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NutriShed: a novel methodological framework for nutrition security planning in urban communities

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Introduction: As urbanization accelerates globally, towns and cities face increasing challenges in ensuring nutrition security for rapidly growing populations within complex and evolving local food systems. In low- and middle-income countries, urban food systems are often characterized by fragmented value chains, extensive geospatial flows of food, and a high degree of informality. These complexities are further exacerbated by climate change and infrastructural constraints, limiting the capacity of urban planners to effectively design nutrition-sensitive interventions. Despite this, there remains a lack of robust methodological tools to guide nutrition security planning in such contexts.
Methods: This paper presents the NutriShed Framework, a novel methodological approach developed through the NutriShed study in Ghana to map the origins, flows, and vulnerabilities of key micronutrients within urban food systems. The framework is illustrated through its application in two Ghanaian settings, Takoradi and Asesewa. Building on the foodsheds concept, the NutriShed Framework integrates dietary assessment, market system analysis, and geospatial techniques to track nutrient flows into, within, and out of urban areas. The approach is implemented through five stages: (i) identification of nutrient gaps among vulnerable population groups using dietary surveys; (ii) quantification of nutrient flows through assessments of markets, traders, and transport systems; (iii) spatial mapping of nutrient flows alongside food system infrastructure, climate risks, and production patterns; (iv) analysis of vulnerabilities in nutrient flows in relation to infrastructure and environmental factors; and (v) identification of nutrition-sensitive interventions using Geographic Information Systems to strengthen nutrient supply and food system resilience.
Results: The detailed empirical findings generated from the application of the framework are reported in separate companion papers.
Conclusion: The NutriShed Framework provides a systematic and scalable tool for understanding and addressing nutrition security within complex urban food systems. By integrating stakeholder engagement throughout the process, it offers practical pathways for informing policy, planning, and investment to enhance resilient and nutrition-sensitive urban food systems.

KEYWORDS
food security, food systems, Ghana, methodology, micronutrients, NutriShed, nutrition security

1 Introduction

As rural-urban migration accelerates and the world becomes ever more urbanized, cities around the world need to be increasingly strategic about options for meeting the human development needs of their populations, in a sustainable fashion. The considerable focus on cities is reflected in initiatives such as, "Healthy Cities", "Smart Cities" and "One Planet Cities" (Calzada et al., 2023) which highlight the importance of aligning city-centered planning within emerging city development frameworks. Food systems are, inevitably, a key aspect of such strategic city planning processes. There is a need to provide equitable and sustainable nourishment opportunities for urban populations while simultaneously enhancing local production capacity to improve food access, ultimately supporting more sustainable consumption patterns.

A nutritionally secure city is one in which every resident (irrespective of their economic or social status) has the ability to sustainably meet their nutritional needs without jeopardizing the immediate and wider environmental integrity. Such conditions align with several Sustainable Development Goals (SDGs), namely the eradication of hunger and tackling of malnutrition (SDG 2), ensuring healthy lives and the promotion of wellbeing (SDG 3), sustainable and resilient cities (SDG 11), and the underlying universal value of "leaving no one behind" (United Nations, 2015). Critically, the achievement of nutrition security must be resilient to shocks that disrupt markets and the food systems that distribute food over time and space (including food systems trade, transport, and storage).

Disruptions in food value chains during the COVID-19 pandemic (Galanakis, 2020) have heightened the need for community planners and the research community to become better prepared to manage food systems using evidence-informed approaches. Furthermore, with the anticipated exacerbations of climate change, its impacts are expected to increase the likelihood of periodic crop failures (Caparas et al., 2021). As a result, the need for policymakers to understand the origins, adaptability and resilience of their food sources is becoming ever more relevant.

The global food system is characterized by complex and often highly informal value chains, particularly across low- and middle-income countries (LMICs). These value chains typically begin in rural production zones, where smallholder farmers form the backbone of agricultural output, and extend into urban centers where the demand for diverse and nutrient-rich foods is growing rapidly due to urbanization and shifting dietary preferences (Ridoutt et al., 2019; Vos and Cattaneo, 2020; Barrett et al., 2022). However, the growth in urban food demand has not been matched by a commensurate transformation in the structure and functionality of urban food markets. In many parts of the Global South, including Ghana and other sub-Saharan African countries, urban food markets continue to operate predominantly as open-air trading spaces, often characterized by congestion, informality, and limited regulatory oversight (Folson et al., 2023; Hannah et al., 2022; Aryeetey et al., 2016). These informal markets play a crucial role in ensuring access to food for the majority of urban dwellers, especially the urban poor, but they also face persistent challenges related to hygiene, infrastructure, and governance. Food handling practices in these settings frequently fall short of basic sanitation and food safety standards, increasing the risk of contamination and foodborne illnesses (Kushitor et al., 2022; Nijhawan et al., 2023; Jaffee and Henson, 2024).

Transportation of food from rural to urban areas is frequently carried out through informal logistics systems, involving small-scale traders and middlemen who lack access to refrigerated vehicles or standardized storage facilities. As a result, perishable foods such as fruits, vegetables, dairy, meat, and fish suffer from high levels of spoilage and waste before they even reach consumers. The absence of cold chain infrastructure and the limited use of modern preservation techniques amplify food loss, reduce availability, and drive up the prices of nutrient-dense foods (Parfitt et al., 2010; Ridoutt et al., 2019). Moreover, as highlighted earlier, these informal market settings are not often poorly regulated, with weak and fragmented coordination among actors across the value chain. This not only affects food quality and safety but also limits opportunities for upgrading these markets through innovation, investment, and policy reform. As a consequence, vulnerable populations face a double burden: poor nutritional outcomes due to limited access to affordable, high-quality food, and increased exposure to unsafe food environments. In West Africa, particularly in Ghana where the NutriShed methodology was implemented, prior studies have examined how local food value chains connect to sub-optimal diets and malnutrition among urban consumers (Mockshell et al., 2022). Despite this, it remains unclear what strategies, if any, urban planners are using to enhance access to nutrient-rich foods in Ghanaian cities, especially for the most socio-economically vulnerable populations. Accordingly, this paper describes the NutriShed methodological framework as a theoretically informed and spatially explicit approach for community nutrition security planning, integrating insights from food environment research, value chains for nutrition and foodshed analysis to identify nutrient gaps, trace nutrient-rich food flows, assess system vulnerabilities and inform locally appropriate nutrition-sensitive interventions.

