Are healthy foods affordable?
The past, present, and future of measuring food access using least-cost diets

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Abstract
This review describes the history, current practice and prospects for measuring a population's access to foods for health using the lowest-cost locally available items, in contrast to quantities actually chosen, so as to distinguish between unaffordability of healthy diets and other causes of malnutrition. Retail prices, cost per day and affordability relative to earnings have been used to measure food access for centuries, driving early definitions of poverty and income thresholds for subsistence. Substitution between items based on food composition was introduced soon after nutrient requirements were quantified, leading to the development of linear programming and other diet modeling techniques. This article describes how and why modern diet cost and affordability metrics have been adopted by international organizations, government agencies and researchers to monitor food markets and guide intervention, concluding with new frontiers for research on other factors limiting access to healthy diets such as cooking costs and time use.

JEL codes
Q11, Q18, I15, I32

Keywords
Price indexes, food composition, diet quality, nutritional value

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1. Introduction and motivation

Having sufficient food to meet nutritional requirements is one of humanity's oldest concerns, with documented records dating as far back as 5000 years ago in Mesopotamia (Postgate, 1994). Mesopotamian records include cereal rations designed to meet the basic requirements of workers, accompanied by specification of more diverse, ideal diets to which higher-income people could aspire (Ellison, 1981). In the modern era, monitoring the adequacy of the global food supplies has been a central focus of international cooperation for over a century, since the League of Nations (1920) began its *Monthly Bulletin of Statistics* tracking changes in food prices and quantities around the world.

Recent innovations in the measurement of food access have been driven by both policy priorities and methodological advances in data collection and analysis. The current internationally accepted definition of food security, established at the World Food Summit of 1996, is "when all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (Committee on World Food Security, 2012). Different aspects of that concept have been measured in different ways, most recently by defining access as affordability of the lowest-cost locally available items in quantities needed to meet national governments' food-based dietary guidelines. These diet cost and affordability metrics are designed to distinguish access from utilization, and thereby guide change in food environments as discussed by Herforth and Ahmed (2015), for the purpose of improving diet quality and nutritional outcomes as measured using a variety of metrics described for example by Lele et al. (2016).

This review summarizes the analytical methods, data sources, and policy applications for the least-cost diets now used to monitor food access globally. Benchmark least-cost diets differ from actual consumption patterns in ways that help distinguish among causes of poor diet quality and thereby guide intervention. Where and when least-cost items are unusually expensive, access to healthy diets can be improved by investments in agricultural production and food distribution towards the frontier of lowest costs observed elsewhere. If prices are at the low-cost frontier but available incomes are even lower, healthy diets remain unaffordable so improving the nutritional quality of diets would require increased earnings, lower nonfood expenditure, or social assistance and safety nets. And if a low-cost healthy diet would be affordable but those foods are displaced by other items, remedies would need to address drivers of food choice beyond price and income, such as preferences and aspirations, or time use and cooking costs in meal preparation.

Calculating least-cost diets that meet nutrient requirements was initially attempted by Stigler (1945), and was done primarily to formulate rations for the military and other feeding programs. Using least-cost items by food group to track international variation in a global standard for diet diversity was introduced by Masters et al. (2018a) in a study of monthly fluctuations by region in Ghana and Tanzania, and by Herforth et al. (2020) for global measurement of costs per day and the total number of people unable to afford healthy diets as a background paper for the UN agencies' flagship report on *The State of Food Security and Nutrition in the World* (FAO, IFAD, UNICEF, WFP and WHO, 2020). Subsequent updates were designed to facilitate monitoring of changes from year to year as detailed in Herforth et al. (2022), including especially formulation of food group targets for a Healthy Diet Basket (HDB) (Herforth et al. 2025) used in the suite of metrics known as the Cost and Affordability of a Healthy Diet (CoAHD) now calculated annually by international agencies (FAO, 2024a; World Bank, 2024a) and national governments such as Nigeria's National Bureau of Statistics (2024).

We begin this review with a brief summary of food price and quantity data available prior to the recent work on cost and affordability of healthy diets, including the prevalence of undernourishment that is

widespread even when prices are low, and the experience of food insecurity as people skip meals, eat less, go to bed hungry and are affected in other ways by lack of money to buy their usual diet. We then describe how least-cost diets based on nutrient requirements were developed and used to guide nutrition assistance in the U.S. and globally, and how monitoring least-cost healthy diets based on food groups can allow decisionmakers to distinguish access from use, thereby guiding efforts to end malnutrition by improving food supply towards the frontier of lowest cost, raising incomes to make those diets affordable, or limiting displacement of healthy diets by less nutritious foods.

2. Prices, incomes, and previous approaches to food security measurement

Food prices relative to incomes are among the first societal conditions to have been measured, with patterns of change clearly revealed by data for recent decades. An early English-language description of how a diet cost metric could be used to assess the adequacy of wages was written nearly 350 years ago by Rice Vaughan (1675). Despite the archaic wording, modern readers will recognize the idea that wages paid to workers should account for the cost of sufficient food, clothing and other things needed for daily subsistence:

> *The hire of Labourers and Servants carrieth with it a resultance of the prices of all things generally necessary for a mans life: Besides, that Reason doth convince that there must be a convenient Proportion between their Wages and their Food and Raiment, the Wisdom of the Statute doth confirm it, which doth always direct the Rate of Labourers and Servants to be made with a regard of Prices of Victuals, Apparel, and other things necessary to their use.*

The first recorded effort in English to actually compute affordability is due to William Fleetwood (1707), prompted not by the needs of low-wage workers but by student requests for more generous stipends at Oxford University. The income threshold for Fellowships had been set at £5 per year more than 150 years earlier, and Chance (1966, page 109) quotes Fleetwood's explanation of the need for an increased allowance spells out much of the logic behind modern food price indexes:

> *To know somewhat more distinctly whereabouts an Equivalent to your ancient £5 will come, you are (as I before hinted) to observe how much Corn, Meat, Drink, or Cloth, might have been purchased 250 Years ago, with £5 and to see how much of the modern Money will be requisite to purchase, the same quantity of Corn, Meat, Drink, or Cloth, now-a-days. To this End, you must neither take a very dear Year, to your Prejudice, nor a very cheap one, in your own Favour, nor indeed any single Year, to be your Rule; but you must take the Price of every particular Commodity, for as many Years as you can (20, if you have them) and put them all together; and then find out the common Price; and afterwards take the same Course with the Price of Things, for these last 20 years, and see what Proportion they will bear to one another; for that Proportion is to be your Rule and Guide.*

Fleetwood's analysis of students' cost of living was based on a fixed basket with 5 quarters of wheat, 4 hogsheads of beer, and 6 yards of cloth. A variety of similar consumption baskets were later proposed for different purposes, such as the weighted average of market prices used by the Massachusetts State legislature in 1780 to adjust the pay of Revolutionary War soldiers, based on a basket of 5 bushels of corn, 68.6 pounds of beef, 10 pounds of sheep's wool and 16 pounds of sole leather (Diewert, 1988).

The concept of affordability links food prices and diet costs to a measure of earnings, the analysis of which dates at least to William Playfair (1821) who charted the price of bread relative to workers' wages in England. Playfair's analysis showed how bread had become increasingly affordable in the 17th and early 18th centuries, but that this history of improvement ended when bread prices began to rise at roughly the same rate as wages. The title of Playfair's pamphlet, "A Letter on Our Agricultural Distresses, Their Causes and Remedies" summarizes how measuring the affordability of food could guide action by comparing food prices to available income. Playfair's chart of the decline followed by stability in the real cost of bread marks the earliest well-documented analysis of diet costs and affordability, using only the one type of food and one source of income for which data were available.

