The Indian food system from crop production to household level availability for sustainable food security

Harshitha Mallik
Assistant Professor &Research Scholar
MMK & SDM Mahila Mahavidyalaya, Mysore
JSS Research Center
harshithamallik99@gmail.com

Divya L
Assistant Professor
PG Dept of Commerce
JSS College of Arts, Commerce and Science
divyapgcommerce.10@gmail.com

Abhishek N
Associate Professor
Dept of Management
Yenepoya University, Manglore
abhishekalmighty93@gmail.com

Introduction

The United Nations set a target of ending world hunger by 2030 in 2015 as part of its second sustainable development objective. The elimination of malnutrition in all its manifestations, along with the prevention of stunted growth and wasting, is an essential component of this objective. This is an important follow-up to the Millennium Development Goals (MDGs), which previously defined and quantified food security in relation to the frequency with which children were underweight (1). The new, committed role is primarily concerned with analysis and judgment. All macronutrients required for proper nutrition are part of this, which goes beyond the typical analysis of caloric intake.

When it comes to developing models and techniques to orient nutritional needs towards sustainability, India stands out as a unique example. India was placed 111th out of 125 nations in 2023 on the Global Hunger Index, which measures undernourishment, stunting, mortality, and child wasting [2]. Despite its ranking, India's progress in reducing malnutrition is falling short of its present economic development and even below that of its poorer surrounding nations.

There is a serious problem with India's food. The term "stunted" (meaning below average height) was used to describe 31.7% of children younger than five in 2022. Children and pregnant women who suffer from chronic undernourishment have their physical and mental development severely and permanently hampered (3). The overall rate of malnutrition in India is 16.5%, which includes a disproportionate number of adults. Dietary intake and variety, illness load, female empowerment, and education all have a role in solving the complicated problem of starvation. While improvements in food consumption cannot eliminate hunger on their own, they are a necessary component of broader social and health systemic changes (4).

Growth in the population and the need for capital are projected to constitute India's nutritional and fitness-related obstacles. By 2050, its already-massive population of 1.45 billion is expected to reach 1.6 billion, surpassing China's population (5). The effects of climate change, water shortages, and the loss of soil fertility have put India in the limelight as a potentially hazardous country (6).

Research on Indian dietary habits and malnutrition rates has mostly relied on household survey data (7).The weight of energy inputs in India's agricultural policy and traditional measures of its performance (8). Rapid development in the production of rich cereal crops has been a goal of agricultural strategies since the Green Revolution of the 1970s, when the world's population began to rapidly increase and the need for food became apparent. India's wheat and rice varieties' political and investment orientation has been a primary focus as the country strives for independence (9). While primary crop output has increased, India's agricultural policies have prioritized grain production, which has increased the country's critical difficulties.

Literature Review

Theoretical framework

This article shows the Indian food system using FAO Food Balance Sheets (FBS) from the FAO statistics database. It starts with agricultural production and ends with per capita food supply (10).FBS compiles extensive data on the production and use of basic commodities and food products all throughout the food supply chain. On a national, regional, and international scale, such information is accessible. India facing the growing problem of food insecurity. This is especially true for developing and rising nations. The FAO's (Food and Agricultural Organisation) generally recognised definition of food security states: "Food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (11).

Heckscher-Ohlin (H-O) theory

A food security theory may be traced back to 1980s works: one by Ricardo, the comparative advantage theory, and the other by Heckscher-Ohlin, the model or factor endowment theory. According to the Heckscher-Ohlin (H-O) theory, a nation would trade in the item that requires the rare element and import the high-quality product that can be made with the plentiful material. This happens when one ingredient is abundant and the other is scarce.

Sen's entitlement approach

After Amartya Sen's entitlements method was refined to examine issues with food security and nutrition, it was used to provide a thorough examination of the causes of famine. To get to the bottom of why people go hungry, this method put an emphasis on endowment and entitlements.

The dynamics of the factors that affect food security

The Indian food supply is highly dependent on the distribution network. Food imports to India are impacted by several variables.

Population growth and supply chain

Numerous studies have shown that when populations grow, food production also increases; nonetheless, current food supplies are insufficient to meet consumer demand. According to Thomas Malthus's "Malthusian population trap," contemporary economists think that reducing food supply or population increase would solve this problem. In the short and long run, food insecurity is worsened by a growing population, says the Malthusian argument.[12] Reducing population growth should be the India's top concern to guarantee food security.