2 Theoretical basis and justification

Current available methodological frameworks for planning community nutrition security include, food environment analysis, value chains for nutrition, and FoodShed analysis frameworks (Figure 1). *Food environment analysis* framework conceptualizes the interface between people and the wider food system, drawing attention to the external and personal domains that shape food acquisition and consumption, including availability, affordability, convenience, quality and desirability of foods (Turner et al., 2018; Herforth and Ahmed, 2015). The framework is useful for understanding the contexts within which people make consumption decisions, including the variety of local sources of food and their "objective" (e.g., opening hours, prices, built and digital infrastructure) and "subjective" characteristics' (i.e., perceptions held by local consumers regarding the hygiene and affordability of food available; Turner et al., 2018; Osei-Kwasi et al., 2021; Choudhury et al., 2025). However, while valuable for analyzing consumer-facing contexts, the framework is less able to explain the upstream and midstream processes that influence whether nutrient-rich foods reach local markets in sufficient quantity, quality, and stability (HLPE, 2017; Downs et al., 2020).

Value chain analysis (VCA) for nutrition extends this perspective by examining how actors, institutions, transport, storage, processing and market arrangements influence the supply, value addition and consumption of nutritious foods (Hawkes and Ruel, 2011; Gelli et al., 2015). VCA employs traditional value chain survey techniques to identify the people, organizations and processes which move and transform nutritionally important produce from "farm to fork" (Hawkes and Ruel, 2011; Allen and de Brauw, 2018). However, conventional VCA often remains commodity-specific and producer-led, making it less suitable for community-level nutrition security planning where the starting point is not a single crop or product, but the nutrient needs of nutritionally vulnerable populations (Maestre et al., 2017) While recent VCA approaches increasingly incorporate spatial analysis and market connectivity, most remain focused on individual commodities and are therefore less able to characterize the diversity of foods, nutrient flows, and interconnected food environment processes relevant to community-level nutrition security planning (Minten et al., 2016; Reardon et al., 2021). VCA tends to start with the producer and then follows the value downstream, as opposed to starting with the consumer and the nutrients which matter to them. They rarely explicitly account for space; yet, food systems are inherently linked to spatial patterns of transport, markets and infrastructure, with food flows influenced by both natural and social geographies.

Foodshed analysis framework provides spatial logic for linking urban food consumption to production regions and transport corridors, conceptualizing cities as dependent on geographically distributed catchments of food supply (Peters et al., 2009; Cleveland et al., 2014). The framework emerged during the 1990s as an approach to link urban food consumption to local, national and international production regions (Getz, 1991; Kloppenburg et al., 1996; Chen, 2012). Similar to the idea of a watershed, foodshed analysis depicts spatially explicit networks of source regions and consumption locations (i.e., network nodes), which are connected by transport routes and associated infrastructures (i.e., the network spokes).

Recent studies have mapped empirical data to define the foodsheds of major cities in West (e.g., Karg et al., 2016, 2023) and East Africa (e.g., Hemerijckx et al., 2023). However, a recent systematic review (Schreiber et al., 2021) highlights a number of pressing research gaps, namely the often relatively rudimentary analyses of diets and nutrition, with studies tending to overlook the origins and seasonal flows of priority nutrients (including iron and Vitamin A) in favor of analyses of commercially important food items. Thus, there is a tendency of foodShed analysis to focus on food commodities rather than priority nutrients, with limited attention to micronutrient adequacy, seasonal flows, infrastructure vulnerabilities and nutrition-sensitive intervention planning (Karg et al., 2016). Micronutrient deficiencies remain a critical public health concern, especially in low- and middle-income countries (LMICs), affecting billions of individuals and contributing significantly to the global burden of disease. Deficiencies in iron and vitamin A impair physical and cognitive development, reduce immune function, and increase morbidity and mortality, especially among women and children (Scott, 2020; Engidaw et al., 2022; Fite et al., 2022). The implications extend beyond individual health, undermining economic productivity and perpetuating cycles of poverty and underdevelopment. For example, iron deficiency alone is estimated to reduce national productivity levels by up to 20% in some LMICs due to its impact on cognitive and physical development/performance (World Health Organisation, 2020). Identifying these deficiencies and addressing them through targeted nutrition interventions is thus crucial for sustainable development and improved public health outcomes.

The NutriShed framework (Akparibo et al., 2025) integrates and extends these approaches described above, by starting with identified nutrient gaps among vulnerable population groups, linking those gaps to nutrient-dense foods, tracing the spatial origins and routes through which these foods enter urban communities, and assessing the infrastructural, climatic and governance vulnerabilities that may disrupt nutrient supply (Figure 2). In doing so, NutriShed shifts the unit of analysis from foods alone to nutrient flows, and from generic food availability to the resilience of local systems to supply nutritionally important foods over time and space (Tendall et al., 2015; Ericksen, 2008). This theoretical integration allows the framework to move beyond describing food environments or individual value chains, toward a planning-oriented methodology for identifying where interventions in production, transport, storage, markets and local governance may strengthen urban nutrition security and food system resilience (Ingram, 2011; HLPE, 2020; Table 1).

The NutriShed approach is illustrated through its application in two Ghanaian cities (Takoradi and Asesewa) and is presented in this paper as a six-step methodological framework. The approach involves identifying vulnerabilities in key nutrients and tracing their inbound flows along supply chains from origin to destination. It also incorporates spatially explicit data on the number, distribution, and characteristics of key food system infrastructures, including markets, food processing facilities, and cold storage systems, thereby enabling a more comprehensive understanding of their role in shaping nutrient flows. Such infrastructures have received limited attention within the foodshed literature, which has largely focused on direct linkages between production and consumption zones (Karg et al., 2016; Swiader et al., 2018). The methodological steps underpinning the NutriShed approach are described below, while detailed findings from its application will be presented in subsequent publications (e.g., Dake et al., 2025; Cooper et al., Unpublished).