Over the 19th and 20th centuries people began to consume an increasingly wide range of foods and other things, sparking interest in cost-of-living indexes that would reflect the total cost of diverse items, weighting each price by its share of expenditure to track the average cost of what people buy. Étienne Laspeyres (1871) advocated for using quantities consumed during the initial observation period, while Hermann Paasche (1874) argued for using the ending period quantities. If the purpose of price indexes is to track the cost of achieving a specific living standard, then indexes should allow for a population's willingness to substitute between items as prices change. In the 20th century, analysis of household survey data allowed those substitution possibilities to be represented by empirically estimated demand systems, summarizing a population's choices in response to income and price changes using a set of simultaneous equations whose functional forms and parameter restrictions are internally consistent (Deaton and Muellbauer, 1980), leading to the development of chained price indexes whose weights vary over time to match each population's expenditure share for each kind of items in the index (Diewert et al., 2009).

The availability of comprehensive price indexes over many goods and services allows the cost of each item to be expressed in real terms, relative to the prices of all other commodities. Some ongoing work is pursuing Playfair's comparison of food prices and diet costs to laborer's wages (Headey et al., 2024a), but most analyses focus on comparing observed nominal prices of food in each current period to a Consumer Price Index (CPI) to reflect the real purchasing power of money in a constant base period. The resulting Consumer Price Index (CPI) is now calculated monthly by almost every national government in the world, with global efforts to harmonize methods and reporting procedures led by the United Nations (UN) Statistical Commission and other international agencies (ILO, IMF, OECD, EU, UN, and WB, 2020).

Comparing food environments in terms of access to a given dietary standard must contend not only with the diversity of items consumed (leading to the use of food price indexes instead of individual item prices), the diversity of income sources (prompting the use of total earnings instead of wages), and the role of nonfood goods and services (driving the use of general CPI to adjust for inflation), but also spatial differences in price levels that call for adjustments based on purchasing power parity (PPP) comparisons. PPP adjustments are based on differences in the average price level for all goods and services in an entire territory, measuring the cost of similar items in different places. This is done within countries using CPI item prices in the U.S. (BEA, 2024) or similar methods elsewhere (Amendola et al., 2023), and done globally between all countries of the world by the International Comparison Program (World Bank, 2024).

2.1 Modern data on availability and price of commonly consumed items

The availability of data on which foods are sold at what price around the world was reviewed by Bai et al. (2021b), showing that by far the most complete and reliable coverage is provided by each country's CPI item lists designed to monitor general inflation, and the internationally standardized PPP items used to compare price levels between countries. Almost every national government now computes a monthly CPI and reports prices for PPP comparisons every few years, with strong incentives for consistent reporting to maintain eligibility for international finance and aid flows. Those price indexes are intended to reflect nationally representative prices for a broad set of items, including dozens of each country's most commonly consumed foods. Other food price data has narrower coverage and less consistency over time, including market information and early warning system prices used to guide farm production and food distribution, or specialized sources tracking prices of specific items from particular marketing channels such as prices posted online, scanned from bar codes, or collected by individual researchers. Some diet cost studies use those specialized price data, but most use CPI and PPP prices that now underpin dozens of research papers analyzing seasonal, spatial and other kinds of variation in diet costs and affordability (Food Prices for Nutrition, 2024a).

The CPI and PPP food items for which retail prices are routinely collected differ from country to country, and the individual item prices used to construct each CPI are not usually available to the public. Even when item prices are available, they may not be in a usable form, because the item description might not

be sufficiently detailed to identify its food composition. Price data collection for CPI requires only that prices refer to the same item from month to month, with no need to specify its exact size or composition. In contrast, data collection for PPP requires that prices refer to the same item in multiple countries, leading to more explicit product descriptions reported as part of the International Comparison Program dataset. Also unlike item prices used for national CPIs, the item prices used for international PPPs are available to researchers on request. They are compiled only every few years and provide only one national average price for each item, but due to their global coverage, high reliability, and official status as government statistics, these PPP prices are the foundation for global diet cost monitoring, while variation within countries is tracked with CPI prices and sometimes other sources as reviewed by Bai et al. (2021b).

Country governments typically report price indexes based on a limited number of the most widely consumed items. In practice, as shown by Bai, Herforth and Masters (2022, Supplemental Figure S2), including more than about one hundred items in the food list for PPP calculations has no impact on estimated least-cost diets, because the additional varieties included are higher-cost options with value-added attributes such as packaging and processing. Only those countries that report fewer than about a hundred food item prices are likely to omit some of the least expensive generic options in every food group needed for a healthy diet. Food lists used for diet cost calculations often omit hot prepared meals and ready-to-eat packaged foods, either because their nutritional composition is unknown, or because they are omitted from a healthy diet due to high added sugar, salt or other harmful ingredients. But even when they are included in a price list, prepared meals and most ready-to-eat packaged foods are not among the lowest cost options because their prices include value added services that make them more expensive per unit of food. Most diet cost measurements also omit a household's own garden or other food production, gleaning or gathering and fishing, and omit any foods received as gifts or charity, because least-cost diets aim to measure food access through each country's commercial food production and distribution system.

Linking food prices to nutritional value begins with each item's attributes needed for health, as reported in food composition databases such as FoodData Central (USDA, 2024a) and similar sources such as those listed by the International Network of Food Data Systems (FAO, 2024b) or the European Food Information Resource Network (EuroFIR, 2024). Item sizes are initially reported in terms of weight, volume or other natural units, and each food composition dataset uses the results of laboratory tests on foods and ingredients to report an item's edible portion and water weight, dietary energy, essential nutrients and other bioactive compounds that affect health. Accounting for edible portion and moisture content is especially important for vegetables and fruits as well as packaged and processed items that may be sold in dry or concentrated form or with high levels of water in the product. Composition data also allows classification of items into nutritionally defined food groups. For example, the high carbohydrate content of potatoes makes it a starchy staple for nutritional purposes, while it is usually classified as a vegetable in production and market data. Nutritional classification schemes differ and evolve over time, for example orange-fleshed sweet potatoes with high vitamin A content may be put in the same food group as carrots and other orange or red vegetables. Matching item descriptions to nutritional composition and food classification is among the most difficult steps in converting item prices to diet costs. To facilitate that step, the software tools for diet cost calculations provided by the Food Prices for Nutrition project includes a food item information database listing more than 500 products commonly found in price datasets, matched item numbers in 13 food composition databases to show typical edible portions and total energy content, classified by food group used in more than a dozen dietary guidelines around the world (Food Prices for Nutrition, 2024b).

2.2 Affordability relative to income and the evolving definition of food security

Comparing food prices or diet costs per day to available income could potentially be done in many ways. The current procedure used for global food security monitoring, done jointly by FAO (2024a) and the

World Bank (2024a), uses each country's income distribution from recent household surveys as compiled by the World Bank (2023), and subtracting nonfood spending observed on average around the national poverty lines adopted by governments at each level of income. As of October 2024 those international poverty lines are $2.15 per day in low-income countries, $3.65 in lower-middle-income countries, $6.85 in upper-middle-income countries, and $24.36 in high-income countries, of which the available household survey data shows average nonfood spending by households around those income levels to be $0.80, $1.61, $3.70 and $13.20 respectively, each expressed in 2017 dollars at PPP prices (FAO, IFAD, UNICEF, WFP and WHO 2024, supplemental table S2.3). This approach was developed for the purpose of monitoring access to healthy diets in the context of other UN and World Bank metrics of global development, using national governments' choices about poverty lines to specify the minimum target for nonfood spending, and replacing the food component of those national poverty lines with the least-cost locally available foods needed for health (Bai et al. 2024).