Gross domestic product (GDP) per capita

A country's ability to provide its citizens with food is directly linked to its GDP per capita and its rate of economic development. The capacity of a nation to import food is a good indicator of its GDP per capita, which in turn affects food security. Despite agriculture's declining contribution to GDP, rising incomes are still one of the variables that helps alleviate food insecurity. But areas where people are struggling to put food on the table are making it harder for real GDP per capita to rise.

Domestic food production

One way to ensure a steady supply of food and avoid shortages is via support by local producers (14) (FAO). While domestic food production plays a role, food imports have been the primary means by which India has been able to ensure its food security. In order to guarantee food security not withstanding environmental deterioration, India has adopted the approach of buying or leasing vast tracts of farmland in neighboring nations like Sudan, Ethiopia, Egypt, etc. But because of the political instability in these nations, many investments have failed.

Inflation

Food security is affected by inflation, both local and international. Many nations that relied on international commerce were in a state of confusion during the 2008 food crisis because of the export limits put in place by the world's leading wheat and rice exporters (15). Food costs in India increased by an average of 5% between 2010 and 2019.India relies heavily on food imports since their people cannot be adequately fed by native sources. However, food price fluctuations might affect these imports. An increase in food imports is a direct result of rising domestic inflation. Subsidies, both direct and indirect, are provided by the governments of the India to keep food prices low and to mitigate the impact of supply interruptions and shocks.

Regional instability

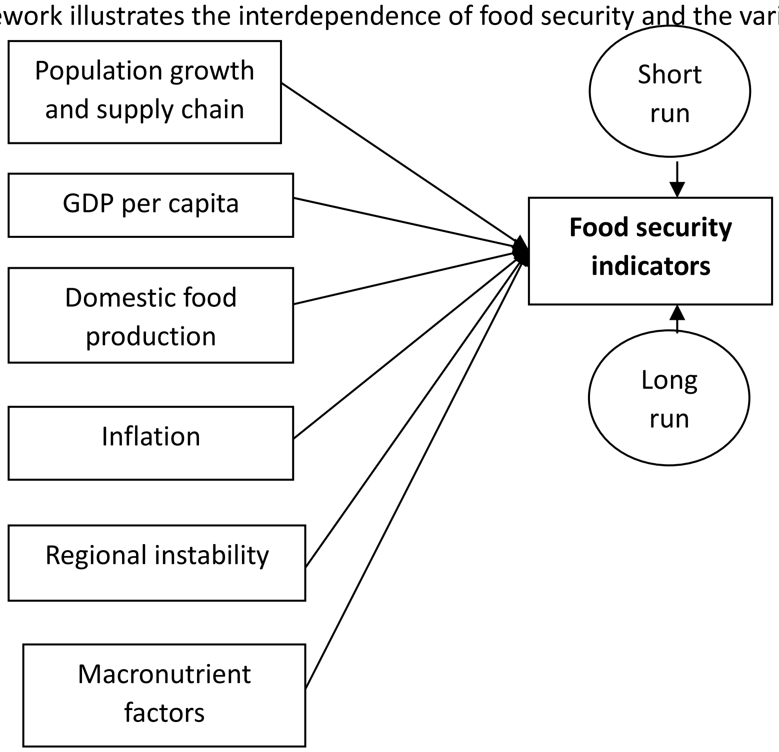
Natural disaster and political unrest might threaten a nation's capacity to provide its citizens with enough food. There is a constant danger of supply interruptions affecting food-importing nations, making them susceptible to food insecurity (16). Important trade routes are especially at risk in the case of nearby political instability. The maritime chokepoint is an important food import route for India; nevertheless, any unrest in the area would have an impact on this route.

Macronutrient factors

In a diet of heavy grains which includes macronutrients such as calories, protein, and fat have a significant influence. Because grains have worse digestibility and amino acid profiles which are superior to those of plant-based legume alternatives and animal products. Protein quality has been the subject of several research; this is especially true for India, where grains make up a major portion of the diet (17). Therefore, macronutrients have become one of the factors for food security.

Conceptual framework

In Figure 1, we can see the theoretical basis for the dynamics of food security in India. This framework illustrates the interdependence of food security and the variables that impact it.



Crop yield is a measure of food security, which is the dependent variable. Factors such as regional instability, macronutrient factors, exports, GDP per capita, domestic food production, and the consumer price index (inflation) make up the five independent variables. Both the short-term and long-term dynamics of the factors affecting food security are shown by the framework. The study's aims, the results of the literature review, and other supporting evidence have all contributed to the determination of the influential elements.