3 Methods of application

The "Nutrished" framework (Figure 2) focuses on tracking spatially explicit nutrient flows into and out of study communities. Sequentially, it: (i) assesses the nutritional needs and priorities within the study communities, (ii) determines regional gaps in production, food markets, and infrastructure, (iii) identifies

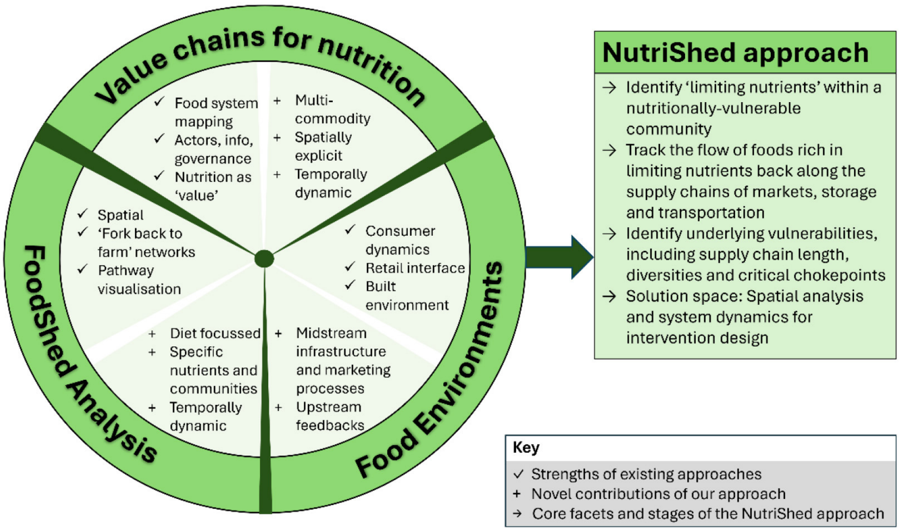

FIGURE 1
Conceptual overview of the links between three existing food systems methodologies, their limitations with regards to community-specific nutrition planning, and the NutriShed approach. Key: ✓ strengths of existing approaches; + novel contributions of our NutriShed approach; → core facets and stages of the NutriShed approach.

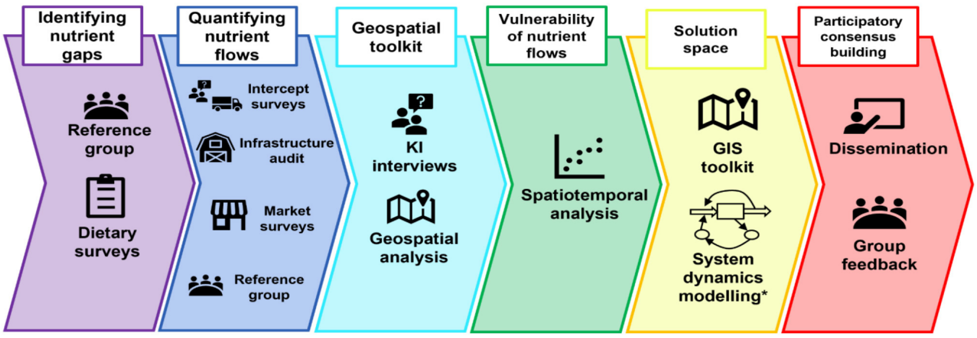

FIGURE 2
Overview of the six sequential stages making up the NutriShed approach. KI refers to Key Informants. As described in text, the reference group of local experts from Stage 1 were consulted at strategic points throughout the project. * As explained in Stage 5, the system dynamics component provides an extension to the geospatial analysis to help understand the feedback loops underpinning the flows of food across their NutriSheds over space and time.

vulnerabilities in critical nutrient flows, and (iv) employs empirical spatial tools and systems modeling to devise strategies for enhancing nutrition security. The key stages/steps of this approach are described in detail, below.

3.1 Stage 1: identifying the nutrient gaps

The NutriShed assessment framework begins with a nutrient gap analysis. We identified specific nutrient deficiencies and nutrition priorities across the study locations. We conducted a household-level dietary assessment survey among women aged 18 years and older (including pregnant women and lactation mothers), adolescents aged 12–18 years, and children aged 2–5 years, in selected households within the two study communities. Women aged 18 years and older were included because of their central role in household food purchasing and meal preparation decisions. This sample was also targeted because they represent a population particularly vulnerable to the adverse effects of inadequate intake of essential nutrients. To avoid intra-household bias, only one eligible person (woman, adolescent, or child) was recruited per household in the dietary assessment survey.

For the dietary assessment survey, we adapted the interactive 24-h recall method developed by Gibson and Ferguson (2008), a method that has been widely applied in low- and middle-income settings and previously used in Ghanaian dietary assessment research (e.g., Abizari et al., 2014; Folson et al., 2023). A multiple-pass approach was employed in conducting the dietary recall interviews. In the first pass, the respondent listed all the foods and drinks (including drinking water) consumed during the preceding 24-h period. In the second pass, the interviewer guided the respondent through each food item listed, in chronological order, probing for more detailed descriptions, including cooking methods and, where relevant, brand names. The third pass involved estimating portion sizes for the reported foods and drinks. In the fourth and final pass, the interviewer reviewed the recall to ensure that all items were accurately recorded. The types and quantities of food consumed were estimated using household measures, food models, volumetric cups, measuring spoons, and a photographic food atlas with weights.

Following the 24-h dietary recall, a nutrient gap analysis was conducted by analyzing the dietary intake reported by participants. At the initial stage of analysis, dietary intake data were translated into nutrients and energy using a combination of the Food Recognition Assistance and Nudging Insight (FRANI) food database, the Research to Improve Infant Nutrition and Growth (RIING) food database, and a compilation of nutrients from the West Africa Food composition database (Folson et al., 2023; Vincent et al., 2019). These databases contain nutrient data on indigenous foods typically consumed in Ghana. These food databases include nutrient content data for macro- and micro-nutrients like energy, carbohydrate, protein, fat, fiber, calcium, zinc, vitamin A, thiamin, riboflavin, niacin, vitamin B6, vitamin B12, folate, iron, pantothenic acid and vitamin C. Food ingredients used in preparing each meal were equated to the closest food code in the RIING database. The consumed quantities (portion sizes) captured in grams were then entered into the RIING database and the code that is the most accurate description of each reported meal was selected in the database. This selection automatically produces nutrient and energy values commensurate with each consumed portion size using MS Excel. This was followed by further analysis using the STATA statistical software (version 17). The estimated average requirement for each nutrient, appropriate for the respective age group and gender, was compared against the respondents' intake to evaluate adequacy. Intake of nutrients less than the Estimated Average Requirement (EAR) were identified as limiting nutrients in the participant groups' diets. The findings of this phase of the study are presented in Dake et al. (2025). In the next stage of the NutriShed framework, the target foods associated with supply of the priority nutrients were tracked to map their flow in and out of the study communities.