Before the availability of data and methods to compute least-cost diets as a measure of food access, the concept of food security -- or its absence, food insecurity -- was measured in a variety of ways as discussed by Barrett (2010) and catalogued by Lele et al. (2016) among others. All of those were based on usual diets actually consumed by the population, relative to a desirable target. Global food security metrics of this type began with a method developed by P.V. Sukhatme to estimate the number of people in each country whose total food intake is below their estimated energy requirements (Sukhatme, 1961). This approach, now known as the Prevalence of Undernourishment (PoU), is based on using survey data to estimate a log-normal distribution of energy intake among people, allowing shifts in each year's total population and national energy supplies to trace changes in the number and percentage of people with insufficient intake. The parameters used to measure PoU vary little from year to year so changes are driven primarily by variation in total national supplies as measured by food balance sheets (FAO, 2001).

The FAO's undernourishment metric was first used to track changes in global food security for all countries in the 1970s, in response to commodity price spikes and famines in several countries that led to the World Food Conference of 1974, where food security was defined as "availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices." (United Nations, 1975). During the 1980s and 1990s, increases in food production and total consumption drove down and stabilized market prices, so attention shifted from availability of adequate world food supplies to distributional concerns, and whether all people at all times are actually able to obtain foods that are available and sold to others.

In the 1980s, a key methodological advance for measurement of food insecurity came from survey methods first developed at Cornell University by Kathy Radimer (1990). Questionnaires to elicit a person's experience of food insecurity, initially known as the Cornell-Radimer Hunger Scale, were first implemented nationally by the USDA and the U.S. Census Bureau in 1995. Modified versions remain widely used today, most commonly as the USDA Food Security Survey Modules (USDA Economic Research Service, 2022), or the FAO Food Insecurity Experience Scale (FIES) questions developed under its "Voices of the Hungry" Project (FAO, 2023c). Both the USDA and FAO surveys measure food insecurity using a set of questions about whether individuals, due to financial constraints or other limitations, have ever skipped a meal, ate less or differently, went to bed hungry, or were otherwise unable to obtain their usual diet at any time over the previous twelve months.

The FAO's undernourishment measure refers to total energy derived from all foods, while food insecurity refers to whether a respondent was ever without enough money or other resources to eat their usual diet. The USDA questionnaire asks specifically about whether the respondent ever, sometimes, or often could not afford "the kinds of food we want to eat" while the FAO does not specify the type of food. This approach ensures that the measure captures variation in food insecurity separately from variation in population's level of food expenditure and diet quality. The one question about diet quality in the USDA

household module asks whether there were times when respondents "couldn't afford to eat balanced meals", and the one question about diet quality for children asks whether they "relied on only a few kinds of low-cost food to feed our children" (USDA Economic Research Service, 2022). The two corresponding questions in FIES relating to diet quality ask "whether, during the last twelve months, was there a time when, because of lack of money or other resources", the respondents "were unable to eat healthy and nutritious food" or "ate only a few kinds of foods" (FAO, 2023c). The few food security questions in USDA and FAO surveys that address diet quality represent a small step towards measuring access to nutritious items that would meet the 1996 definition of food security. These questions do effectively ask people whether they could afford "balanced meals" in the USDA survey, or "healthy and nutritious food" in the FAO surveys, but these terms lack quantification, and are left to the respondent to interpret. The outcomes are typically presented as an aggregate score based on responses to multiple questions—with responses to individual questions rarely reported. Measurement aligned with the 1996 mandate calls for a much greater effort to match food items with their nutritional characteristics, and add up the estimated costs per day as discussed below.

3. Development and use of benchmark least-cost diets for health

In economic terms, least-cost diets that meet nutritional requirements identify the frontier of cost-effectiveness for foods in a population's health production function (Grossman, 1972). That counterfactual benchmark can then be contrasted with foods chosen based on revealed preferences in observed demand systems, as in Deaton & Muellbauer (1980). A variety of other goals and constraints might lead people not to consume the least cost items needed for health, but even if people wanted and could afford them, food attributes for health are unobservable credence goods. Consumers cannot see, taste or smell many of the most important components in food that will affect their future health, so buyers must rely on other information such as health claims and premium prices, leading to the widespread belief that healthier foods are generally more expensive (Haws et al., 2017). Studies using actual data on health-related attributes can compare costs per calorie for each type of food as in Headey and Alderman (2019), or per unit of an individual nutrient across all types of food as in Ryckman et al. (2022, 2021b, 2021a), or per unit of a multidimensional quality index such as an item's Health Star Rating, Nutri-Score or Food Compass Score, thereby revealing that healthier items may or may not be more expensive (Martinez et al., 2024).

A central challenge in comparing foods and measuring diet quality is that multiple attributes are all needed for survival and health, each complementing the others as joint inputs to biochemical and physiological processes inside the body (Masters and Finaret, 2024). Overall diet quality scores such as those reviewed for the World Health Organization by Verger et al. (2023) take account of substitution among foods in delivering each attribute, and also consider complementarity among the attributes needed to avoid deficiencies and protect against diet-related diseases. Systematic monitoring of access to all food attributes needed for a healthy diet was made possible only recently, based on matching CPI and PPP item prices to food composition and nutritional requirements per day.

Modern metrics of dietary requirements for health are typically represented in terms of fixed targets or upper and lower bounds for a set of specific attributes, based on laboratory, clinical and epidemiological evidence about the normal range of variation within which people face relatively low disease risks. The role of food in health outcomes could potentially be modeled as a continuous function with dose-response based on relative risks as in Wang et al. (2020), but the use of discrete upper and lower bounds is helpful for diagnostic purposes and also reflects the range of variation actually observed among healthy people.

Soon after the first essential nutrient requirements and food composition databases became available in the early 20th century, George Stigler (1945) described how an analyst might estimate the least expensive combination of foods needed to meet recommended intake of each nutrient. The first linear programming algorithm to find an exact solution was then developed by George Dantzig (1990, 1963), in response to

interest in least-cost diets and other optimization problems during and after World War II. Since then, least cost diets for nutrient adequacy have been widely used to formulate rations, guide nutrition assistance, and use constrained optimization to provide insight into actual food choices (Wallingford and Masters 2025).

In recent years, diet modeling has moved beyond essential nutrients to other requirements for a healthy diet specified in national food-based dietary guidelines. Modern dietary guidelines specify that a healthy diet should meet a person's energy requirements using a mix of food groups, as in the U.S. MyPlate (USDA and HHS, 2020) or the U.K. Eatwell Guide (NHS, 2024) and similar publications by dozens of governments worldwide as compiled by the FAO (2024b) and reviewed by Herforth et al. (2019). Each country's guideline results from a government-sponsored effort to establish a scientific consensus on foods for health, as documented for example by Cullum (2024). Analyses commonly start with how widely consumed foods can be combined so that total intake is likely to meet energy needs within upper and lower bounds for all essential nutrients, and then consider various other food attributes influencing health. A diet model with nutritional constraints can be solved for a variety of objective functions, such as similarity to national average consumption (Wilde and Llobrera, 2009) or goals based on palatability constraints (Gerdessen and de Vries, 2015) and specific applications such as school meals (Stern et al., 2023), nutrition assistance (Wallingford et al., 2024) and other interventions (Knight et al., 2024).

