Abstract

This study evaluates the nutritional quality of meals using real-world data from the Swiss digital nutrition cohort, applying the Nutrient Balance Concept (NBC) framework. Nutrient quality was assessed through three indices: the Qualifying Index (QI), Disqualifying Index (DI), and Nutrient Balance (NB)[1], each computed per 2000 kcal portion. Results revealed consistent underperformance in nutrient quality across certain meal types (particularly snacks) while lunches maintained the most favorable profiles. Widespread deficiencies in fat-soluble vitamins (A, D, E), calcium, and iron were identified, alongside significant weekend declines in nutrient adequacy. The NBC framework effectively captured these disparities, confirming its utility for large-scale dietary assessments. Findings underscore the need for personalized nutrition tools, fortified foods, and time-sensitive dietary guidance to improve population-level nutrient adequacy.

Examining Nutritional Quality of Meals On a Swiss Digital Nutrition Cohort - Report

Sophie Holtz

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1 Introduction

1.1 Context & Motivation

Micronutrient adequacy is a fundamental aspect of dietary quality, yet most large-scale nutrition studies focus primarily on energy intake or macronutrient composition, overlooking critical micronutrient imbalances. These imbalances—both deficiencies and excesses—are associated with increased risks of chronic diseases, including cardiovascular disorders, metabolic syndrome, and certain cancers. In practice, the effects of under- or over-consumption of specific micronutrients (e.g., vitamins A, D, iron, sodium) vary systematically by food choice, meal timing, and day of the week.

This study applies the Nutrient Balance Concept (NBC) framework introduced in the foundational metric paper [1], which defines three complementary indices for quantifying food and meal-level nutritional quality:

1. **Qualifying Index (QI)**: The ratio of each *beneficial* nutrient (e.g., vitamins, minerals, fiber) contained in a 2000 kcal portion of a given food relative to its Dietary Reference Intake (DRI) value [3].

2. **Disqualifying Index (DI)**: The ratio of each *harmful* nutrient (e.g., added sugars, saturated fats, sodium) contained in a 2000 kcal portion relative to its DRI or Maximum Recommended Value (MRV).

3. **Nutrient Balance (NB)**: A comprehensive score (0–100%) quantifying how well a food or meal satisfies *all* qualifying nutrient requirements simultaneously in a 2000 kcal portion.

These indices provide a more precise measure of nutrient density than conventional approaches, capturing both beneficial and harmful nutrient effects while quantifying overall nutrient balance. This study tests the applicability of this framework using real-world data from the Swiss digital nutrition cohort.

1.2 Aims & Questions

This analysis addresses three fundamental research questions aligned with the NBC framework:

- **Spatial Variation**: How do nutrient quality indices differ across:
  - Food groups (e.g., grains vs. proteins)?
  - Meal types (breakfast, lunch, snack, dinner)?
- **Temporal Patterns**: What cyclical variations exist in:

  - Daily meal sequences?
  - Weekday vs. weekend consumption?

- **Key Drivers**: Which specific micronutrients most strongly determine:
  - QI values (qualifying nutrients)?
  - DI values (disqualifying nutrients)?

This study aims to validate the NBC model in a practical setting, identify strategic opportunities for improving dietary quality, and provide a detailed characterization of nutrient intake patterns.

2 Methods

2.1 Data Sources and Preprocessing

The primary data source for this study was meal-level data from the Swiss digital nutrition cohort. This dataset was integrated with nutrient composition data from OpenFoodFacts, using food barcode matching to ensure accurate nutrient profiles. To prepare the data for analysis, incomplete records lacking critical food group or nutrient information were removed, and all nutrient values were standardized to consistent units to facilitate direct comparisons. This process resulted in a processed dataset (`df_food_filtered_with_food_group.csv`) suitable for downstream analysis.

2.2 Nutrient Index Computation

For each nutrient j, the base nutrient ratio was computed as:

$$\text{Base ratio} = \frac{\text{amount}_j \times \text{conversion\_factor}_j}{\text{DRI}_j} \tag{1}$$

This base ratio was then scaled to account for a standard 2000 kcal portion, yielding the final scaled ratio:

$$\text{Scaled ratio} = \text{Base ratio} \times \frac{2000}{\text{energy\_kcal\_eaten}} \tag{2}$$

Qualifying Index (QI)

$$QI = \frac{E_d}{E_p} \times \frac{1}{N_q} \sum_{j=1}^{N_q} \frac{a_{qj}}{r_{qj}} \tag{3}$$

where:
E_d = daily energy needs (2000 kcal)
E_p = energy in the amount of food or meal analyzed (kcal)
a_{qj} = amounts of qualifying nutrient (g, mg, or µg)
r_{qj} = DRI of qualifying nutrient (g, mg, or µg/day)
N_q = number of qualifying nutrients considered
If QI was above 1.0, the food is nutrient-dense, while a value less than 1.0 indicates an energy-dense.This QI is particularly sensitive when values fall below 1.0, where small increases in nutrient content can substantially improve the index, reflecting significant reductions in nutrient deficiencies.

Disqualifying Index (DI)

$$DI = \frac{E_d}{E_p} \times \frac{1}{N_d} \sum_{j=1}^{N_d} \frac{a_{dj}}{r_{dj}} \tag{4}$$

where:
a_{dj} = amounts of disqualifying nutrient (g or mg)
r_{dj} = MRV of disqualifying nutrient
N_d = number of disqualifying nutrients considered
If DI is greater than 1.0, the disqualifying nutrients exceed their MRVs relative to energy, while a value below 1.0 means they remain within safe limits. DI is sensitive when it significantly exceed 1.0, as reducing these extreme values can lead to substantial overall improvements.

Nutrient Balance (NB)

$$NB(\%) = \frac{1}{N_q} \sum_{j=1}^{N_q} \min\left(\frac{a_{qj}}{r_{qj}},\ 1\right) \times 100 \tag{5}$$

An NB score of 100% indicates that all qualifying nutrients are fully satisfied, while lower scores reflect varying degrees of nutrient imbalance. The NB index is equally sensitive across its entire range, as it weights all qualifying nutrient equally, regardless of their individual deficits.

2.3 Data Cleaning Pipeline

The initial dataset contained 399,824 food records (`df_food`), which underwent several filtering steps to improve data quality. First, small portion sizes were excluded, removing entries where the consumed weight was less than 30 g or the energy content was below 30 kcal. This reduced the dataset to 154,800 records (61.3%). Next, outlier detection procedures were implemented to remove physiologically implausible nutrient values. For nutrients with established Tolerable Upper Limits (ULs) [2], any record exceeding the UL was removed. For other nutrients, records were excluded if intake exceeded three times the corresponding DRI. This step eliminated 5,317 records (3.4%), resulting in a final cleaned dataset of 149,483 meals.

2.4 Statistical Analysis

Data Preparation To ensure the validity of the statistical analyses, the data underwent several transformations to approximate normality and stabilize variance. The Nutrient Balance (NB) scores were logit-transformed to map the percentage scale (0-100%) to an unbounded range, improving the symmetry of the distribution:

$$\mathrm{NB} = \log\left(\frac{p}{1-p}\right)$$

where p represents the proportion of fully satisfied nutrients. Qualifying Index (QI) and Disqualifying Index (DI) values were shifted by a small constant (10^{-6}) to avoid undefined values for zero observations and subsequently Box-Cox transformed, which is known to reduce skewness and heteroscedasticity.

To assess the suitability of parametric tests, two critical assumptions were evaluated:

- **Normality:** Assessed using the D'Agostino-Pearson test, which jointly tests skewness and kurtosis, providing a more comprehensive assessment than the Shapiro-Wilk test for large samples.
- **Homoscedasticity:** Evaluated with Levene's test, which is robust to deviations from normality and provides a direct test of variance equality across groups.

Group Comparisons To identify significant differences in nutrient indices across meal types, two main approaches were used:

- **Welch's ANOVA:** Applied if normality and homoscedasticity assumptions were met. This version of ANOVA is more robust to unequal variances than the classic ANOVA, making it suitable for real-world dietary data.
- **Kruskal-Wallis Test:** Used as a nonparametric alternative when assumptions were violated, testing for median differences without assuming normality.