3.2 Stage II: quantifying nutrient flows

The next step of the NutriShed approach focused on identifying and quantifying the flow of target foods (foods identified as having high content of priority nutrients) into our study communities. This process required surveys to collect primary data on (a) quantities of the different target foods being transported into our study sites (e.g., via road intercept surveys), (b) the range and characteristics of different food systems infrastructures located within the vicinity of our local communities (e.g., roads, food processing units and storage facilities), and (c) the conditions and characteristics of local markets receiving the inbound flows of our target foods within our study communities.

The first survey targeted food market actors including suppliers, commission agents, market managers, and market queens (i.e. women leaders of female traders' associations), operating at diverse locations including markets, lorry stations, food warehouses, and port facilities within the study communities. The aim of this survey was to collect data on the geographical origins, destinations, and sizes of food flows reaching the communities, as reported by local market actors. The surveys also gathered information on the number, capacities, and routes of traders, as well as the provenance, volumes, and types of nutrient-dense foods.

A second survey focused on traders and market agents and targeted those transporting produce into the study communities using mobile-based survey techniques. These surveys were designed for rapid administration, taking only 5–10 min to collect data on the origins, destinations, and types of commodities flows as well as the quantity of food being transported.

A third survey, the road intercept survey, helped triangulate the first and second surveys. It tracked the movement of vehicles transporting food products in and out of major access roads. These surveys were conducted over three consecutive days during both the peak production seasons (July/August) and the lean season (February/March). Conducting the survey across 3 days enabled the research team to capture routine weekday trading and transport activities while minimizing the influence of atypical fluctuations associated with isolated events or market disruptions. Repeating data collection across the two contrasting seasonal periods also allowed assessment of seasonal differences in food availability and distribution patterns.

Information collected from traders at the roadside included the sources and destinations of food loads, the overall weight, and the composition of commodities.

To support the triangulation of data, a special reference group was established at the study sites to help verify the sources, quantities, and seasonal variations of nutrient flows. The findings of these surveys are reported in a separate paper (Afagbedzi et al., Unpublished).

3.3 Stage III: geospatial toolkit

In stage III, the aim was to depict and characterize the NutriSheds for both of our study sites (i.e., Takoradi and Asesewa) and across seasons (i.e., dry and wet seasons), particularly with regards to the quantity and quality of food systems infrastructure (e.g., roads, population densities, storage and processing facilities), climate vulnerability, and variations across seasons (Figure 3).

To compliment this analysis, we collected multiple sources of open-access geospatial data (raster or vector formats) to understand the wider food systems enabling environment associated with our study regions and across Ghana, more broadly. These datasets included national level land cover and land use from the remote sensing derived MERIS GlobCover dataset, the locations of different national and regional roads via OpenStreetMap, population hexagons for the country at 400 m resolution via Kontur Population (available via United Nations Office for the Coordination of Humanitarian Affairs (OCHA) services), and estimates of the climate risk and conflict risk as determined by the Climate-Conflict-Vulnerability Index (CCVI) of the German Federal Foreign Office (Table 2). These secondary datasets provide a canvas upon which to overlay the primary datasets from Stage II. This enabled analysis

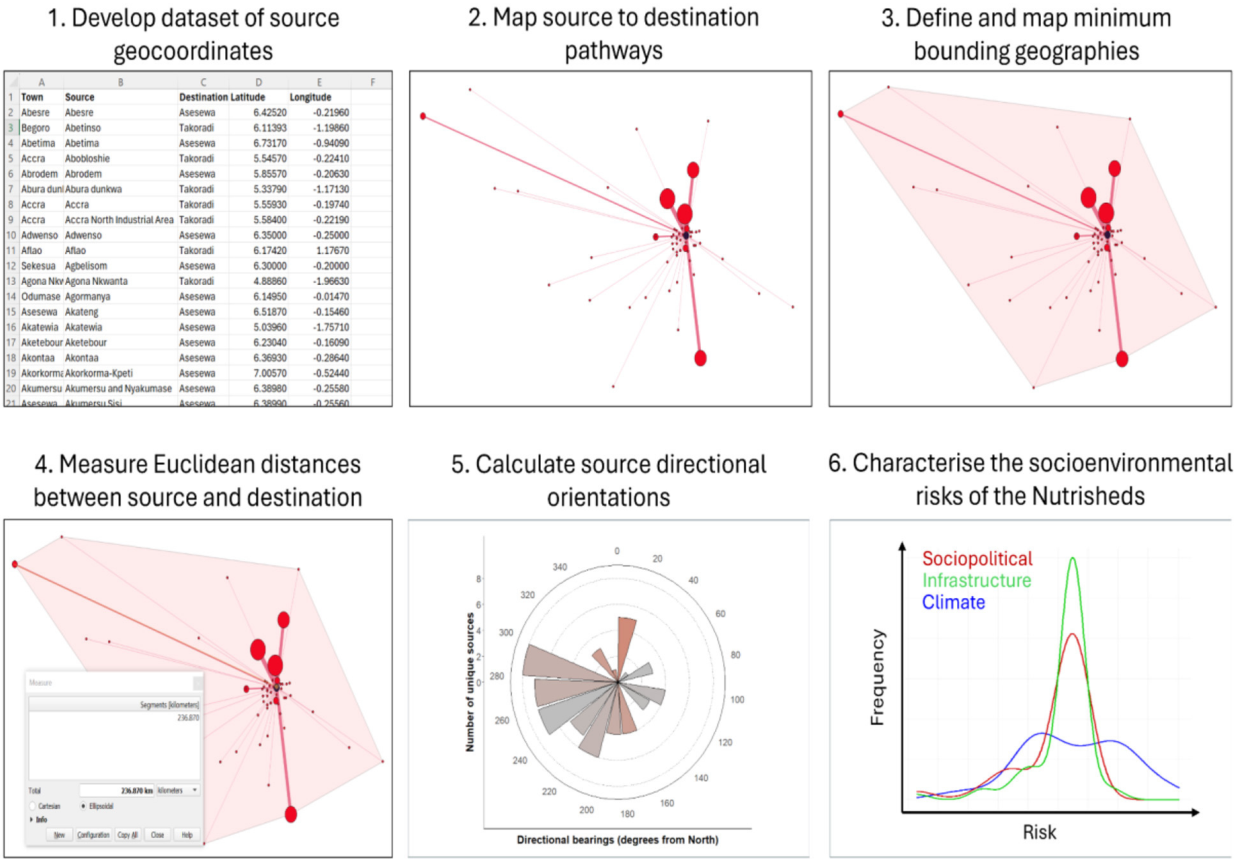

FIGURE 3
Graphical illustration of the key geospatial analysis techniques used to map and characterize the NutriSheds of our source nutrients flowing into Takoradi and Asesewa.

of road density, population density, and climate data in the study communities.