Identifying foods for health when item prices are available is commonly done by solving for the least expensive options, so as to identify the most cost-effective foods providing health attributes in the required proportions. These least-cost diet models begin with energy and nutrients, for example in the formulation below:

$$\min_{cg}\{CostOfNutrientAdequacy_{cg} = \Sigma_i \mathbf{p_{ic}} \times q_{icg}\} \quad (1)$$

subject to:

$$\Sigma_i \mathbf{d_{ie}} \times q_{icg} = \mathbf{EER_g} \quad (2)$$

$$\Sigma_i \mathbf{d_{in}} \times q_{icg} \geq \mathbf{LB_{ng}} \quad (3)$$

$$\Sigma_i \mathbf{d_{in}} \times q_{icg} \leq \mathbf{UB_{ng}} \quad (4)$$

$$q_{icg} \geq 0 \quad (5)$$

This illustrative model shown here would identify the most affordable foods to meet nutrient requirements in each country (c) for each demographic group (g), when added up over all food items (i) at local prices (p) in whatever quantities (q) would meet the group's estimated energy requirement (EER) and keep each nutrient (n) above its lower bound (LB) and below its upper bound (UB) based on food composition data for the item's density (d) in terms of dietary energy (e) and individual nutrients (n). The items included in these benchmark diets differ by country, but the nutritional constraints they meet are drawn from the global evidence base such as the Dietary Reference Intakes for the U.S. and Canada produced by the National Academies (2023), and the broadly similar Dietary Reference Values published by the European Food Safety Authority (2024). Drawing on the same global evidence base, combined with similarities but also differences in how foods provide nutrients, leads to systematic patterns in how foods can most cost-effectively be combined to meet diverse needs across and within national populations (Bai et al., 2022; Kuri et al., 2024).

Actual dietary guidelines start with nutrient adequacy and then add other health-related attributes for which each country's authorities identify a sufficient scientific consensus. Each national guideline development process draws on the same global evidence base which often leads to similar conclusions, grouping items into nutritionally defined categories and recommending target levels of each food group. Herforth et al. (2022) used quantitative guidelines from 10 regionally representative countries, and semi-quantitative food guides from 30 countries to identify the most commonly recommended food groups, and derive the average proportions recommended of each food group. These guidelines use a wide range of

locally appropriate items and dishes to illustrate what a healthy diet looks like in their country, but classify items into similar nutritionally defined groups with similar recommended number and quantity of items from each food group.

The commonalities among national dietary guidelines identified by Herforth et al. (2022) specify that a globally relevant benchmark healthy diet would include at least 11 locally available items from 6 globally standardized food groups. This Healthy Diet Basket (HDB) is calibrated to energy balance at 2,330 kcals/day, based on the needs of the median adult woman aged 19-30 in the World Health Organization's global reference population of healthy individuals, which happens to be almost exactly the average of all age-sex groups in that population. To meet nutrient needs and protect against diet-related diseases, the HDB specifies that the 11 items should include at least 2 starchy staples each at 580 kcal/day, one legume, nut or seed product at 300 kcal/day, oil or fats at 300 kcal, two animal source foods each at 150 kcal, two fruits at 80 kcal each, and three vegetables at 37 kcal each. The target diversity in and between groups reflects the mix of nutrients provided by each type of food, for example the high level of micronutrient density per kcal of fruits and vegetables. As a result, using the least-cost options to meet these food group targets stays within lower and upper bounds for almost all essential nutrients, and similar levels of nutrient adequacy are achieved with almost all countries' own national guidelines as shown by Herforth et al. (2025; 2022).

The Cost and Affordability of a Healthy Diet developed by Herforth et al. (2020) has been reported annually for all countries in the *State of Food Security and Nutrition in the World* reports beginning in 2020 (FAO, IFAD, UNICEF, WFP and WHO, 2020.). Starting in 2022, the method was updated to use the HDB targets and adopted as a joint exercise by the FAO (2024a) and the World Bank (2024a). This is done using national average item prices from PPP comparisons, and country governments can track variation in access to that same global HDB target using monthly prices from each region collected for their CPI, as done by Nigeria's National Bureau of Statistics (2024). Country governments can also use their CPI data to track access to a country-specific dietary guideline as done for example in Ethiopia (Ethiopian Public Health Institute, 2025, Alemayehu et al., 2023), or draw on price data collected specifically for food market information systems as in Ghana (Herforth et al., 2024).

In each case, identifying the least cost items to meet food group targets is computationally and conceptually much simpler than diet modeling to meet nutrient requirements. Because food groups are mutually exclusive, least cost diets to meet HDB targets require only rank order comparison to select the lowest-priced items within each category, whereas diets for nutrient adequacy require linear programming to solve a system of simultaneous equations. The simplicity and clarity of meeting HDB targets has facilitated its adoption, along with availability of a software toolkit (Food Prices for Nutrition, 2024b) with Excel templates as well as Stata and R code that is prepopulated with item descriptions matched to food composition data and nutritional targets. Those computational tools can then be installed on each analyst's own computers and integrated into local workflows to track healthy diet access in each country.

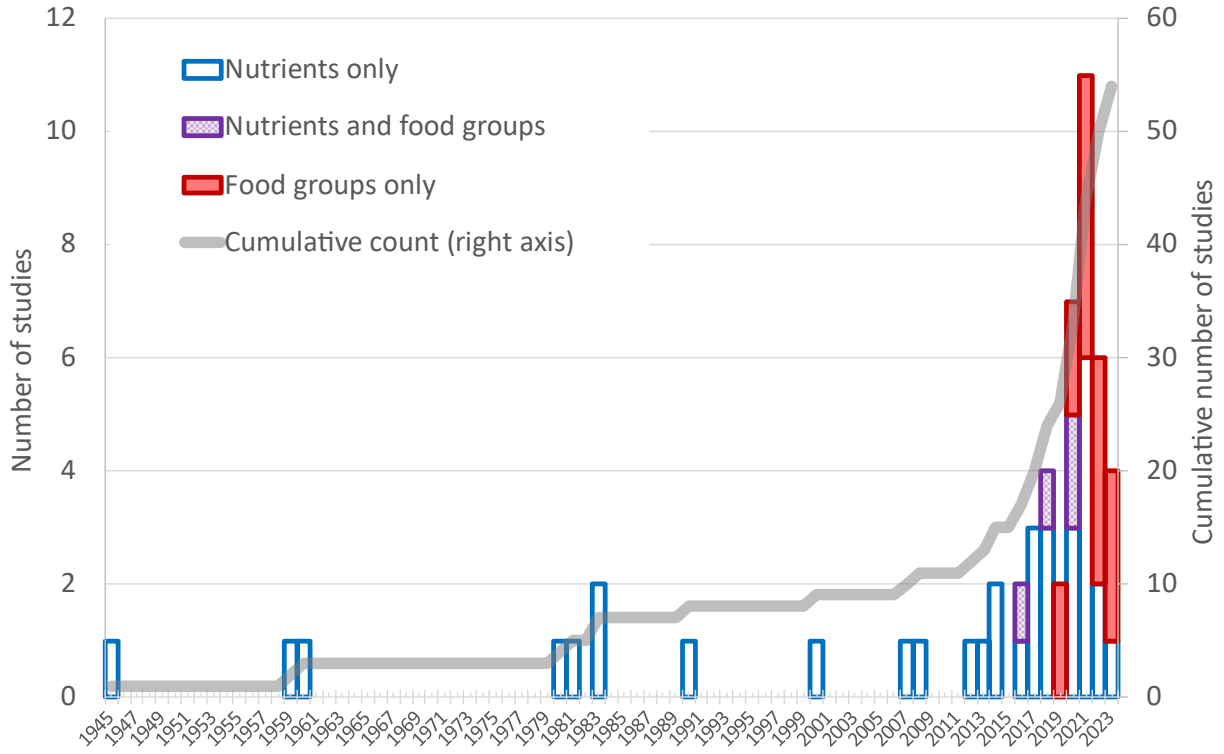
Prior to development of HDB targets and the global CoAHD approach to tracking the cost and affordability of healthy diets, the more computationally difficult diet models based on linear programming were used for a wide range of purposes. The first published use of least-cost diets to track changing access to nutrient adequate foods over time is O'Brien-Place and Tomek (1983) for the U.S., followed much later by applications for low-income countries such as Uganda (Omiat and Shively 2017) and Malawi (Schneider, 2022; Schneider et al., 2023). Comparisons among all countries of the world were pioneered by Allen (2017). Bai et al. (2021a) compare the minimum cost of purchasing a nutrient adequate diet in 177 countries. For operational work within countries, the World Food Program and its partners also developed specific Cost of the Diet software tailored to each population with whom they work (de Pee et al., 2017).