Research Methodology

Data collection methods

Most of the information included in this analysis came from secondary sources, such as reports of FAO and the World Bank. The FAO report (2021) is used to construct the statistics for per capita food supply.[18] The World Bank's database and publications provide the statistics for various factors, such as regional instability, exports, Gross domestic product per capita, populace development, buyer cost

ISBN code 978-93-83302-74-1

file, nearby food creation, and consumer prices.[19] The study's era (1981–2021) was chosen because there was an abundance of data during that period, and a 40-year duration allows for solid conclusion.

Mapping the current Indian food system

The FAO Balance sheet gives the information about food supply chain. These give data of crop production & exports, crop imports and stocks, crop area replanted, feed, other uses, and the food supplied (in kilograms per capita per annum). Contained in these balances are specifications of all basic foods and trading items in every food group such as grains, roots, and tubers, oilseeds and pulses, fruits and vegetables, seafood, meats, and dairy.

FBS provide the sole comprehensive dataset for item chain examination. Consequently, they do not provide an ideal picture of the relative importance of each step in the food distribution and manufacturing process, but they do give a useful overview. In this work, we found that there is a difference between the household-level findings of national nutrition surveys and a top-down model that uses FAO FBS (see findings section below).

Food loss and waste statistics broken down by supply chain step are not provided by FBS. So, in order to be consistent with FAO publications, the food loss statistics have been computed using the South Asian regional percentages [20]. The seven commodity groupings and five phases of the supply chain (farming creation, postharvest dealing with and capacity, handling and bundling, dissemination and utilization) are examined in these percentage numbers for food losses.

Table 1 Provides the percentage values that were applied according to commodity category and supply chain stage.

Scenerio	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution	Consumption
Cereals	6%	7%	3.5%	2%	3%
Roots and tubers	6%	19%	10%	11%	3%
Oilseeds and pulses	7%	12%	8%	2%	1%
Fruits and vegetables	15%	9%	25%	10%	7%
Meat	5.1%	0.3%	5%	7%	4%
Fish and seafood	8.2%	6%	9%	15%	2%
Milk	3.5%	6%	2%	10%	1%

Source: Author’s compliance

Multiplying the bulk quantities of commodities by the FAO macronutrient nutritional parameters allowed us to determine the overall nutritional value at each level of the supply chain [21]. The calorie count, protein content, and fat content were all examined in this study. Given that grains are more often consumed in India than other countries, and since grains typically have worse absorbability and amino acid (AA) profiles contrasted with meat and vegetables, protein quality is a significant issue in India [22]. Subsequently, protein admissions have been adapted to absorbability utilizing FAO edibility values to appropriately evaluate constraints in the quality of the Indian diet. [23]

All variables have been standardized to average per person per day(popped) accessibility utilizing UN population measurements and forthcoming information [24]. This ensures consistency and helps us understand the food framework at the singular stock level. Although this gives a mean availability value per person, it doesn't take into consideration how the population's real supply of macronutrients varies. We acknowledge that dietary needs differ across age groups, genders, and levels of physical activity; however, to provide relatable metrics for food loss in the system, it is necessary to normalize food units to average per capita supply levels. Estimating this comparative with demographically weighted normal nourishing prerequisites, as made sense of underneath, is suitable for estimating the risk of malnutrition.

Next, the suggested consumption values were compared to the estimated macronutrient supply. According to the Food and Agriculture Organization (FAO), the "Average Daily Energy Requirement" (ADER) for the Indian population is 2269 kcal popped. An individual's ADER is the average number of calories needed to stay at a healthy weight, considering their age, gender, height, weight, and level of physical activity [25]. Because protein needs might differ even amongst otherwise healthy people, the recommended daily allowance (RDA) is usually two standard deviations (SD) higher than the average need. This gives people a buffer in case they accidentally fall short of their daily recommended intake. Proteins with an edibility score of 1.0 have a 'safe' (recommended) consumption of 0.83 g/kg/d of body mass according to the World Health Organization (WHO) [26]. Since vegetarianism in India is often associated with reduced consumption of complete proteins derived from animals, the Indian Institute of Nutrition advises that vegetarians increase their total protein consumption to 1 g/kg/d [27]. Based on mean body weight, this amounts to 55 grams of protein per day for typical girls also, 60 grams of protein each day for normal men [28]. The World Wellbeing Association's lower safe admission of 0.83g/kg/d would be decreased to 50 grams of excellent protein each day for a typical 60-kilogram person, as our research aims to adjust for protein digestibility. Thus, we have used this RDA value of 50 gpppd in our research.