Post-hoc comparisons were conducted using:

- **Games-Howell Test:** For parametric data, accounting for unequal variances and sample sizes.
- **Dunn's Test:** For nonparametric data, providing pairwise comparisons while controlling for the family-wise error rate.

Temporal and Cluster Analysis Temporal patterns in nutrient intake were examined using paired Wilcoxon tests to assess within-subject differences across time points, such as weekday versus weekend variations. For clustering, Ward's linkage was applied to z-scored nutrient indices, minimizing the total within-cluster variance. This approach was chosen for its ability to identify hierarchical structures in complex, high-dimensional nutrition

3 Results

3.1 Micronutrient Improvement Potential

As shown in Figure 1, boosting intake of qualifying nutrients disproportionately impacts QI, with fat-soluble vitamins (A, D, E) offering the largest gains. The nutrient with the greatest mean improvement potential (increase in QI if intake reaches 100% DRI) is vitamin A (3.4%), followed by vitamin D (3.3%) and vitamin E (2.8%). Key minerals—iron (2.5%) and potassium (2.1%)—also show notable potential, while folate, calcium (2.0%), and magnesium (1.5%) provide moderate gains. In contrast, B-vitamins like thiamin/B_1 (1.2%) and niacin (1.0%), along with trace elements such as zinc (0.6%), contribute minimally. This hierarchy underscores that dietary interventions targeting fat-soluble vitamins (A, D, E) would yield the most significant QI improvements.

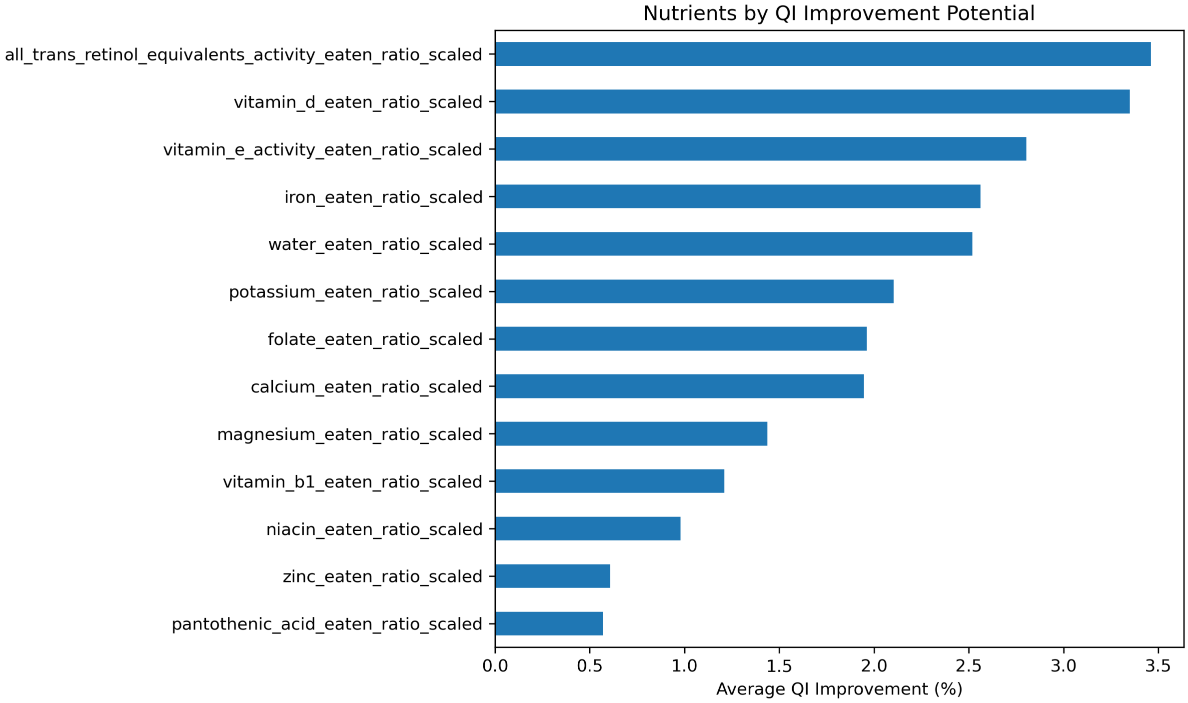


Figure 1: **Micronutrient Improvement Potential.** The relative impact of increasing the intake of various nutrients on the Qualifying Index (QI). Fat-soluble vitamins (A, D, E) demonstrate the greatest potential for QI improvement, followed by key minerals like iron and potassium. In contrast, B-vitamins and trace elements contribute minimally.

3.2 Composite Indices by Meal Type

As illustrated by Figure 2, meal quality follows distinct weekly patterns. Lunch maintains superior nutritional quality throughout the week, reaching peak median QI values (0.86 on Wednesday) before declining 26% to 0.62 by Saturday, while simultaneously demonstrating the lowest disqualifying index (DI range: 0.72–0.75). Dinner shows relative stability, with QI values oscillating modestly between 0.58 and 0.64 (∼9% weekly variation) alongside a parallel U-shaped DI trajectory (0.58–0.64). Breakfast exhibits the most pronounced nutritional erosion, with QI scores linearly decreasing from 0.55 on Monday to 0.41 on Saturday (–25%, $R^2 = 0.96$) accompanied by progressive DI worsening (+0.06/week). Snacks remain the poorest performers overall (QI: 0.42–0.60; DI: 0.65–0.73), though Sunday shows a notable 31% QI recovery compared to Friday levels.

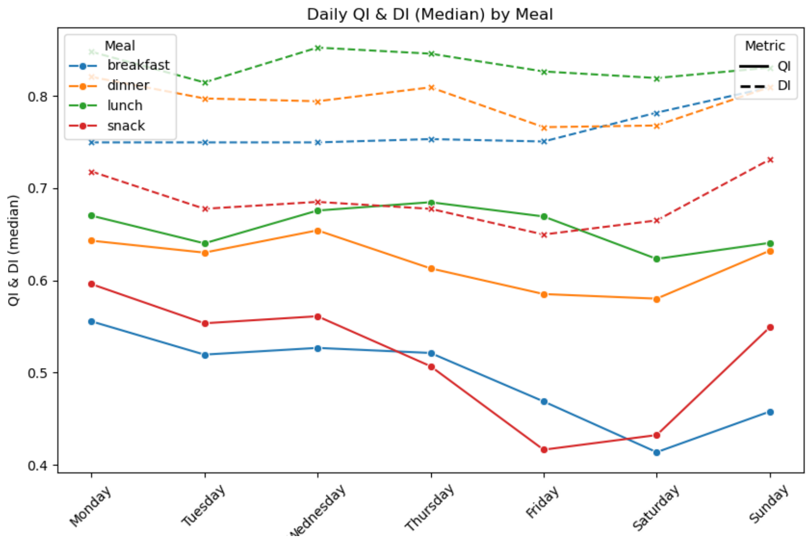


Figure 2: **Median daily QI and DI by Meal Type.** Median Qualifying Index (QI) and Disqualifying Index (DI) values across different meal types throughout the week. Lunch consistently maintains the highest nutritional quality, while snacks exhibit the lowest QI and highest DI, reflecting their typically lower nutrient density and higher levels of harmful nutrients.

Figure 3 contrasts median QI (left panel) and DI (right panel) for weekday (blue) versus weekend (orange) meals. Across all four meal types, weekend distributions shift unfavorably: breakfast QI falls from approximately 0.48 on weekdays to 0.43 on weekends, while DI rises from about 0.78 to 0.82, and the weekday IQRs remain notably tighter. Lunch shows a similar pattern, with median QI decreasing from roughly 0.68 to 0.63 and DI increasing from 0.75 to 0.79 on weekends, accompanied by greater spread. Snack quality also deteriorates—median QI drops from about 0.56 to 0.52 and DI climbs from 0.85 to 0.88—while dinner is least affected (QI shifts marginally from 0.62 to 0.60, DI from 0.72 to 0.74). These patterns indicate a consistent reduction in nutrient density and an increase in disqualifying nutrients during weekend eating, particularly at breakfast and lunch.