The development of new price indexes based on the lowest-cost items in each food group began by targeting the Minimum Dietary Diversity for Women (MDD-W) threshold, defined as consumption of at least 5 out of 10 nutritionally defined food groups (Arimond et al., 2010) which had been found to predict micronutrient adequacy (Martin-Prével et al., 2015). Tracking the lowest cost items needed to include at least 5 of the 10 food groups each day provided a simple way to calculate percentage changes in the cost of meeting that dietary diversity target, which could then be compared to the earlier approach using linear programming to identify the lowest cost items to achieve nutrient adequacy (Masters et al., 2018a).

Since the development of MDD-W, other metrics of diet quality use additional food group classifications, such as the Global Diet Quality Score that classifies intake as low, medium or high levels of 25 distinct food groups (Bromage et al., 2021), or the Global Dietary Recommendations score to limit risk and protect against non-communicable diseases (comprising NCD-Risk and NCD-Protect scores), which uses 18 distinct food groups (Herforth et al., 2020), (WHO, FAO, and UNICEF, 2024). Other diet quality metrics such as the U.S. Healthy Eating Index (NIH, 2024) use food group targets combined with other attributes such as whole grains (in contrast to refined grains) and unsaturated fats (in contrast to saturated fats). Just as consumer price indexes evolve in response to changes in spending patterns (BLS, 2024; Cavallo, 2024), diet cost metrics can evolve to reflect the nutritional criteria used to define a healthy diet. Some of this work occurs in high income countries such as Penne and Goedemé (2021) for Europe, but interest in the lowest possible cost of a healthy diet arises primarily in low and middle-income countries, for which a recent summary of diet cost monitoring efforts is provided in Herforth et al. (2024).

To illustrate the growth and composition of least-cost diet research, we conducted a non-exhaustive but systematic search for English-language studies using cost minimization to identify food items and quantities for a human diet satisfying a set of nutritional or food group requirements. An initial search of Google Scholar led to 363 candidate studies, from which we excluded conference abstracts, dissertations, non-English language items, and research articles that did not model human diets, leading to 42 items retained for full-text screening. Of those, 26 studies actually used cost minimization and were retained, and full-text screening also revealed citations to an additional 28 articles that met our inclusion criteria despite not having our search terms in their title. The result of this search is a set of 54 studies published between 1945 and 2023, which we classified by type of nutritional constraints as shown in Figure 1.

Figure 1. Annual and cumulative number of least-cost diet studies by type of constraint, 1945-2023



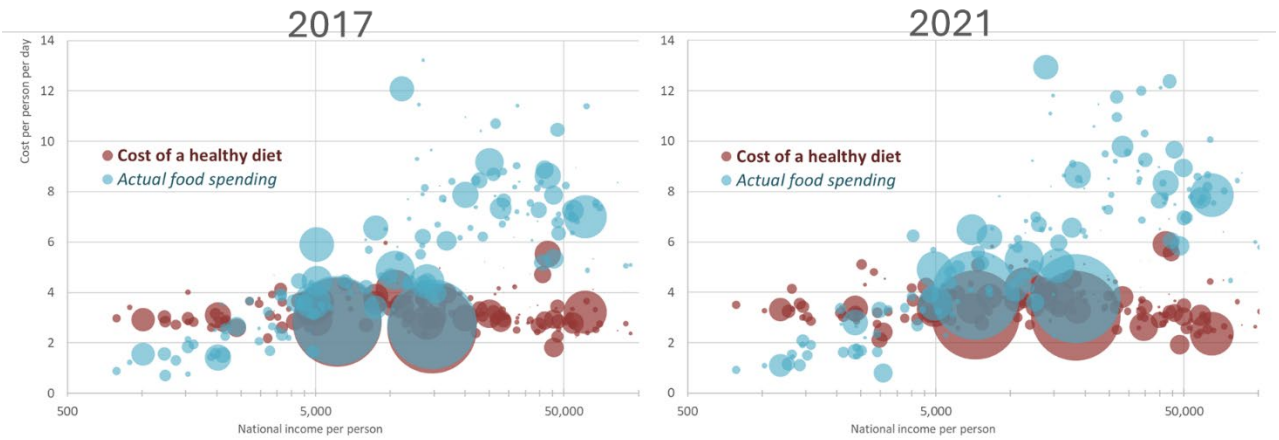
Note: Data shown are the number of least-cost diet studies identified through Google Scholar, PubMed and references cited by later studies. Bibliographic data on each study is shown in the supplemental materials Table S1, accompanied by a PRISMA diagram showing the full count of studies found.

Figure 1 reveals that after Stigler (1945) there were only occasional published studies using least-cost diets for nutrient adequacy until they began to appear almost every year from 2012 onwards. The annual number of such studies is shown as white bars with a border. Then studies appeared in 2016 and 2018 that introduced food group constraints as well as nutrient requirements, shown in shaded purple, followed by studies from 2019 onwards that used only food groups shown in red. That sequence began with a study in Copenhagen to quantify the additional costs beyond nutrient adequacy of meeting a variety of other constraints (Parlesak et al., 2016), followed by a study in Ghana and Tanzania of monthly and regional variation in the lowest cost items to meet MDD-W standards of diet diversity and also nutrient requirements (Masters et al., 2018a), and studies in South and Southeast Asia tracking the cost of meeting local dietary guidelines (Dizon et al., 2019; Mahrt et al., 2019). Those national studies were soon followed by global analyses using item prices reported for PPP calculations, first to meet national governments' dietary guidelines (Herforth et al., 2020) and EAT-Lancet recommendations (Hirvonen et al., 2020), followed use of the Healthy Diet Basket standard for annual monitoring (Herforth et al., 2022).