The primary data collected in Stage II required the digitisation of survey responses in order to be mapped. During the road intercept surveys, transporters were asked to provide the names of the production villages for each of the different items being transported, as well as the name of a nearby town to help triangulate the exact village (i.e., in case of multiple villages with the same name). The locations of production villages were then digitized in Microsoft Excel by exporting the latitudes and longitudes from Google Maps. Where villages were not present on Google Maps, we searched for popular public mapping websites such as MapCarta, Latlong.net and Tageo. Where villages could not be located after the above two steps, we used the geo-coordinates of the nearby town associated with the production village that was provided during the intercept survey. Across both seasons and destinations, this process produced 770 records of food inflows (i.e., food items, quantities, transport modes etc.) and 274 records of outflows (details in our forthcoming paper, Cooper et al., Unpublished).

These Excel datasets were then exported as Comma Separated Values (CSV) files readable as Delimited Text layers in the open access GIS software QGIS (v.3.28). From here, the Nutrisheds of each limiting nutrient were mapped using two of QGIS's in-built geospatial processing functions, namely (i) "Join by lines (hub lines)" - which provides straight line Euclidean geometry connections between source locations and destination locations (i.e., Asesewa and Takoradi), and (ii) the "Minimum bounded geography" tool using "convex hull" geometry - which creates a polygon representing the smallest region that encloses all of the source locations for a given limiting nutrient (e.g., iron) flowing toward our two study sites (i.e., Asesewa and Takoradi). Similar to a watershed, i.e., the topographic features which bound a river catchment, the convex hull here represents the catchment area bounding all sources of our limiting nutrients within the survey periods.

The previous steps mapped the flow of nutrients across space (i.e., from source to destination). We performed two further calculations to understand the spatial dimensions of the different Nutrisheds across seasons. First, the "Distance to nearest hub (Line to hub)" tool calculates the Euclidean distance in kilometers between each source location and destination - estimating the minimum distances that each nutrient flow must travel to arrive at our study sites. This calculation generated information on how the cumulative quantities of nutrient supplies vary with distance from the study sites - thus depicting the dependency of Takoradi and Asesewa on local and/or distant food supplies. Second, to understand the orientation of the Nutrisheds, we used QGIS's inbuilt trigonometric functions (i.e., "atan" function) to calculate the directional bearing (i.e., 0-359°) of each Euclidean pathway between source and destination. Specifically, compass bearings were estimated from the relative differences in the longitude and latitude coordinates of each pathway, allowing the dominant directional orientation of limiting nutrient flows to be calculated for each nutrient, destination and season combination.

TABLE 1 Summary of theoretical basis.

Theoretical Framework/ Concept	Contribution to the NutriShed Framework
Food environmental analysis	Explains how availability, affordability, access, quality and desirability shape food acquisition and diets (Turner et al., 2018; Downs et al., 2020).
Value chains for nutrition	Explains how actors, markets, transport, storage and processing influence the supply and nutritional value of foods (Gelli et al., 2015; Hawkes and Ruel, 2012).
Foodshed analysis	Provides the spatial logic for mapping where food comes from, how far it travels, and how cities depend on production catchments (Peters et al., 2009; Cleveland et al., 2014).
Resilience/ vulnerability thinking	Strengthens the focus on shocks, seasonality, climate risk, infrastructure gaps and system fragility (Peters et al., 2009; Tendall et al., 2015).
NutriShed framework	identifies nutrient gaps, maps nutrient-rich food flows, and assesses infrastructure and climate vulnerabilities; strengthening the theory section should mainly involve making this conceptual integration explicit (Akparibo et al., 2025)
Nutrition security framing	Keeps the framework anchored in nutrient adequacy for vulnerable groups, not simply food availability.

Building on the traditional Euclidean distances depicted in foodshed analysis, the NutriShed framework calculates the indicative time taken for nutrient-dense food sources to travel (i.e., "flow") between source location and the study sites. In QGIS, the road network vectors for Ghana, Togo and Benin can be "rasterized" to calculate the "least cost pathways" for food flows between source and destination—defined by the route through the road network which has the least cumulative cost of all alternatives (Douglas, 1994; Tang and Dou, 2023). The cost of moving one 1 km raster grid cell was calculated as the inverse of the speed limit for a given road type, such as 100 km/h for motorways and 90 km/h for trunk highways (Government of Ghana, 2013). Using QGIS's inbuilt "Least Cost Pathway" tool, the distance and likely duration (i.e., distance divided by maximum speed limit) of food flows into our study sites can be derived.

As a result of the above analyses, for each of the four limiting nutrients flowing into Asesewa and Takoradi, we are able to compare seasonal estimates of (i) the number of production sources and the associated catchment area, (ii) the variation in supply contributions against distance from Asesewa and Takoradi, (iii) the directional dependency of nutrient inflows into our study sites, and (iv) indicative estimates of the time taken for nutrient-dense food flows to travel to their consumption communities.

3.4 Stage IV: assessment of nutrient flow vulnerabilities

Stage IV of the NutriShed approach aims to provide insights for town and city planners into (a) the origins of the key limiting nutrients flowing into their communities, (b) the current usage of existing food system infrastructures (e.g., storage and

TABLE 2 Description of the primary and secondary datasets forming part of the NutriShed approach.

Dataset	Primary/ secondary	Coverage	Resolution	Source
Rapid food consumption surveys	Primary	Our study communities—Takoradi and Asesewa	Household level	Primary data collection
Food flow intercept surveys	Primary	Our study communities—Takoradi and Asesewa	Point data	Primary data collection
Food systems infrastructure (e.g., processing facilities, cold storages, collection centers)	Primary	Our study communities—Takoradi and Asesewa	Point data	Primary data collection
Market characteristics	Primary	Our study communities—Takoradi and Asesewa	Point data	Primary data collection
Globcover—land cover map for Ghana	Secondary	National	300 meters	MERIS data via Amerigeoss repository
Ghana New 260 District administrative boundaries	Secondary	National	Not relevant	ArcGIS hub
Roads	Secondary	National	Point data	GeoFabrik OpenStreetMap portal
Population density	Secondary	National	400 m	Kontur population
Climate-conflict-vulnerability index	Secondary	Global	0.5° or 55 km	CCVI online portal

processing facilities) within their communities, and (c) the potential vulnerability of the NutriSheds to anthropogenic and/or climatic disruption. To this end, for each of the four NutriSheds across the two study sites and two seasons, we quantified (i) all-weather road densities, (ii) climate risk, (iii) conflict risk, and (iv) the current congruence between the use of existing food system infrastructures and the needs of the limiting nutrient flows.

