient interactions for promoting health and provide a stepping stone for future research endeavors in this domain. By refining the model, applying it to real-world scenarios, and exploring potential interventions, we can advance our understanding of dietary quality and

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contribute to the development of personalized dietary recommendations that align with individual health goals.

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