Mapping potential near-term and long-term scenarios

Reducing gathering, postharvest, and appropriation misfortunes and further developing harvest yields were two strategies that emerged from our first research as having the potential to significantly increase food supply at the household level. Thus, these techniques have been used to map out both medium-term (up to 2030) and long-term (2050) scenarios. Note that these scenarios don't take consumer preferences into account when calculating demand, but rather concentrate on domestic supply-side initiatives to increase food availability.

The analysis included a baseline scenario for 2030 (based on the assumption that yields remain unchanged and population growth keeps pace with UN forecasts) as well as three other scenarios beyond that year:

Scenario 1 There was an assumption that food supply chain losses could be cut in half at the creation, post-reap, handling, and dissemination stages in the event that there was a significant change to postgather the executives practice, legitimate freezing, and effective circulation. To put it another way, this would bring its relative losses down to the level of industrialized countries [32]. Assumption of constancy in consumption (home trash) was made in this scenario.

Scenario 2 The assumption was made in scenario 1 that food chain losses would be cut in half, means that all essential crops would achieve 50% of their achievable yield (AY). Better agricultural management, irrigation, and fertilizer methods allowed all important crops to reach 50% AY. The term "attainable yield" refers to the harvest that is possible after using optimal methods of pest, nutrient (i.e., non-limiting) and water management.

Scenario 3 (reaching 75% AY across all main crops): The same assumptions as in scenario 2, with the exception that crop yield gains are anticipated to achieve 75% rather than 50% AY.

The following were the long-term (up to 2050) scenarios:

Scenario 1(cutting food waste in half): This scenario followed the same premise as the last one, which is to cut food waste in half at each step of the supply chain: production, post harvest, processing, and distribution. Since this would need a substantial change in post-reap the executives strategies, reasonable refrigeration, and proficient circulation, a half decrease is more feasible in the long run than in the short.

Scenario 2(reach 75% AY for all important crops): following the same premise as scenario 3, which is to close the yield gap to 75% AY for all crop kinds, this scenario was also implemented.

Scenario 3(each important crop reaching 90% AY): it was believed that every crop type was able to close the yield difference to 90% AY.

All indicators were re-normalized to 'per person per day' (pppd) in order to account for population predictions for 2030 and 2050. This was done using a projected Indian population gauge from the Unified Countries' .

The improvement in crop yields was calculated by bringing the gap between the stated achievable yields (AY) and the present farm yields (FY). A region's average on-farm yield is called FY, while the financially feasible (or ideal) yield that could be accomplished under ideal circumstances by involving best practices in water and manure application, and technology is called AY. The percentage of maximum achievable yields (AY) that were estimated from published crop-specific numbers in India were used to calculate the estimated gains in agricultural yields [33].

Nutrient and water management improvements would mostly account for the noticeable increase in production. Scenarios in this research were developed with the near-term goals of 50% and 75% AY in mind. By 2030, 50% AY should be theoretically achievable; many crops have already achieved this, and the ones that haven't usually miss the mark by 3-5% . In the short term, aiming for 75% AY—which would be a gain of more than 20% in yield—would be very ambitious. Nevertheless, with substantial investment in agricultural management and best practices, it may be possible to achieve 75% AY or even higher in the long run.

The assumption that the yield gap would be closed to 75% and 90% AY is the foundation of our forecasts up to 2050. We compared the required growth rates to India's historical yield growth rates to see whether these estimations were reasonable. Because temperature thresholds play such a significant role in total crop tolerance, the impacts of environmental change on yields are quite susceptible to different greenhouse gas emission scenarios. This makes it difficult to determine the exact climatic effects in the year 2050. Accordingly, we used a literature analysis [34] of field information and environment model discoveries to compute normal rate changes in yields of Indian principal crops. Demand for meat and dairy products in India is expected to rise till 2050 as a result of rising incomes and changing eating habits. Assuming FAO predictions for 2050 are accurate, per capita consumption will rise from an estimated 3.1 kilogram of meat per person per year in 2007 to 18.3 kg in 2050, and from 67 kg to 110 kg of milk and dairy products per person per year [36]. Factors relating to the efficiency of energy and protein conversion were used to determine the shift in the macronutrient demand for animal feed for the four most common kinds of livestock: beef cattle, dairy cattle, and poultry [37].

The first baseline (2011) study assumed that the general designation of land for crop determination and the per individual allotment of yields for resowing and non-food purposes were identical.