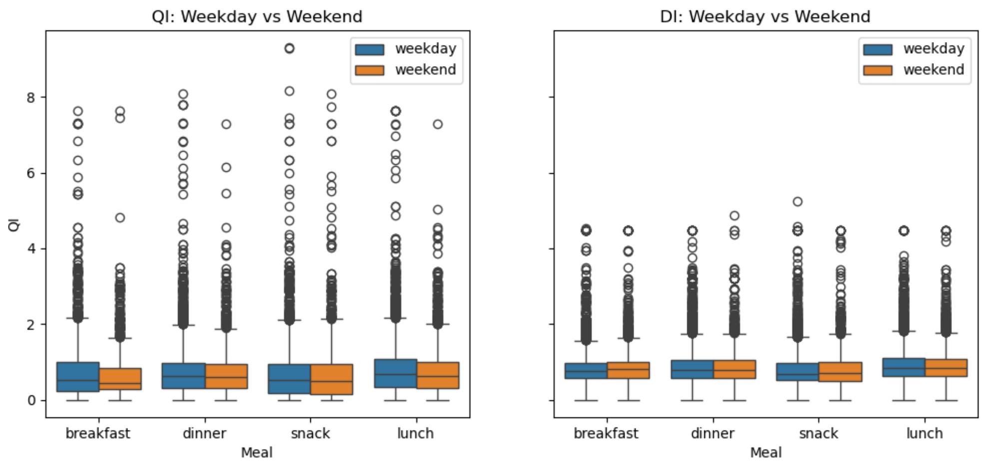
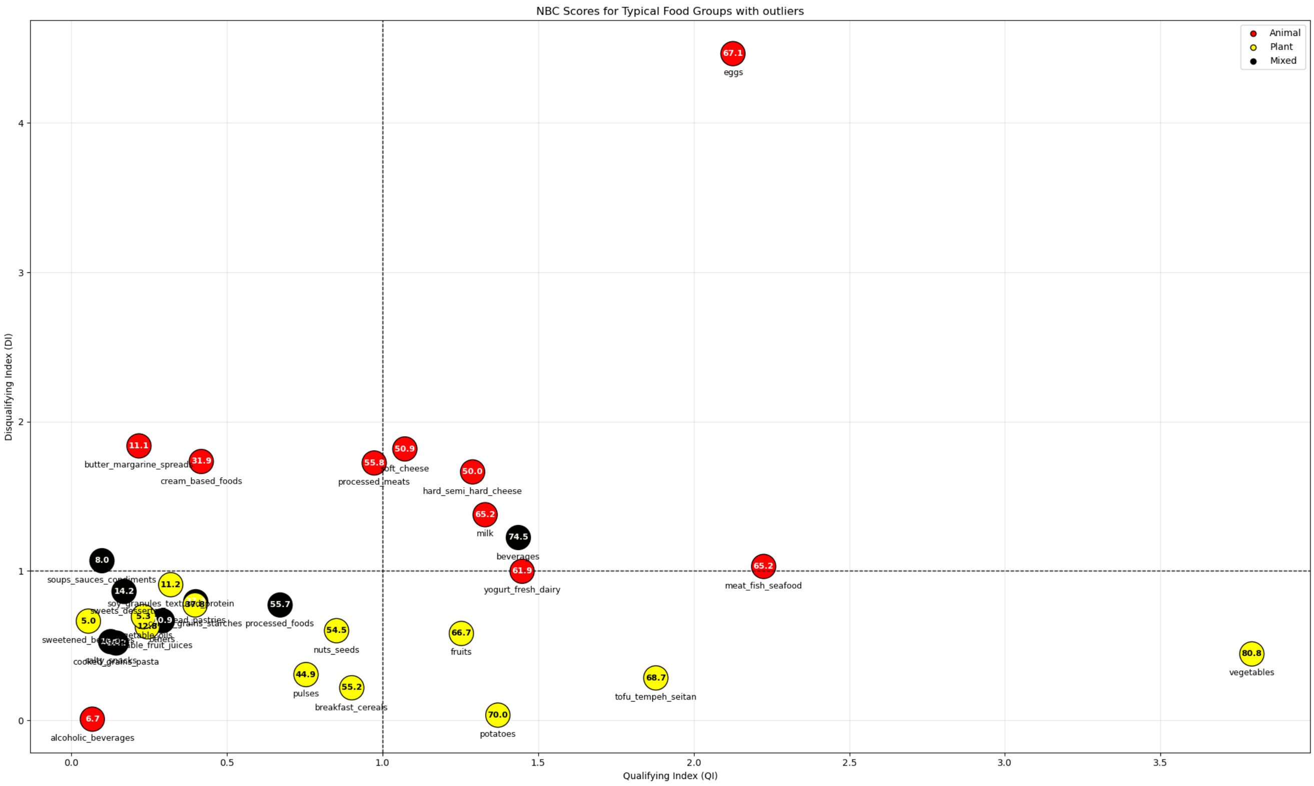


Figure 3: **Weekday vs. Weekend Nutrient Quality.** Comparison of median QI (left) and DI (right) for weekday (blue) versus weekend (orange) meals. Nutritional quality consistently decreases on weekends, particularly for breakfast and lunch, indicating a shift towards lower nutrient density and higher intake of harmful components.

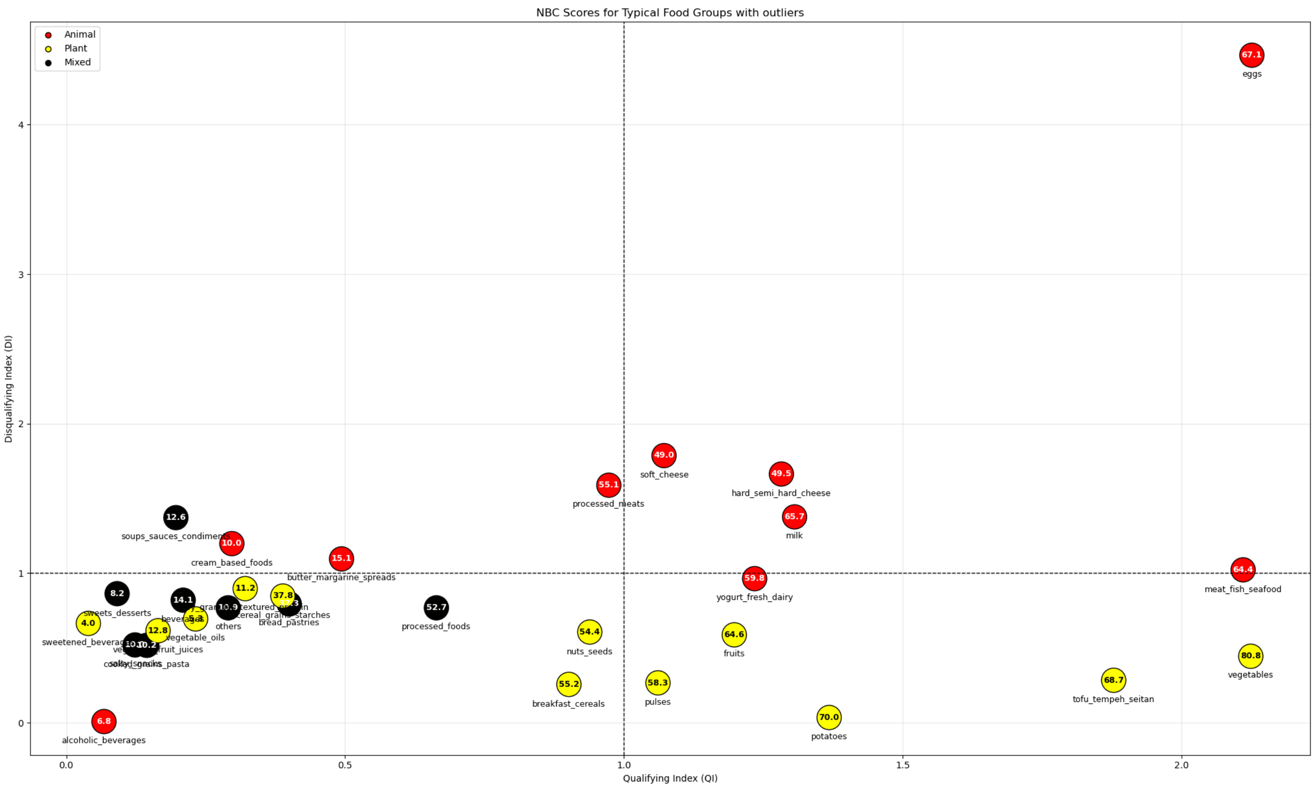
3.3 NBC Scores for Typical Food Groups

To further validate the robustness of our nutrient indices, we examined the distribution of Qualifying Index (QI) and Disqualifying Index (DI) scores across common food groups, both with and without extreme outliers, as shown in Figure 4. This analysis reveals several key patterns consistent with the original NBC framework. Nutrient-dense items like vegetables exhibit high QI values and low DI scores, reflecting their strong contribution to overall nutrient adequacy. In contrast, processed and animal-derived foods, such as processed meats and cheeses, tend to cluster in the high DI, low QI quadrant, indicating their poor nutritional balance despite potentially high protein content.