4. Results of global least-cost diets in contrast to actual food spending

The first and most important finding from using least-cost healthy diets to measure food access globally is summarized in Figure 2, presenting benchmark results computed from item prices for 168 and 173 countries in 2017 and 2021, along with actual food expenditure from national accounts for 168 and 166 countries in 2017 and 2021 respectively. Both are reported by the International Comparison Program, from which diet cost and food expenditure results are published jointly by the FAO and the World Bank.

Figure 2. Least cost healthy diets and actual food spending by national income, 2017 and 2021



Note: Data shown are FAO and World Bank estimates, all in 2017 US dollars at PPP prices. Diet cost and food spending for 2017 and 2021 was published in FAO, IFAD, UNICEF, WFP and WHO (2022), and the data for 2021 was published in FAO, IFAD, UNICEF, WFP and WHO (2024b). Circle sizes are proportional to population in each year, and the horizontal axis shows national income (GNI) per person at PPP prices, both from the World Bank (2024b).

The global pattern in Figure 2 reveals how the least expensive items in quantities needed for a healthy diet, shown as red circles proportional to country populations, typically cost about $3-4/day in constant US dollars at PPP prices. That cost level is not correlated with national income, shown here using a log scale along the horizontal axis. In contrast, actual food spending rises with income, from far below the minimum cost of healthy foods in low-income countries, to far above that minimum cost in high-income countries. These diet costs are based on food item prices used for PPP comparisons, and food spending is from national accounts. Both kinds of data are collected by government statistical organizations and intended to be nationally representative, reported through the International Comparison Program (ICP). The series of diet costs from 2017 onward is available from FAOSTAT (2024a) and the World Bank (2024a).

The central discovery illustrated by Figure 2 is that least-cost healthy diets generally cost between $2.50 and $5.00 per day, while national average food spending ranges from around $1 to over $10 per day, and national income varies from under $5 to over $100 per day. Analyses within countries reveal the same pattern, with seasonal or spatial variation and periodic food price spikes causing minimum diet costs to fluctuate in real terms by a factor of about two, while actual food spending can vary by a factor of ten or more, and real incomes within countries can vary much more than that. Analyses of least-cost diets are just beginning to reveal the kind of spatial and seasonal patterns first documented across East Africa by Bai et al. (2020b), partly through accumulation of more studies with existing methods, and also a variety of methodological improvements as suggested for example by Headey et al. (2024b).

5. Policy uses and future directions for least-cost diets research

The least-cost diets research described in this review has already revealed important insights for policies and programs around the world, leading to a variety of recent initiatives and potential innovations to provide even more useful guidance.

A first use of least cost diets in food policy analysis is to identify the frontier of cost-effectiveness in delivering foods for health, showing which items can deliver each food group at the lowest cost per day, and revealing where or when consumers are not being reached by those low-cost supply chains. For

example, the relatively high cost of healthy diets found in Latin America and the Caribbean have already triggered analysis and advocacy to improve production and distribution of lower-priced options in required food groups (FAO, IFAD, PAHO, UNICEF, WFP, 2023), and some initial work has studied whether and how import restrictions affect access to low-cost options for a healthy diet (Gilbert et al. 2024).

A second important use is to track affordability of even the least expensive options relative to incomes available for food, revealing the need for higher earnings, social protection and nutrition assistance. One early example of impact on social protection concerns debates over the appropriate minimum wage in Nigeria, where news accounts report that the National Bureau of Statistics' diet cost data was helpful in anchoring negotiations between trade unions and the government (Gulloma, 2024).

A third kind of application is to compare benchmark diets to foods actually chosen, so as to identify where and when least-cost items in a healthy diet are displaced by more expensive and often less healthful options. Food choice among affordable options is driven by a wide range of potentially modifiable factors, including the ways that food marketing might alter consumers' aspirations as well as taste and cultural factors that drive choices towards or away from the products needed for health (Costlow et al. 2025). Public funds are sometimes used to help consumers meet health needs at low costs, such as the Shop Simple with MyPlate app for low-cost recipes that meet the Dietary Guidelines for Americans (USDA, 2024b).

Beyond these applications of existing methods, methodological innovations could provide more timely and accurate analysis for decision makers around the world.

One set of innovations concerns food price data collection, where improvements could address both systematic biases and random errors related to the selection of food items, market locations, timing of data collection and other factors. Bias could arise because prices collected to measure inflation aim to capture total expenditure including premium items, whereas measuring food access calls for data on the least expensive options in marketplaces serving populations with poor diet quality. Beyond those potential biases, there are great opportunities to improve data quality and timeliness by upgrading data collection and analysis from older paper-based and other error-prone systems to modern systems that use preprogrammed tablets for nearly immediate feedback to field staff about data quality, and nearly immediate forwarding of results for processing into diet costs and affordability results. One recent example concerns webscraping online prices to track availability and price of the lowest price options by the UK's Office of National Statistics (ONS, 2022) and in research (Cavallo and Kryvtsov, 2024).

A second type of innovation concerns methods for data analysis and transformation into diet costs. The first step of the process, matching items to food composition, could be improved with new data sources and matching tools, including estimates of variance and changes in the energy density and nutrient composition of each food. The second step of specifying dietary requirements is continuously improving, thanks to innovations in dietary guidelines, definitions of diet quality and food ratings. Each kind of data has variance that could potentially be aggregated into estimated confidence intervals for each diet cost, including uncertainty about prices and also food composition or health requirements as introduced by Bai et al. (2022).

A third focus of innovation could be to expand the agenda beyond access and affordability at the market, to consider meal preparation costs as a factor in food choice and a barrier to consumption of healthy diets. Existing work focuses on market prices and diet costs for retail items, but being able to afford the ingredients for a meal is just the first step towards improved nutrition. Meal preparation practices and associated costs are highly variable across households and there is not yet any practical way to measure the cost differentials in meal preparation between different foods and dishes that might comprise a healthy

diet in each context, but new methods are being developed as researchers and decisionmakers including the Indian government shift their focus from individual foods to meals and daily diets (Masters et al., 2021a; Ministry of Finance, 2020).

Finally, there are many opportunities for the data and methods developed in monitoring healthy diet access to be used for development goals beyond nutrition and health. Much of the same data about retail markets and food use can be used to consider the cost and affordability of reaching goals for environmental sustainability, social inclusion and other concerns. Those questions can be addressed using modeled diets, or for individual foods using a true cost accounting framework (Kennedy et al., 2023).

5. Conclusions

In summary, a long tradition of using food prices and least-cost diets to understand access to food has led to monitoring of the cost and affordability of diets as a global indicator of food security, with important insights for improving the availability and affordability of foods in the quantities needed for health. Historical retail prices, as well as analyses of commodity prices and national accounts data, provide insights into the volatility and composition of retail prices, to inform their use in monitoring physical and economic access to healthy diets. Efforts from the Food Prices for Nutrition project and international institutions to monitor the cost and affordability of healthy diets provide policy-relevant diagnostics where healthy diets are unaffordable, as well as where millions who can afford healthy diets do not choose them. These insights highlight important areas for future research, including options for improving the precision of estimates and incorporating non-market or hidden costs that affect consumption decisions, such as meal preparation or environmental costs. High frequency, sub-national monitoring using existing retail food price data collected by national governments can support decision-making and methodological advances.