Results

Current food system pathway

For calories, absorbable protein, and fat, Fig. 1 shows the macronutrient courses from crop creation to remaining food accessibility. As sources of info and results to the food framework, the relative measure of commodities, imports, and stock change is negligible across all macronutrients. Achieving food self-sufficiency via agricultural policy is central to India's agenda, and this outcome is consistent with that. It is possible to reach this level of food self-sufficiency until 2050 using just measures to reduce food waste and increase agricultural yields? That is the goal of this study's scenarios.

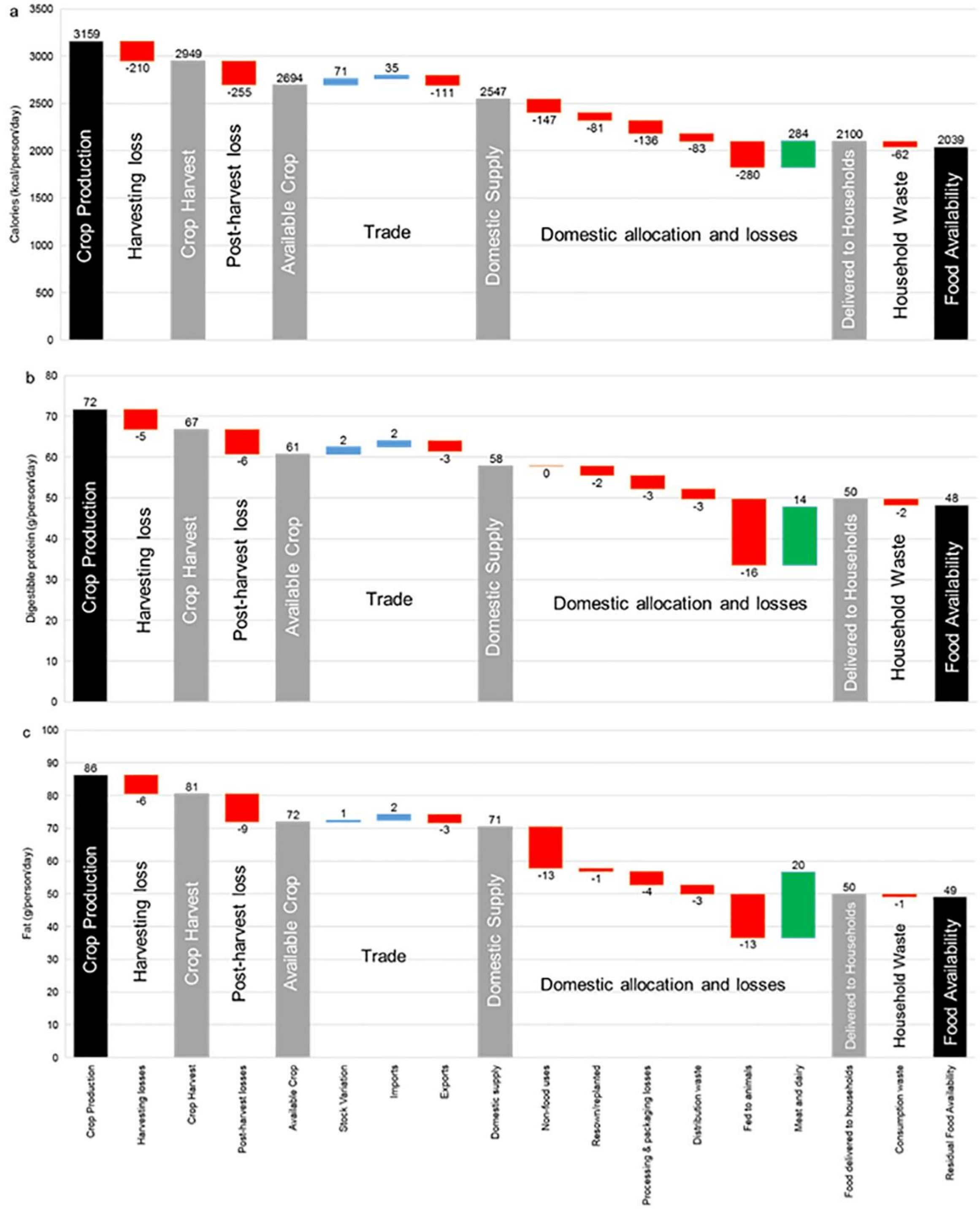


Fig 1. Production and losses in the Indian food system from `field to fork' in 2011.