Interestingly, the removal of extreme outliers significantly clarifies the overall nutrient landscape, reducing the visual skew introduced by ultra-processed items and highlighting the more typical performance of mainstream food categories. This approach aligns closely with the NBC's emphasis on balanced, nutrient-dense diets, reinforcing the validity of our QI, DI, and NB metrics in capturing real-world dietary quality.



(a) With Outliers



(b) Without Outliers

Figure 4: **NBC Scores for Typical Food Groups.** Comparison of Qualifying Index (QI) and Disqualifying Index (DI) for common food groups, both with (left) and without (right) extreme outliers. High-DI foods like processed meats and cheeses stand out, while nutrient-dense items like vegetables exhibit high QI and low DI.

3.4 Nutrient Density Heatmap

Figure 5 illustrates stark disparities in nutrient adequacy across meal types when normalized to 2000 kcal intake, quantified as median scaled ratios (intake/DRI). Protein emerges as the sole consistently sufficient nutrient, exceeding DRI thresholds at all meals (median $\sim$1.2×). In contrast, dietary fiber remains suboptimal (0.45–0.83×), peaking at breakfast but falling 45% short of requirements at dinner. Mineral provision follows a tiered pattern: phosphorus achieves moderate coverage (0.61–0.87×), while calcium (0.12–0.17×), iron (0.11–0.28×), and potassium (0.17–0.23×) languish below 30% of DRI targets. Vitamin deficiencies prove even more acute—fat-soluble vitamins (A, D, E) and B_{12} register 0× median availability, indicating over 50% of meals lack detectable amounts. Water-soluble vitamins show marginally better but still inadequate retention: vitamin C (0.3–0.6×), B_1 (0.17–0.53×), and niacin (0.4–0.5×) all fail to meet half the DRI in most meals. Disqualifying components remain constrained, with added sugars highest at breakfast (0.46× MRV) and sodium stable near 0.15× MRV. A complementary analysis of mean values (Appendix Figure 13) largely confirms these deficiencies, although mean-based fiber and B-vitamin ratios are 10–20 % higher, reflecting a small subset of exceptionally nutrient-dense meals."

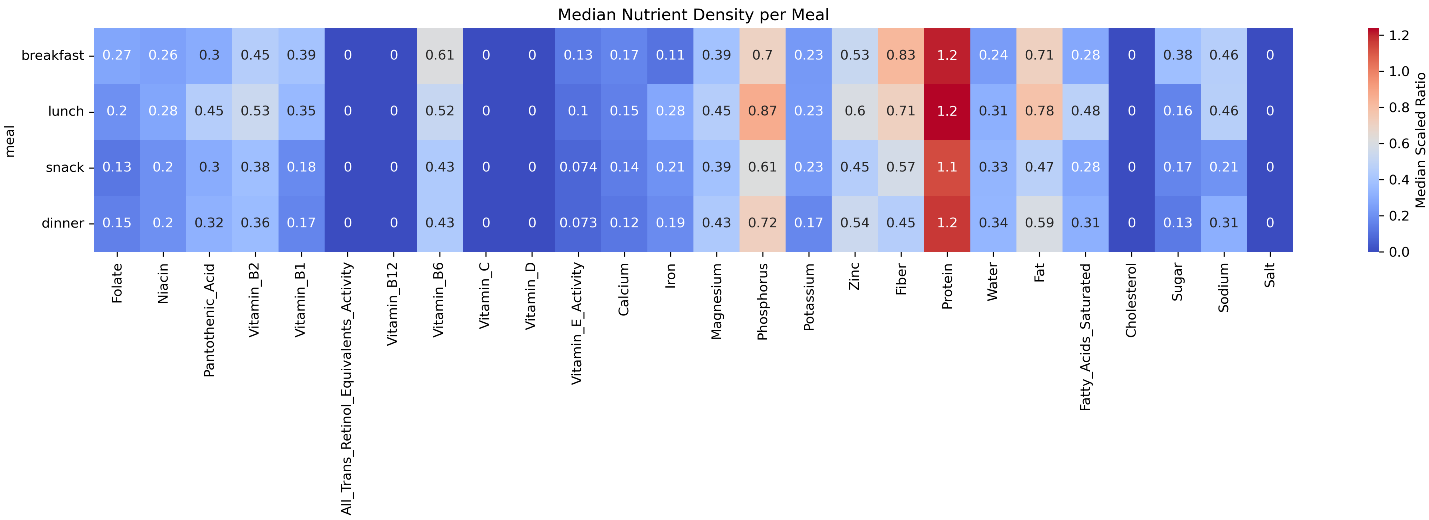


Figure 5: **Median Nutrient Density Heatmap.** Scaled nutrient adequacy across meal types, normalized to 2000 kcal. Protein consistently meets or exceeds Dietary Reference Intakes (DRI), while critical nutrients like calcium, iron, and fat-soluble vitamins (A, D, E) often fall below 30% of recommended levels, highlighting widespread micronutrient deficiencies.

3.5 Meal-Type Quality Differences

Figure 6 presents the distribution of the three core nutrient indices—Qualifying Index (QI), Disqualifying Index (DI), and Nutrient Balance (NB)—across four meal types: breakfast, lunch, dinner, and snacks. The Kruskal-Wallis omnibus tests confirmed significant overall variation for each index ($QI : H = 338.45, p < 0.001$; $DI : H = 594.35, p < 0.001$; $NB : H = 122.01, p < 0.001$), supporting the hypothesis that nutritional quality varies systematically across meal contexts.

Post-hoc Mann-Whitney U tests revealed that nearly all pairwise meal comparisons were statistically significant ($p < 0.01$), highlighting clear nutritional disparities. Lunches consistently demonstrated the highest median QI values, reflecting superior nutrient density, while snacks exhibited the lowest QI, indicating their generally lower nutrient density and higher caloric concentration. The extreme snack-lunch contrast ($p < 10^{-50}$) underscores the fundamental nutritional divide between these meal types.

In terms of DI, snacks had the highest median values, reflecting a greater concentration of potentially harmful components, while breakfasts showed the lowest median DI, likely due to their typically simpler composition and lower processed content. However, the wide interquartile ranges for snacks indicate substantial heterogeneity, capturing the diverse nutritional quality of this category. Finally, the NB scores further differentiate meal types, with lunches again outperforming all other categories in overall nutrient balance. The relatively lower NB for snacks and the broad distribution for dinners suggest that these meal types often fail to achieve balanced nutrient profiles, despite potentially higher caloric content.

These findings reinforce two critical observations: (1) lunches maintain the most favorable nutrient profiles across all indices, consistent with their typically balanced composition, and (2) snacks present the greatest nutritional challenge, combining high variability with consistently lower nutrient density and balance.