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Supplemental information for

Are healthy foods affordable? The past, present, and future of measuring food access using least-cost diets

Annual Reviews of Resource Economics (2025)

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Table S1. Illustrative list of studies calculating least-cost human diets, 1945-2023

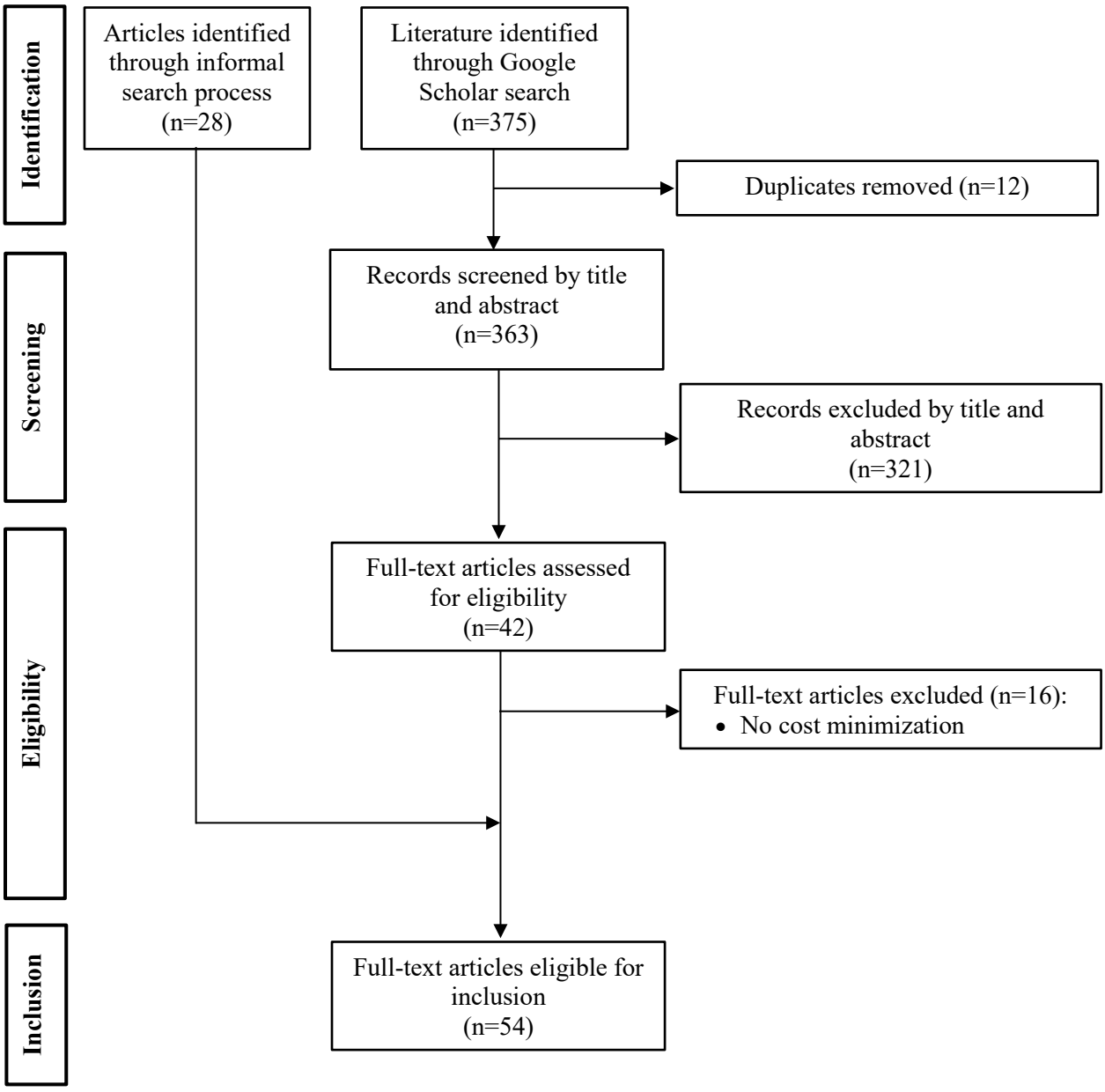
Author, year	Article title	Journal title or publisher	Method
Stigler, 1945	The cost of subsistence	J. Farm Econ.	N
Smith, 1959	Linear programming models for the determination of palatable human diets	J. Farm Econ.	N
Beckmann, 1960	On the determination of an adequate diet at minimum cost	Trabajos de Estadistica	N
Locks, 1980	The "Stinger gap": the difference between the "cost of subsistence" and that of a minimum-cost noninstitutional diet with palatability	Comput. Ind. Eng.	N
Foytik, 1981	Very low-cost nutritious diet plans designed by linear programming	J. Nutr. Educ.	N
Anderson and Earle, 1983	Diet planning in the third world by linear and goal programming	Programming. J. Oper. Res. Soc.	N
O'Brien-Place and Tomek, 1983	Inflation in food prices as measured by least-cost diets	Am. J. Agric. Econ.	N
Dantzig, 1990	The diet problem	Interfaces	N
Conforti and D'Amicis, 2000	What is the cost of a healthy diet in terms of achieving RDAs?	Public Health Nutr.	N
Chastre et al., 2007	The minimum cost of a healthy diet: findings from piloting a new methodology in four study locations	Save the Children UK	N
Raffensperger, 2008	The least-cost low-carbohydrate diet is expensive	Nutr. Res.	N
Frega et al., 2012	What linear programming contributes: World Food Programme experience with the "Cost of the Diet" tool	Food Nutr. Bull.	N
Baldi et al., 2013	Cost of the diet (CoD) tool: first results from Indonesia and applications for policy discussion on food and nutrition security	Food Nutr. Bull.	N
Geniez et al., 2014	Integrating food poverty and minimum cost diet methods into a single framework: a case study using a Nepalese household expenditure survey	Food Nutr. Bull.	N
Gerdessen and de Vries, 2015	Diet models with linear goal programming: impact of achievement functions	EJCN	N
Termote et al., 2014	Assessing the potential of wild foods to reduce the cost of a nutritionally adequate diet: an example from eastern Baringo District, Kenya	Food Nutr. Bull.	N
Biehl et al., 2016	What does it cost to improve household diets in Nepal? Using the Cost of the Diet Method to model lowest cost dietary changes	Food Nutr. Bull.	N
Parlesak et al., 2016	Use of linear programming to develop cost-minimized nutritionally adequate health promoting food baskets	PLOS ONE	N+G
Allen, 2017	Absolute poverty: When necessity displaces desire	Am. Econ. Rev.	N
Deptford et al., 2017	Cost of the Diet: a method and software to calculate the lowest cost of meeting recommended intakes of energy and nutrients from local foods	BMC Nutr.	N
Omiat and Shively, 2017	Charting the cost of nutritionally-adequate diets in Uganda, 2000-2011	Afr. J. Food Ag. Nutr. Dev.	N
Akhter et al., 2018	Change in cost and affordability of a typical and nutritionally adequate diet among socio-economic groups in rural Nepal after the 2008 food price crisis	Food Secur.	N
Ghazaryan, 2018	Can locally available foods provide a healthy diet at affordable costs? Case of Armenia	Dev. Stud. Res.	N
Masters et al., 2018	Measuring the affordability of nutritious diets in Africa: price indexes for diet diversity and the cost of nutrient adequacy	Am. J Agric. Econ.	N+G
Shafii et al., 2018	Least cost diet for children two to three years in Malaysia using linear programming approach	JCRINN	N
Dizon et al., 2019	The cost of a nutritious diet in Afghanistan, Bangladesh, Pakistan, and Sri Lanka	Glob. Food Secur.	G
Mahrt et al., 2019	Household dietary patterns and the cost of a nutritious diet in Myanmar	IFPRI	G
Bai et al., 2020	Seasonality of diet costs reveals food system performance in East Africa	Sci. Adv.	N
Dizon and Wang, 2020	Diet quality and food prices in India	World Bank	G