Food pathways in (a) calories;(b) digestible protein; and (c) fat from crop production to residual food availability, normalized to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain.

Table 1. Mean macronutrient availability in baseline and potential waste and yield scenarios in 2030.

Scenario	Mean caloric availability; kcalpppd (percentage of population below average requirement)	Mean digestible protein availability; gpppd (percentage of population below average requirement)	Mean fat availability; gpppd (percentage of population below average requirement)
Recommended Daily Intake (RDA)	2269	50	
2011 Baseline Scenario	2039 (66%)	48 (56%)	49
Scenario 1 (halving food losses)	1665 (89%)	39 (83%)	40
Scenario 2 (achieving 50% AY)	1754 (84%)	42 (75%)	43
Scenario 3 (achieving 75% AY)	1831 (80%)	42 (75%)	46

Average macronutrient availability in baseline and projected scenarios to 2030, relative to average population requirements. Scenario 1 is based on the assumption of halving food losses across the supply chain; and scenarios 2 and 3 achieving 50% and 75% of attainable yields across all crops, respectively. The percentage of the population which would fall below average requirements based on dietary distribution data is reported in brackets.

In order to ensure the accuracy of our top-down supply model, we compared it with data from India's National Sample Survey (NSS), which measures dietary intakes twice a year via surveys of all Indian households. Daily caloric intakes of 2206 kcal in urban areas and 2233 kcal in rural areas were recorded by the NSS (2020-21) report. Both populations consumed 60 g of protein, and urban areas consumed 58 g of fat while rural regions consumed 46 g [38]. We find a robust association with fat consumption and a somewhat decreased caloric availability compared to the NSS intake numbers in our top-down study. Our findings on digestible protein cannot be directly compared to the NSS data as the latter only provides total protein without considering quality or digestibility. Our research, however, indicates that, after removing digestibility ratings, the overall average protein availability is 57g pppd, which is within 5% of the NSS consumption estimates.

The post-harvest waste and agricultural production phases of the food chain in India account for most of the calorie and protein losses, while processing and distribution account for a smaller but substantial portion. There are very little losses throughout the consumption period. Rather than edible protein, where misfortunes to contending non-food utilizes are negligible, higher fat misfortunes generally emerge because of oilseed crops being distributed for non-food purposes. With an info yield proportion for calories and protein close to one and a clear humble creation of fats, India's transformation of harvest-based creature feed to meat and dairy products seems to be rather efficient compared to the typical worldwide food supply chain [39]. Due to its lacto vegetarian inclinations, it prefers pasture-fed dairy cattle over grain-fed poultry and other animals. This farming system is unique in that it meets most of its livestock feed needs from crop wastes, byproducts, and pasture lands.

There is insufficient availability compared to minimal needs for all macronutrients on a per capita basis. Distributions of population intake reveal the scale of this problem in India. By extrapolating the normal macronutrient accessibility to the populace conveyance (expecting a log-typical dissemination and a confidence interval of 0.26), we find that 66% (826 million) of the population is at danger of not getting enough energy and 56% (703 million) of the population is in risk of not getting enough protein.

Potential future pathways

Scenario findings for 2030. Table 1 summarizes the results of scenario assessments that looked at ways to increase agricultural yields and decrease food waste...

The normal per capita calorie, absorbable protein, and fat accessibility all dip under the 2021 pattern, and waste or yield enhancements neglect to stay up with population increment until 2030 under all scenarios. Distribution of availability reveals significantly more potential malnutrition at present levels of food disparity. Under no circumstances will more than three quarters of the population be able to meet their daily calorie and protein needs. This amounts to widespread starvation in India in 2030, even if we achieve our gaint goals for increased productivity.

If these predictions pan out, India would not be able to achieve SDG2's Zero Hunger objective by 2030. Scenario findings for 2050. By 2050, the supply of macronutrients for households in India may be severely affected by the country's expected population boom and the effects of climate change on agricultural production. These possible implications are shown in our 2050 baseline scenario, which assumes that agricultural output improvements will remain at present levels. The complete paths of the store network are displayed in Figure (2). This finding emphasizes the need of making significant gains in agricultural yields at the supply chain level, even while lowering food system losses is a key component in increasing availability at the household level.