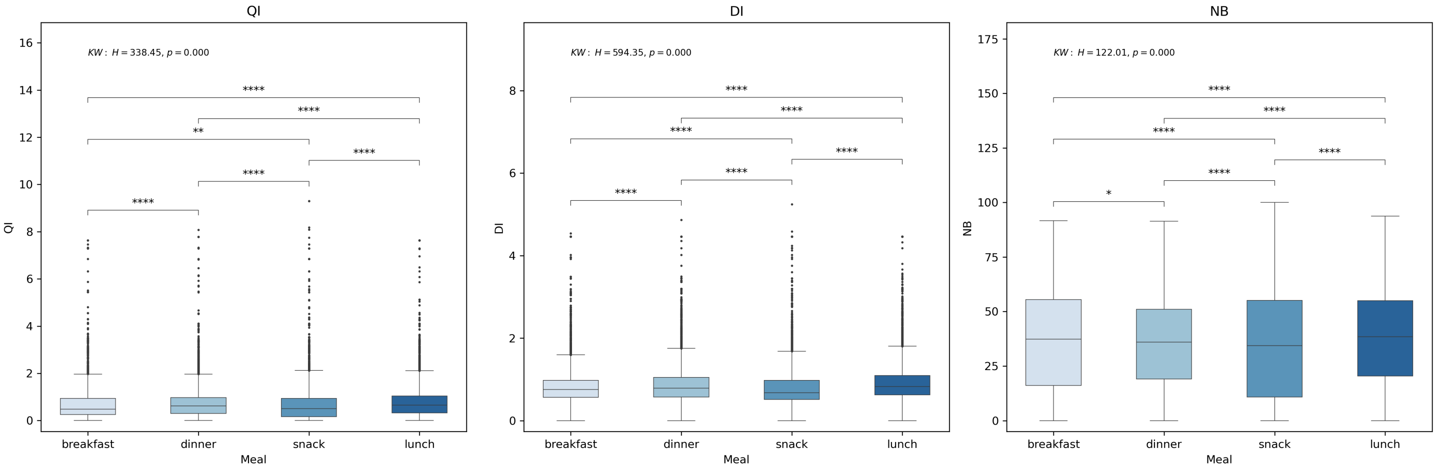


Figure 6: **Meal-Type Quality Differences.** Results of Mann-Whitney U tests comparing QI, DI, and Nutrient Balance (NB) across meal types. Lunches generally score highest for nutritional quality, while snacks consistently underperform, reflecting their typically processed and nutrient-poor composition.

4 Discussion

4.1 Main finding

Our findings reveal systematic disparities in dietary quality across meal types and nutrients, with three critical patterns emerging: (1) pervasive deficiencies in fat-soluble vitamins (A, D, E) and B_{12} across all meals, (2) a clear meal hierarchy where lunches consistently outperform snacks (QI $\Delta = 0.44$, $p < 10^{-50}$), and (3) significant temporal declines in nutritional quality during weekends, particularly for breakfasts (–25% QI). These results align with prior studies highlighting snack-centric diets as a driver of micronutrient gaps but extend the evidence by quantifying meal-type-specific vulnerabilities and temporal rhythms.

4.2 Implications

The findings from this study have significant implications for public health nutrition and dietary policy. The consistent underperformance of snacks, which exhibited the lowest Qualifying Index (QI) and highest Disqualifying Index (DI), highlights the urgent need for targeted nutritional interventions. This is particularly relevant for ready-to-eat and processed foods, which often lack essential nutrients while containing excessive levels of harmful components. Our nutrient density heatmap reveals critical shortfalls in calcium (0.12–0.17× DRI) and iron

(0.11–0.28× DRI), emphasizing the importance of fortification strategies that prioritize these minerals alongside fat-soluble vitamins like A, D, and E. Additionally, the observed weekend declines in nutrient quality underscore the need for behavioral interventions aimed at promoting healthier eating patterns during high-risk periods. These findings suggest that personalized nutrition tools, such as dietary apps incorporating biomarker data, could significantly improve nutrient adequacy. Policymakers might also consider establishing standardized "balanced meal" certifications to guide consumer choices, particularly for breakfast and snack products, which showed the steepest nutrient declines.

4.3 Limitations

Despite the strengths of this study, several limitations should be acknowledged. First, the reliance on self-reported dietary intake data introduces a potential source of bias, as individuals often underestimate their caloric intake or misreport food portions, potentially inflating QI scores by reducing the total energy denominator. This limitation is particularly relevant for foods consumed outside the home, where portion control is less precise. Additionally, the use of fixed Dietary Reference Intakes (DRIs) assumes a uniform nutrient requirement across populations, which may not capture the diverse needs of different demographic groups. For example, vitamin D requirements vary significantly based on skin pigmentation, geographic location, and sun exposure, potentially limiting the personalized applicability of the QI index. Moreover, this analysis does not account for nutrient bioavailability, which can differ substantially between food sources (e.g., heme vs. non-heme iron), potentially overestimating the adequacy of plant-heavy diets. Finally, the Swiss cohort used in this study represents a relatively homogeneous population, which may limit the generalizability of these findings to more diverse global dietary patterns. To address these limitations, future research should incorporate biomarkers, consider bioavailability adjustments, and expand to more diverse populations to improve the accuracy and applicability of these nutrient indices.

4.4 Comparison to Theoretical Expectations

Our findings align closely with the theoretical framework established by Fern et al. (2015) [1] for the Nutrient Balance Concept (NBC), which defines optimal meal quality as achieving QI values around 1.6 ± 0.4, DI values consistently below 1.0, and NB scores above 87% for composite meals. Our analysis largely supports these benchmarks, with lunches consistently achieving the highest QI values (median 0.86 midweek) and snacks performing the worst, in line with NBC predictions. However, the absolute QI values in our dataset (0.42 to 0.86) were generally lower than the theoretical range, likely reflecting the more granular nutrient composition data used in this study compared to the broader USDA nutrient database referenced by Fern et al. This highlights the importance of data resolution in nutrient index calculations.

In terms of DI, our results also align with the NBC model's expectations, showing that processed, energy-dense foods like snacks exhibit the highest DI values, reflecting excessive intake of harmful nutrients. This observation supports the NBC's core insight that nutrient-dense and energy-dense foods must be carefully balanced to maintain overall diet quality. The clear separation between high-QI, low-DI foods (e.g., vegetables, tofu) and low-QI, high-DI foods (e.g., processed meats, dairy products) observed in our data reinforces this principle (Figure 4).

However, our results also highlight some critical nutrient deficiencies, particularly for fat-soluble vitamins and essential minerals like calcium and iron, aligning with the NBC's recognition that many composite meals fall short in these areas. This suggests that the NBC metrics remain a valuable framework for identifying nutrient gaps in real-world meal patterns but may benefit from refinement to account for local dietary habits and specific meal compositions.

Additionally, Figure 12 illustrates the challenge of maintaining nutrient balance when aggregating diverse foods. While some components achieve high QI and NB scores individually, their combination often dilutes overall nutrient quality, resulting in lower NB scores. This finding reinforces the NBC paper's observation that achieving comprehensive nutrient balance at the meal level is significantly more challenging than for isolated foods.

Overall, our data confirm the core findings of the NBC model, while also highlighting the variability introduced by real-world dietary patterns. This underscores the need for more personalized, context-specific dietary assessments, particularly for populations with diverse eating habits.

4.5 Future Directions

Building on the insights from this study, several promising research pathways could enhance the precision and impact of nutrient quality assessments. Personalization is a critical next step, integrating QI, DI, and NB metrics with individual biomarkers to account for personalized nutrient needs. This approach would move beyond population-level estimates, enabling tailored dietary recommendations that reflect each individual's unique metabolic and physiological requirements.

Temporal optimization also represents a promising area for aligning nutrient intake with the body's circadian rhythms and varying metabolic demands. For instance, key micronutrients like magnesium influence sleep quality and circadian regulation, suggesting that meal timing may significantly impact nutrient utilization and health outcomes. Developing meal-type-specific DRIs that account for these temporal variations could improve the precision of dietary assessments. Technological integration into digital health platforms, such as mobile apps or wearable devices, offers substantial potential for real-time dietary monitoring and personalized nutrition guidance. Embedding QI, DI, and NB calculations into these tools could provide users with immediate feedback on their dietary choices, helping to mitigate nutrient quality declines observed during weekends or high-risk periods.

Finally, longitudinal validation remains essential for establishing the long-term health impacts of these metrics. Pairing QI, DI, and NB data with cardiometabolic outcomes in large, diverse cohorts could validate their prognostic utility, inform public health strategies, and guide targeted interventions, such as nutrient-dense product development. These approaches collectively have the potential to transform nutrient profiling from a static, one-size-fits-all assessment to a dynamic, personalized, and predictive tool for optimizing dietary quality and long-term health outcomes.

5 Conclusion

This study demonstrates the practical utility of the Nutrient Balance Concept (NBC) framework for assessing dietary quality in a large, real-world nutrition cohort. Using meal-level data, we confirmed that nutrient quality varies significantly across meal types, with lunches consistently achieving the highest Qualifying Index (QI) and lowest Disqualifying Index (DI) scores, while snacks performed the worst across all metrics. This hierarchy aligns well with theoretical expectations, reinforcing the NBC model's capacity to differentiate nutrient-dense from energy-dense foods.