Table S1 (continued)

Author, year	Article title	Journal title or publisher	
Herforth et al., 2020	Cost and affordability of healthy diets across and within countries	FAO	N+G
Hirvonen et al., 2020	Affordability of the Eat-Lancet reference diet: a global analysis	Lancet Glob. Health	N+G
Kachwaha et al., 2020	Assessing the economic feasibility of assuring nutritionally adequate diets for vulnerable populations in Uttar Pradesh, India: findings from a "cost of the diet" analysis	Curr. Dev. Nutr.	N
Raghunathan et al., 2020	Affordability of nutritious diets in rural India	Food Policy	G
Sarfo et al., 2020	The impact of local agrobiodiversity and food interventions on cost, nutritional adequacy, and affordability of women and children's diet in Northern Kenya: a modeling exercise	Front. Nutr.	N
Bai et al., 2021	Cost and affordability of nutritious diets at retail prices: evidence from 177 countries	Food Policy	N
Baye et al., 2021	Whole egg powder makes nutritious diet more affordable for Ethiopia: A cost of the diet and affordability analysis	Matern. Child. Nutr.	N
Bose et al., 2021	The difficulty of meeting recommended nutrient intakes for adolescent girls	Glob. Food Secur.	N
Dizon et al., 2021	The cost of a nutritious diet in Bangladesh, Bhutan, India, and Nepal	World Bank	G
Gupta et al., 2021	Ground truthing the cost of achieving the EAT lancet recommended diets: Evidence from rural India	Glob. Food Secur.	G
Laborde et al., 2021	COVID-19 pandemic leads to greater depth of unaffordability of healthy and nutrient-adequate diets in low- and middle-income countries	Nat. Food	G
Malvar, 2021	Cost optimization of food diet for adult Filipino patients with stage 1 or stage 2 chronic kidney diseases	Turk. J. Comput. Math. Educ.	N
Masters et al., 2021	The cost and affordability of preparing a basic meal around the world	Springer, Cham	G
Mekonnen et al., 2021	Affordability of healthy and sustainable diets in Nigeria	Front. Sustain. Food Syst.	G
Moatsos, 2021	Global extreme poverty: Present and past since 1820, in: How was life? Volume II: New perspectives on well-being and global inequality since 1820	OECD	N
Nowar et al., 2021	Cost of nutrient adequate diet (CoNA) during COVID-19 pandemic and its affordability	Bangladesh J. of Pol. Economy	N
Ambikapathi et al., 2022	Global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity	Nat. Food	G
Bai et al., 2022	Global variation in the cost of a nutrient-adequate diet by population group: an observational study	Lancet Planet. Health	N
Herforth et al., 2022	Methods and options to monitor the cost and affordability of a healthy diet globally: Background paper to The State of Food Security and Nutrition in the World 2022	FAO	G
Mahrt et al., 2022	Nutrition as a basic need: a new method for utility-consistent and nutritionally adequate food poverty lines	IFPRI	G
Obaid et al., 2022	Cost of nutritious diet for children in Pakistan and effects of imminent Afghan refugees on existing consumption pattern	J. Appl. Econ. Bus. Stud.	G
Schneider, 2022	Nationally representative estimates of the cost of adequate diets, nutrient level drivers, and policy options for households in rural Malawi	Food Policy	N
Islam et al., 2023	Cost of recommended diet CoRD) and its affordability in Bangladesh	Foods	G
Mekonnen et al., 2023	Affordability of healthy diets is associated with increased food systems performance in Nigeria: state-level analysis	Agric. Food Econ.	G
Mwambi et al., 2023	Cost and affordability of a healthy diet for urban populations in Thailand and the Philippines before and during the COVID-19 pandemic	BMC Public Health	G
Schneider et al., 2023	Assessing the affordability of nutrient-adequate diets	Am. J Agric. Econ.	N

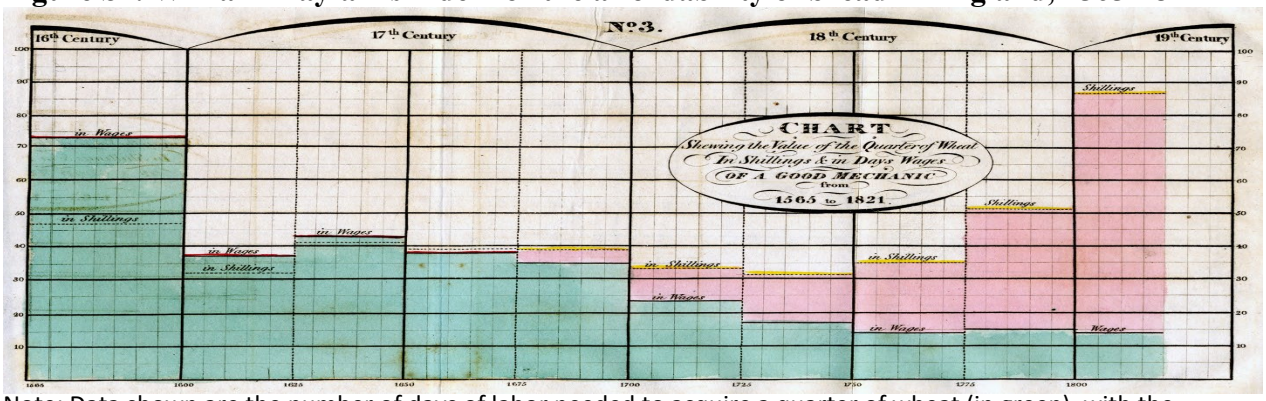
Note: Articles were retrieved from Google Scholar by searching for key words in the title of articles, using the search query, *allintitle:("least cost" OR "cost minimization" OR "cost and affordability of" OR "cost of" OR affordable OR affordability) (diet OR "healthy diet" OR "nutrient adequate diet" OR "nutritious diet"),* on 6 June 2023. A total of 26 articles retrieved by this query use cost minimization to identify food items and quantities for a human diet that satisfies a set of nutritional or food group requirements. An additional 28 articles that were not retrieved by this search query, and that met our inclusion criteria, were identified by the authors. Method category *N* includes studies calculating least-cost diets subject to essential nutrient requirements; method category *G* includes studies calculating least-cost diets subject to food group requirements; method category *N+G* includes studies calculating least-cost diets subject to essential nutrient requirements and least-cost diets subject to food group requirements.

Figure S1. Search and selection results for least-cost diet studies



Note: Data shown summarize search and selection results in the format used for systematic reviews, as specified in the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (https://www.prisma-statement.org).

Figure S2. William Playfair's index for the affordability of bread in England, 1565-1821



Note: Data shown are the number of days of labor needed to acquire a quarter of wheat (in green), with the nominal price of wheat also shown (in pink). Source is William Playfair (1821), *A Letter on Our Agricultural Distresses, Their Causes and Remedies: Accompanied with Tables and Copper-plate Charts, Shewing and Comparing the Prices of Wheat, Bread, and Labour, from 1565 to 1821* (London: William Sams).

Figure S2 shows the first known long-term effort to monitor food access and affordability, comparing the price of bread to workers' wages.

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