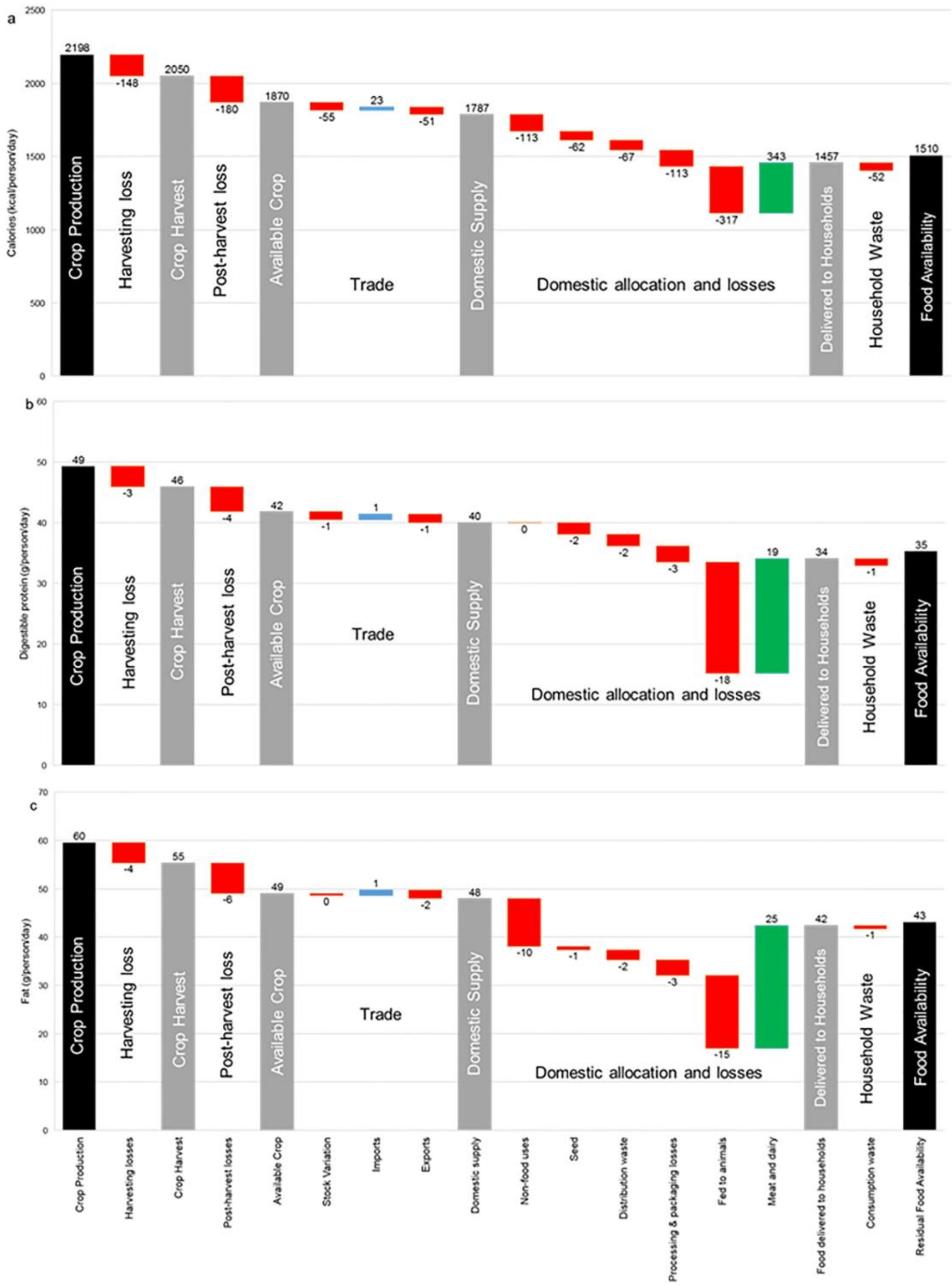


Fig 2. Production and losses in the Indian food system from field to fork under baseline conditions in 2050.

Food pathways in (a) calories; (b) digestible protein; and (c) fat from crop production to residual food availability, normalised to average per capita levels assuming equal distribution under 2050 baseline conditions. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs;

green bars indicate meat and dairy production; and grey bars indicate macronutrient availability at intermediate stages of the chain

Table 2. Mean macronutrient availability in baseline and potential waste and yield scenarios in 2050.