Our findings revealed pervasive nutrient gaps, particularly for fat-soluble vitamins (A, D, E), calcium, and iron, which were consistently undersupplied across all meal types. These deficiencies, combined with the observed weekend declines in nutrient quality, underscore the need for targeted interventions, such as personalized nutrition tools, fortified food products, and meal-type-specific dietary guidelines.

Moreover, the analysis highlights the challenge of maintaining nutrient balance at the meal level, as individual components often achieve high QI and NB scores in isolation but tend to dilute each other's nutritional impact when combined. This observation supports the NBC model's premise that overall dietary quality cannot be fully captured by isolated nutrient metrics alone.

Future research should prioritize integrating biomarker data, refining DRIs to account for temporal variation, and expanding cohort diversity to capture the full spectrum of dietary behaviors. These steps will be critical for advancing the precision and applicability of nutrient profiling frameworks in diverse populations, ultimately supporting more personalized and effective dietary recommendations.

References

[1] Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A., & Drewnowski, A. (2015). The Nutrient Balance Concept: A New Quality Metric for Composite Meals and Diets. *PLoS ONE*, 10(7), e0130491. https://doi.org/10.1371/journal.pone.0130491

[2] European Food Safety Authority (EFSA). (2024). *Overview on Tolerable Upper Intake Levels as Derived by the SCF and EFSA NDA Panel*. Version 10. European Food Safety Authority. https://www.efsa.europa.eu/.../ndatolerableuil.pdf

[3] European Food Safety Authority (EFSA). (2017). *Dietary Reference Values for nutrients: Summary Report*. EFSA Supporting Publications 2017:14(12), e15121. https://doi.org/10.2903/sp.efsa.2017.e15121

A Additional Figures

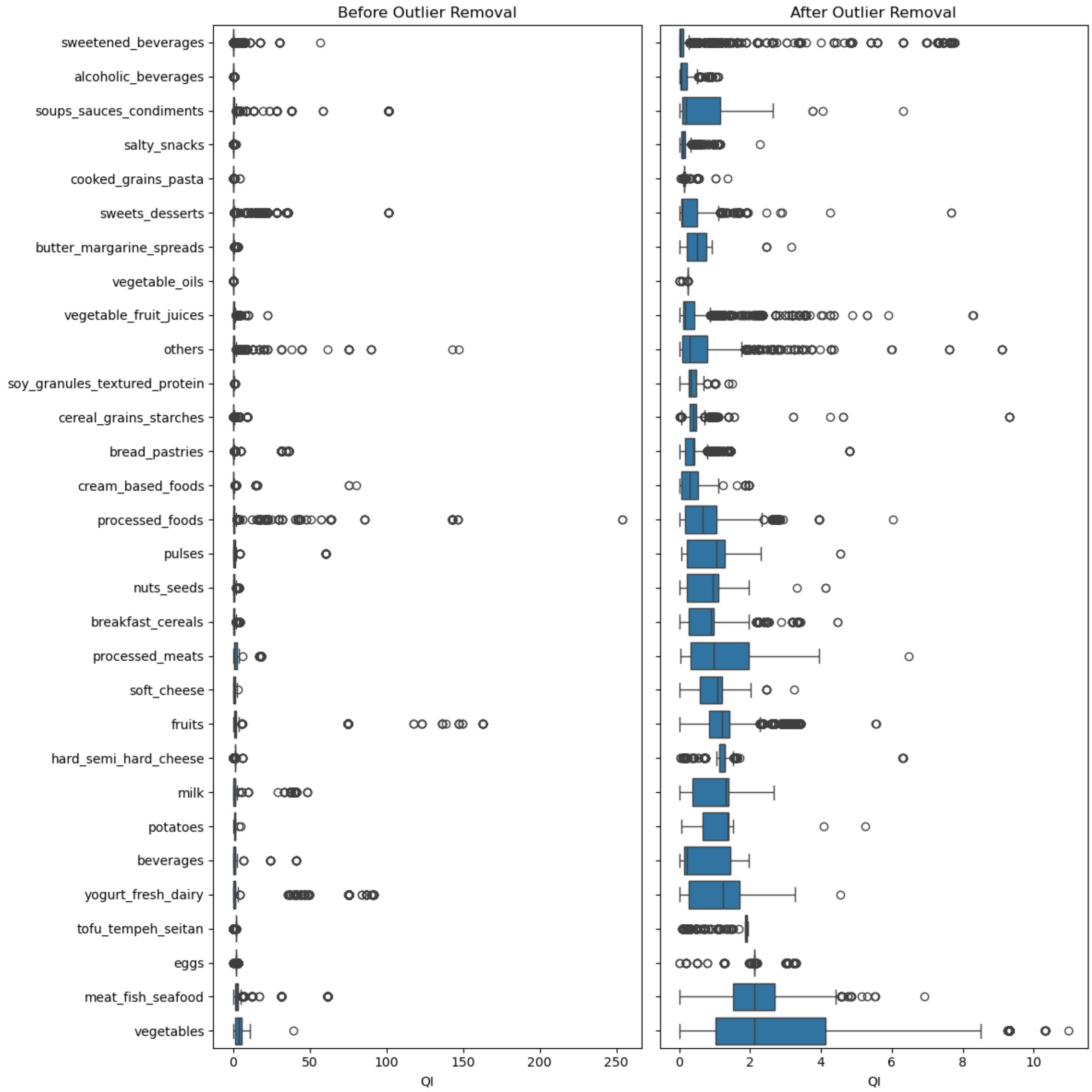


Figure 7: **QI Distribution by Food Group.** Distribution of Qualifying Index (QI) values across major food groups, highlighting significant variation in nutrient density. Certain groups, like fruits and vegetables, exhibit consistently higher QI scores, while processed snacks tend to score lower.