Unlike feeder road tracks that are vulnerable to being washed away during heavy rainfall events, all-weather roads provide relatively permanent and reliable transportation routes to connect producers with downstream consumers throughout the year (Rammelt and Leung, 2017; Weatherspoon et al., 2017). Therefore, as a proxy for the level of road connectivity between source locations and study communities, we calculated the density of all-weather roads within each NutriShed (km/1,000 Km^2). As per OpenStreetMap data available via the online repository GeoFabrik, all-weather roads are considered as those labeled "primary", "secondary", or "tertiary" classifications; as such, roads labeled as "track", "residential", "service", "path" and "bridleway" were omitted from the analysis using the QGIS layer filter function. Lastly, road density was calculated by dividing the summed length (km) density of the three included road classifications within a particular Nutrished by the total area (km^2) of the NutriShed. NutriSheds with comparatively low road densities are considered to be relatively vulnerable to poor connectivity, including a sparsity of alternative routes in case the primary route between source and destination is impassable (e.g., during a flood event).

Next, the climate and conflict risks of all NutriSheds were quantified using georeferenced data from the Climate-Conflict-Vulnerability Index (CCVI) dataset of Mittermaier et al. (2024). Publicly available at 0.5° resolution, the CCVI integrates multiple global coverage datasets to quantify local climate and conflict risks across the entire globe. As detailed in Mittermaier et al. (2024), the climate and conflict risks at any given point are a function of "climate/conflict exposure" multiplied by "vulnerability". "Climate exposure" is a composite index of current (i.e. past 3 months) and accumulated (i.e. past 7 years) droughts, heatwaves, heavy precipitation, wildfires, floods and tropical cyclones, and the mean precipitation anomaly (past 30 years relative to 1951–1980 baseline), mean temperature change (past 30 years relative to 1850–1900 baseline), and relative sea level rise from 1993–2005. Next, conflict exposure' is a composite index of the intensity and persistence of (a) local conflict and (b) popular interest (i.e., protests and riots). Lastly, vulnerability' is a composite index constituting 14 indicators of socioeconomic (e.g., gender inequality, health vulnerability, economic deprivation), political (e.g., civil rights deprivation, ethnic marginalization) and demographic (e.g., uprooted people, population growth) vulnerabilities. For our NutriSheds, we use QGIS's in-built "Distance to nearest hub (Line to hub)" function to associate each production source with its nearest recorded data point for climate risk and conflict risk; in turn, for the catchment areas, the spatial "clip" tool is used to subset the climate risk and conflict risk values located within the convex hull of each NutriShed catchment.

In addition to the nutrient flow data, we also analyzed the geospatial data collected on the markets, storage and processing infrastructures for nutrients dense foods (NDFs) in Asesewa and Takoradi. In particular, we explored the number and type of different infrastructures (e.g., cold storages, regular storages, processing facilities, and collection centers), and documented the practices related to storage and/or processing nutrient-rich target food identified. Cooper et al. (Unpublished) reports detailed findings of this component of the Framework application.

3.5 Stage V: identify catchment level nutrition-sensitive strategies and interventions

Stage V employed Geographical Information Systems (GIS) techniques to examine the solution space of alternative interventions to boost nutrient supplies toward underserved study communities. The process involved analyzing catchment area land-use and identifying potential for local production to bolster nutrient supply. We used spatial multi-criteria decision analysis to examine strategic locations for new markets or cold-storage facilities. The geospatial analysis was extended by qualitative systems dynamic modeling to scope potential future (i.e., multi-decadal) trade-offs emerging from the solution space, including modeling the key feedback loops and system archetypes (Senge, 2006) driving the distributions of nutrients, environmental impacts, and the participation of women and other underrepresented groups in NutriShed. The use of systems modeling here represents an expansion of the traditional FoodShed methodology, which has traditionally mapped and quantified the movement of food over space (e.g., Karg et al., 2016; Hemerijckx et al., 2023; Karg et al., 2023), but stopped short of unpacking the qualitative reasons underpinning these patterns (e.g., the motivations of individual food traders and the ways in which government policies shape food flows over space and time). A portfolio of strategies was then compiled for community stakeholder consideration – the details are reported in Cooper et al. (Unpublished).

4 Engaging with stakeholders/reference groups

Throughout the project, we engaged with relevant community- and national-level experts, decision-makers, and key actors (Reference Group) informally from start, and meeting them formally during this phase. To ensure effective participatory planning, and buy-in, two types of meetings were held with the Reference Groups in Asesewa and Takoradi. Reference Group members were selected based on their expertise, and roles in health, agriculture and education in their respective districts and at the national level.

The first Reference Group meeting involved national-level experts, community leaders, non-governmental organization (NGO) actors, and academics. This meeting presented the project plan and solicited their input to ensure implementation feasibility, and to identify all relevant stakeholders to involve. The second Reference Group meeting brought together supply chain actors, including traders and retailers, to discuss the perceived benefits and trade-offs of the proposed study. Subsequently, a broader range of stakeholders, including the Reference Group, from each city, were engaged during the dissemination of the preliminary findings. This convening generated conversations around local production of nutrient rich foods, transportation and barriers to healthy eating.

4.1 Ethics approval

Ethical approval for this study was obtained from the Ethics Committee for Basic and Applied Sciences (ECBAS), University of Ghana (Approval Number: UG-ECBAS050/22-23). All participants provided informed consent prior to participation, and the study was conducted in accordance with relevant ethical guidelines and regulations.

5 Results

As this paper focuses on presenting the NutriShed methodological framework, the detailed empirical findings generated from the application of the framework are reported in separate companion papers. This approach allows the present manuscript to concentrate on describing the conceptual and analytical stages of the framework and its methodological contribution to nutrition security planning. Specifically, the findings from *Stage I*, which identify limiting nutrients in the diets of vulnerable urban populations, are reported in Dake et al. (2025) (see preprint: *Exploring Limiting Nutrients in the Diets of Urban-Dwelling Women, Children and Adolescents in Two Cities of Ghana*). The results from Stages II and III, which examine food supply chains and map spatial nutrient flows into the study cities, are presented in a forthcoming paper by Afagbedzi et al. (Unpublished). Finally, the findings from Stages IV and V, which assess food system vulnerabilities and identify nutrition-sensitive planning interventions, are reported in Cooper et al. (Unpublished). Together, these papers demonstrate the application of the NutriShed framework across its different analytical stages, while the present paper provides the overarching methodological foundation and integrated framework that underpins these analyses.

6 Discussion

6.1 Contribution of the NutriShed framework to nutrition security research

The NutriShed framework contributes to addressing an important methodological gap in the analysis and planning of nutrition security within urban food systems. Rapid urbanization in low- and middle-income countries has increased the complexity of food supply chains and nutrient distribution pathways. While existing approaches, including foodshed analysis and value chain analysis (Getz, 1991; Chen, 2012; Kloppenburg et al., 1996), provide useful insights into food sourcing, commodity flows, and market systems, they are not specifically designed to trace the movement, accessibility, and spatial distribution of essential nutrients across urban food environments. NutriShed builds on these approaches by integrating nutrient flows, dietary relevance, and spatial food system dynamics to support nutrition-sensitive urban planning and decision-making. The NutriShed framework provides a structured methodological approach for mapping the spatial flows of key micronutrients into and within cities, thereby offering a novel way to assess vulnerabilities in nutrient supply chains and urban food system infrastructure. By integrating dietary assessment, market system analysis, and geospatial mapping, the framework advances existing approaches that often examine food environments or value chains in isolation.

6.2 Relevance for urban food system planning and policy

The NutriShed framework has important implications for urban nutrition planning and food system governance. By identifying where key nutrients originate and how they move through urban supply chains, the framework can support policymakers and urban planners in diagnosing vulnerabilities in nutrient availability. This is particularly relevant in rapidly urbanizing settings where food systems are characterized by informal markets, fragmented value chains, and climate-related risks. The framework therefore provides a potential decision-support tool to inform nutrition-sensitive urban planning, strengthen food system resilience, and guide interventions aimed at improving the availability of nutrient-rich foods.

Another important feature of the NutriShed framework is its relevance for low- and middle-income country (LMIC) urban contexts, where food systems are often poorly documented and dominated by informal actors. The approach allows researchers to capture complex nutrient flows through informal markets, transport systems, and regional food production networks that are typically overlooked in conventional food system analyses. As such, the framework provides a practical methodological tool for generating evidence in settings where routine food system data are limited.

6.3 Overall lessons learned from the application of the NutriShed framework

Pre-testing and thorough training played a pivotal role in the successful implementation of the NutriShed study. A mixed-format approach to training, incorporating both online and in-person sessions, was employed to ensure that all enumerators, including police officers, fully understood the survey tools and objectives. In Takoradi, enumerators practiced dietary interviews in a school setting under the supervision of both school authorities and a field supervisor, enabling enumerators to address potential data collection issues prior to field data collection.

Reconnaissance activities, including prior investigations on market days along trade routes, as well as a pretest conducted on the Sekondi–Accra Road, significantly contributed to the optimization of field data gathering strategies. Engaging market women leaders (also known as market queens in Ghana) in each of the cities provided insights into market schedules, helping to align the survey days with "specific market days" for particular foods.

In Takoradi, the field team was organized into smaller units of 3–4 individuals, with the most experienced members assigned as the team leader for each division. These smaller teams proved to be highly effective, covering more ground, ensuring accountability, and facilitating quick responses to any issues that arose. The use of smaller, well-organized teams also helped to streamline task-sharing, reduce data collection time, and improve overall efficiency and accuracy.

The structure and communication within the team were further enhanced through the use of local enumerators, who were familiar with the language, local navigation, and community dynamics. This approach not only increased trust from community members but also contributed to more efficient training and improved data quality, as many enumerators had previous fieldwork experience. The enumerators' formal education, with the lowest qualification being senior high school certification and the highest being a first degree, further contributed to the quality of the data collected. Regular field presence and open communication channels with the field supervisor played a significant role in boosting team morale and ensuring the accuracy of the collected data.

The logistics of the survey were well-supported by the provision of essential tools and supplies. Enumerators were equipped with reflective vests, name tags, pens, and notepads, which enhanced professionalism and provided backup in the event of digital tool failures. Daily preparedness was also ensured through early morning phone calls to team leaders and police officers during intercept surveys, enabling the reassignment of roles in cases where team members were unavailable due to illness or other reasons. Incentives and allowances were provided to both enumerators and police officers throughout the data collection process, covering transport and communication expenses and ensuring smoother coordination between supervisors and fieldworkers. Additionally, respondents in the surveys were given incentives, such as books and pens, as compensation for their time and participation.

Engagement with the community and road users was an ongoing process throughout the survey. Repeated interactions with drivers, police officers, and market actors helped to build trust and foster voluntary compliance. Some informed community members, having been briefed by enumerators, took the initiative to explain the nature of the surveys to others, further increasing community participation and trust in the process. Health and safety measures were prioritized during the survey. The use of reflective vests improved visibility, particularly at checkpoints, while nose masks provided protection against dust and other airborne particles.

Appointment scheduling was another critical element in ensuring the success of the dietary surveys. Targeted scheduling with parents helped to avoid missed appointments, and conducting interviews after school hours and on weekends proved to be the most effective strategy. By scheduling appointments with both parents and children, the team ensured that dietary and backtrack surveys were conducted at convenient times, thereby maximizing efficiency and minimizing the risk of missed interviews. Given that school children had lessons from 8:00 am to 3:00 pm, it was crucial to schedule interviews outside of these hours to ensure successful data collection.

6.4 General challenges encountered in applying the NutriShed framework in the study sites

One of the primary challenges encountered during the dietary surveys was availability of participants at home. Meeting adolescents at home for interviews was challenging because they spent much of the day in school. This issue was mitigated by arranging appointments after 3:00 pm and on weekends. Secondly, the estimation of food quantities was difficult for younger respondents; they were unable to accurately recall or describe the content of meals they had consumed, without adult supervision. We had to follow up some of them in school to gather missing information. This approach was further challenged by the need for appropriate parental permissions to enable their wards to be accessed at school.

During the data collection period, ongoing road construction created significant disruptions to the intercept survey, particularly in Takoradi. Active roadworks led to certain roads being blocked on specific days. These unexpected changes in traffic patterns disrupted some planned data collection activities. In such situations, supervisors worked with enumerators and the local police to identify alternative stop points.