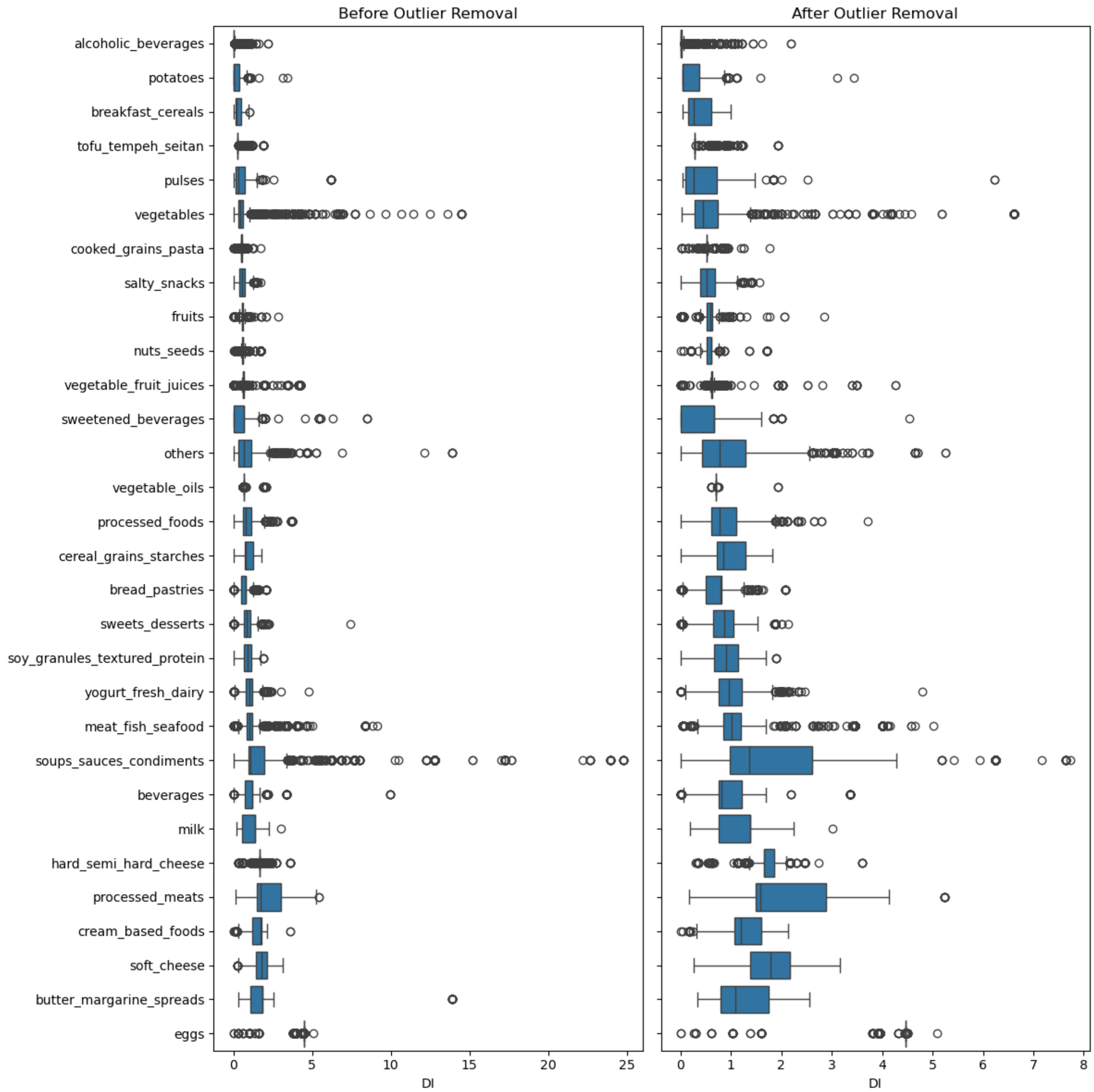


Figure 8: **DI Distribution by Food Group.** Distribution of Disqualifying Index (DI) values across major food groups. Processed and high-fat food groups tend to exhibit higher DI scores, indicating greater levels of harmful nutrient components.

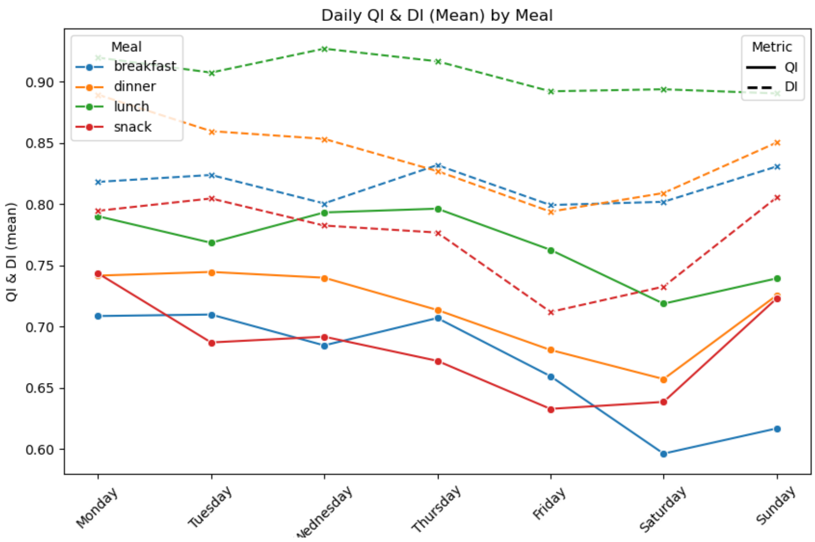
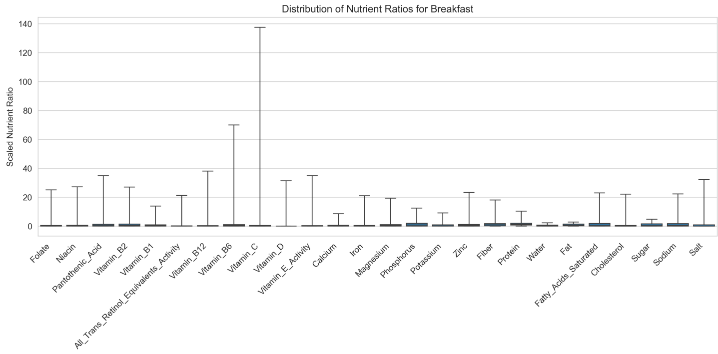
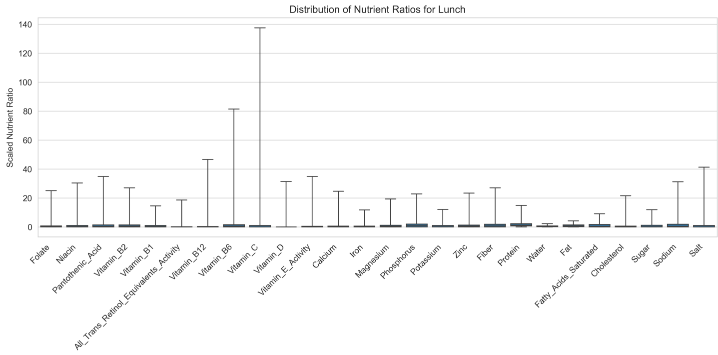


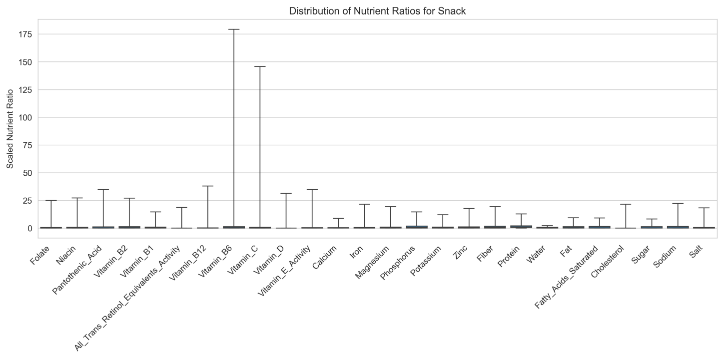
Figure 9: **Mean Daily QI and DI by Meal Type.** Average Qualifying Index (QI) and Disqualifying Index (DI) values across meal types, highlighting how different eating patterns contribute to overall dietary quality. Lunch generally maintains higher QI and DI values.