Language was a barrier to the identification of some indigenous foods. For example, waterleaf (*Talinum Triangulare*), known as *bokoboko* in Asesewa, is known as *kotubete* in Takoradi. The study team had to learn and adapt to the indigenous names of various foods in order to effectively communicate the prioritized foods during the intercept surveys.

During the intercept surveys, some drivers were hesitant to stop at police checkpoints and will speed off due to fear of potential challenges from being stopped by the police. Additionally, the police officers' attention was divided between their normal duties and supporting the data collection efforts, which occasionally resulted in missed opportunities for data collection. Punctuality also posed a challenge, as delays from either police officers or enumerators sometimes hindered the timely commencement of early morning data collection.

Logistical constraints further complicated the intercept surveys. As stated previously, some roads were under construction or redirected, leading to unexpected traffic patterns and increased dust levels, which affected both the enumerators and the survey respondents. Moreover, some police checkpoints were situated at distances that were not ideal for intercept surveys, requiring the team to temporarily set up checkpoints in alternate locations. Lastly, there was a noted low police presence in Asesewa, which hindered the survey process. The involvement of Community Police Assistants (CPAs) was deemed necessary to address this issue, but their limited authority and lack of respect within the community reduced their effectiveness in supporting the survey activities.

These challenges were addressed through adaptive iterative problem-solving strategies, based on engagement with stakeholders. These strategies helped to mitigate the impact of the barriers and enabled the data collection activities to be completed.

6.5 Methodological innovations and strengths

A key strength of the NutriShed approach is its integrated multi-stage methodology, which links population nutrient needs with food supply chain dynamics and spatial food system infrastructure. This integration allows the framework to move beyond traditional foodshed or food environment analyses by explicitly focusing on nutrient flows rather than only food commodities. The staged design, identifying nutrient gaps, mapping food supply chains, analyzing spatial flows, and assessing vulnerabilities, provides a systematic process that can be replicated in other urban settings. The use of geospatial tools further strengthens the framework by enabling the visualization of nutrient supply networks and identifying geographic bottlenecks in urban food systems.

7 Limitations

This study has several limitations that we acknowledge here. First, the road intercept survey approach may have introduced selection bias, as drivers who agreed to stop and participate may systematically differ from those who did not, potentially affecting the representativeness of observed food flow patterns, although we know from experience that the decision to stop or otherwise is linked to risk of police harassment and not linked to the cargo *perse* Second, data collection was conducted over a relatively short sampling period and therefore may not fully capture seasonal variability in food availability, transport dynamics, and nutrient flows, which are known to fluctuate across agricultural and market cycles in Ghanaian urban food systems. Third, although the NutriShed framework provides important insights into the spatial movement and sources of nutrients entering urban areas, it is less able to capture inequities in intra-urban nutrient distribution, including differences in physical access, affordability, and utilization of nutrient-rich foods across neighborhoods and socioeconomic groups.

In addition, the NutriShed framework relies on multiple data sources, including dietary surveys, market assessments, and geospatial analyses, which can be resource-intensive and may limit its immediate application in data-poor settings. Mapping nutrient flows also depends on the availability and quality of market and supply chain data, which may vary considerably across contexts. Similarly, the spatial depiction of source locations is dependent upon the underlying resolution of geospatial data available; therefore, in territories where Google Maps and OpenStreetMap coverage is relatively sparse (e.g., the Amazon Rainforest and Sahara Desert), the analysis may need to be conducted at a relatively aggregated spatial scale (e.g., larger administrative units such as a state or district) or utilize relatively country-specific sources of data (e.g., national censuses). Finally, while the framework enables identification of potential vulnerabilities within urban nutrient supply systems, it does not in itself assess the effectiveness of interventions designed to address these vulnerabilities.

Future applications of the framework could be strengthened through longitudinal and seasonally repeated sampling, integration of household- and neighborhood-level food access data, and incorporation of more granular spatial equity analyses to better understand intra-urban disparities in nutrition security.

8 Future research and methodological development

Future research could further refine and expand the NutriShed framework in several ways. First, additional applications in diverse urban contexts would help test its adaptability and generalisability across different food system structures. Second, integrating the framework with climate risk modeling and food price monitoring could enhance its ability to assess emerging threats to urban nutrition security. Third, the approach could be linked with participatory planning processes involving policymakers, food system actors, and community stakeholders to strengthen the translation of evidence into actionable policy interventions

9 Conclusions

Urbanization is placing increasing pressure on food systems, making nutrition security an urgent priority, particularly in the context of climate change, supply disruptions, and socio-economic inequalities. The NutriShed framework offers a novel methodological approach to assess and map the spatial flows of essential nutrients within urban food systems. By integrating dietary assessment, market analysis, geospatial mapping, and infrastructure evaluation, the framework enables the identification of nutrient gaps, supply chain vulnerabilities, and opportunities for targeted nutrition-sensitive interventions.

Applied in Ghanaian cities such as Takoradi and Asesewa, NutriShed demonstrates how locally grounded evidence can support urban planners and policymakers in strengthening food system resilience and improving equitable access to nutritious foods. As cities continue to grow, methodological tools such as NutriShed will be increasingly important for informing evidence-based strategies that integrate nutrition considerations into urban planning and sustainable food system development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the University of Ghana Ethics Review Committee for basic and applied sciences (Approval no. UG-ECBAS 050/22-23. The studies were conducted in accordance with the local legislation and institutional requirements. The participants/participants' legal guardians/next of kin provided their written informed consent to participate in this study.

Author contributions

RoA: Methodology, Writing – original draft, Validation, Project administration, Conceptualization, Resources, Writing – review & editing, Funding acquisition. RA: Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Validation, Data curation, Resources, Writing – original draft, Project administration, Funding acquisition. GC: Writing – review & editing, Formal analysis, Data curation, Validation, Methodology, Writing – original draft, Supervision, Conceptualization, Funding acquisition. FD: Writing – review & editing, Supervision, Writing – original draft, Validation, Methodology, Investigation, Data curation, Formal analysis. SA: Supervision, Validation, Investigation, Methodology, Data curation, Writing – review & editing, Writing – original draft, Formal analysis. EY: Writing – review & editing, Investigation, Data curation, Formal analysis. BO: Data curation, Writing – review & editing, Investigation, Formal analysis. CE: Project administration, Investigation, Writing – review & editing. BS: Conceptualization, Resources, Writing – review & editing, Funding acquisition, Validation, Methodology, Project administration.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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