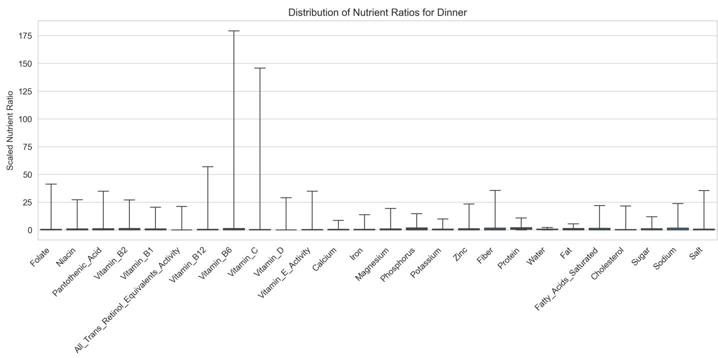
(a) Breakfast



(b) Lunch

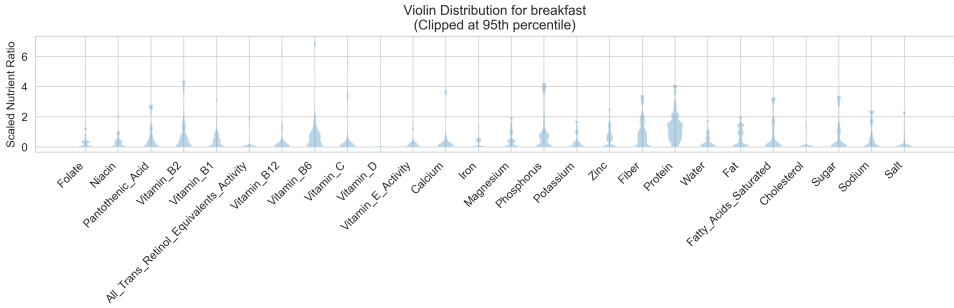


(c) Snack

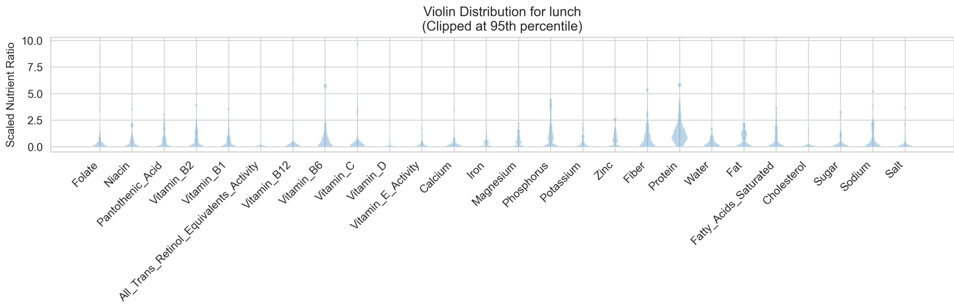


(d) Dinner

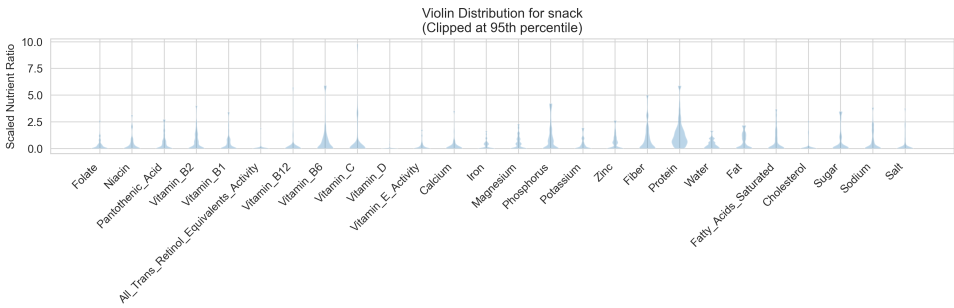
Figure 10: **Nutrient Distribution by Meal Type.** Boxplots illustrating the distribution of key nutrient ratios for different meal types. Breakfast and snacks exhibit the widest variability, reflecting inconsistent nutrient density.



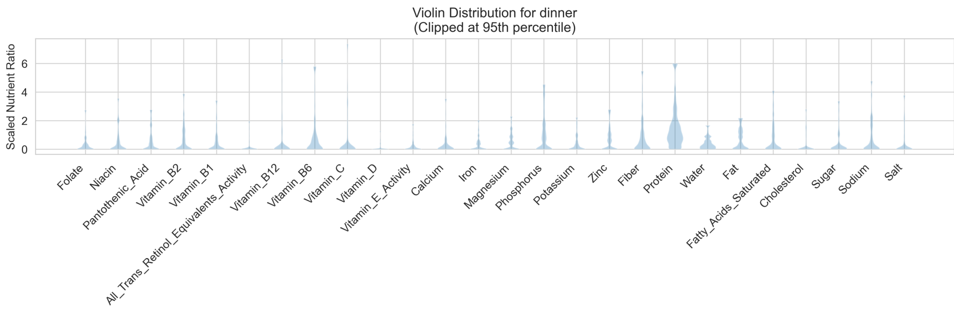
(a) Breakfast



(b) Lunch



(c) Snack



(d) Dinner

Figure 11: **Violin Distribution of Nutrients by Meal Type.** Nutrient distributions for different meal types, showing the spread and central tendency of key nutrient ratios. Lunch generally has the most nutrient-dense profile, while snacks exhibit the widest variability.

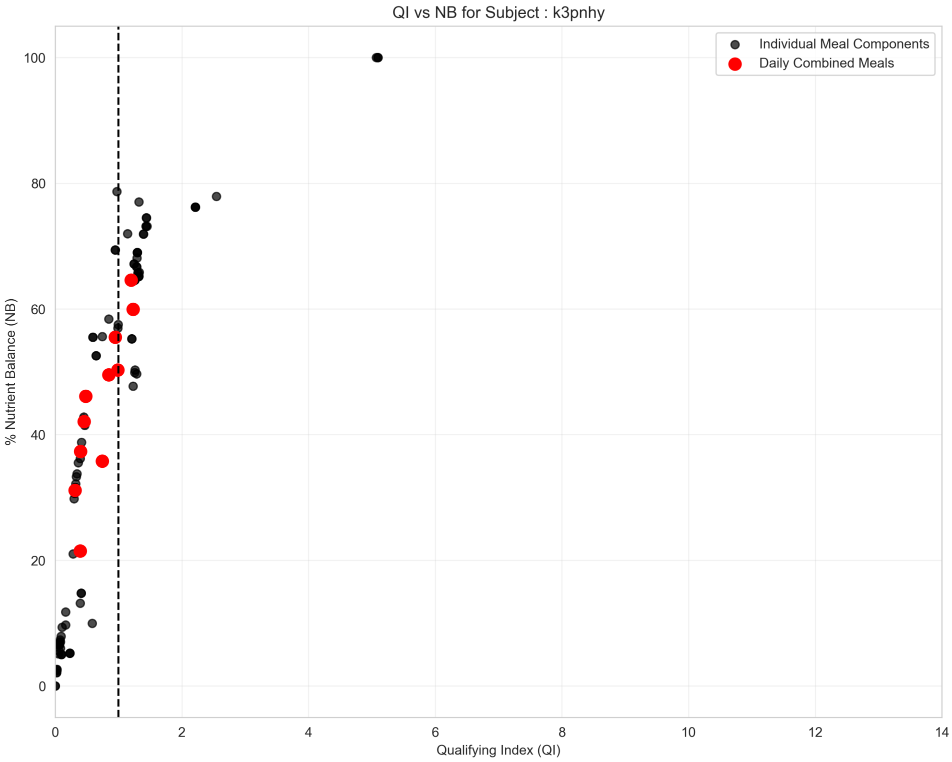


Figure 12: **Relationship Between QI and NB for Individual Meal Components and Daily Combined Meals.** Individual components (black) often achieve high QI and NB scores, while their combination (red) can reduce overall nutrient balance, reflecting the complex trade-offs in real-world diets.

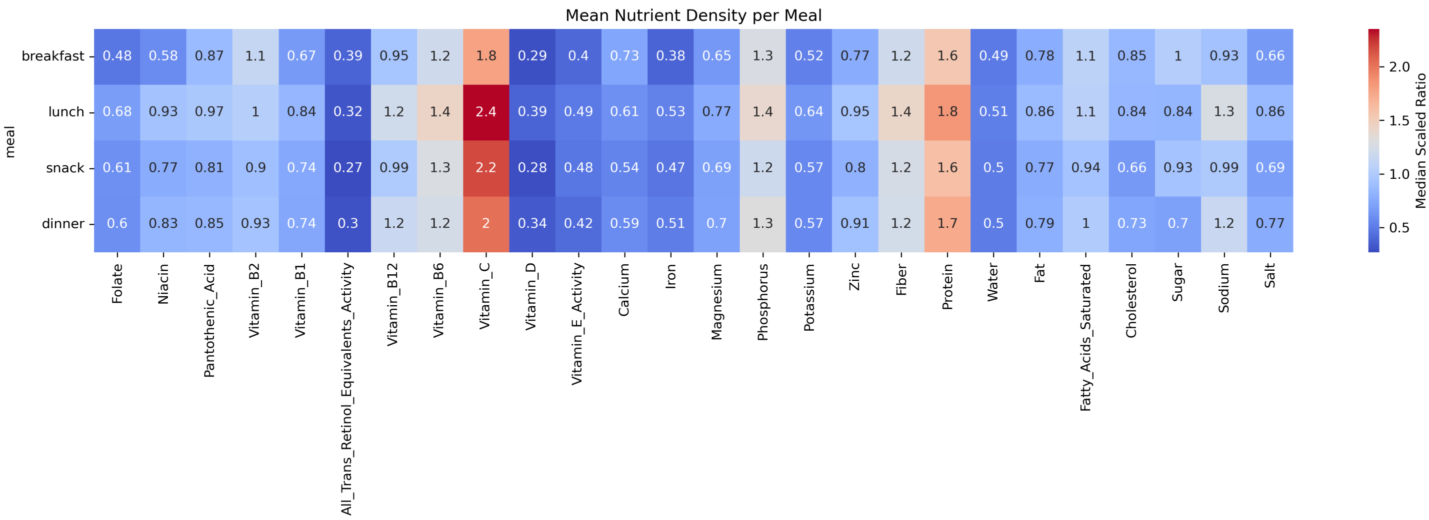


Figure 13: **Mean Nutrient Density Heatmap.** Average nutrient adequacy across meal types, normalized to 2000 kcal. Protein consistently exceeds DRI thresholds, while other essential nutrients like calcium, iron, and fat-soluble vitamins often fall significantly short.