Scenario	***Mean caloric availability; kcalpppd (percentage of population below average requirement)***	***Mean digestible protein availability; gpppd (percentage of population below average requirement)***	***Mean fat availability; gpppd (percentage of population below average requirement)***
Recommended Daily Intake (RDA)	2269	50	
Baseline 2050	1405 (97%)	33 (95%)	42
Scenario 1 (halving food losses)	1661 (89%)	39 (83%)	51
Scenario 2 (achieving 75% AY)	1721 (86%)	40 (81%)	57
Scenario 3 (achieving 90% AY)	2099 (62%)	48 (56%)	66

Average macronutrient availability in baseline and projected scenarios to 2050, relative to average population requirements. Scenario 1 is based on the assumption of halving food losses across the supply chain; and scenarios 2 and 3 achieving 75% and 90% of attainable yields across all crops, respectively. The percentage of the population which would fall below average requirements based on dietary distribution data is reported in brackets.

Discussion

Our research used a standardised, relatively simple statistic (per person per day) to assess the entire food framework, from crop result to leftover food accessibility. To increase food security and supply efficiency, it is important to identify levels within the food system. This holistic approach is crucial for this purpose. The fundamental structure is adaptable, so it may be used to study any nutrient or amino acid in the diet at any size (international, national, or even micro). This makes it possible to do comparable evaluations for any country, which might lead to a better knowledge of food system hotspots and prospects for efficiency gains. This might pave the way for national food programs to zero down on the areas where they will have the most impact.

Our research shows that India's present dependence on domestic food production has several serious flaws. Additional calculations using FAO FBS confirm this: while accounting for 17.8% of the world's population in 2011, India contributed a merger 10.8% of total calories, 9% of digestible protein, and 11.8% of fat. Worldwide crop output in 2021 was 1.34x1016kcal, 3.62x1014g of digestible protein, and

3.33x1014g of fat, according to estimates based on Faustas data on worldwide crop production and nutritional composition variables. There were 1.44x1015 kcal, 3.27x1013 g of digestible protein, and 3.93x1013 g of fat produced in India in 2021. Producing enough food to meet everyone's needs at such high levels makes self-sufficiency implausible, even in an ideal food system. Also, even if India's population were to level off, it's doubtful that local production could solve the country's food need on its own.

Inadequate supply of macronutrients, or malnutrition, is already a serious problem in India. All three macronutrients must be readily available and consumed in sufficient amounts for nutrition to be considered appropriate. Reduced physical and mental development [40], increased susceptibility to disease and infection [41], poorer recovery and increased mortality from disease [34], and lower productivity [42] are all negative outcomes of protein-energy malnourishment (PEM), which occurs when an individual's protein and energy intake are inadequate. According to our findings, India would not be able to fulfill its needs for all three macronutrients according to its current self-sufficiency strategy, which involves increasing domestic agricultural yields and implementing waste reduction methods. Both the 2030 and 2050 scenarios indicate a considerable rise in levels of undersupply and, by extension of malnutrition.

For future strategies to successfully combat hunger, this has significant ramifications. Since the Green Revolution, the main goal of agricultural policy incentives in India has been to boost grain output, namely rice and wheat, in order to achieve caloric food security [9]. A diet high in carbohydrates (> 65–70% of total calories consumed) may be severely deficient in variety when it comes to providing other essential nutrients [43]. There is less room for nutritional variety now that lacto vegetarianism is so popular [44].

So far, India has mostly concentrated on increasing production of energy-dense crops, such as grains, roots, and tubers, in an attempt to reduce caloric insufficiency [45]. Our research, on the other hand, points to the importance of diversifying protein and fat consumption and decreasing micronutrient deficiencies as ways to change dietary composition away from carbohydrate dependence [46]. So, it's important to address caloric deficit and malnutrition at the same time in the future plans by increasing the intake and supply of high-quality fats and proteins in a balanced way.

Our analysis of macronutrient availability in India reveals substantial population-level disparities. This is probably related to the fact that poverty and wealth inequality are still major issues in modern India [8]. We find that even if average macronutrient supplies meet requirements, a large extent of the complete populace is currently in danger of lack of healthy sustenance because of the great CV in dispersion, which is exacerbated by enormous imbalances in food supply and dietary admission. This makes it progressively hard for India to address its lack of healthy sustenance challenges. Although this approach takes into consideration the distribution of dietary needs using RDA values, these values do not take into consideration the distribution of consumption. Thus, given present levels of inequality, SDG2 (where all individuals' needs are satisfied) requires a rise in the national mean consumption to 3600 kcal pppd, 82g pppd digestible protein, and 105g pppd fat. Regardless of whether crop creation stage level was to comprise the summit of the food framework, this would still be much higher than the current national pppd supply figures.

This study investigates India's food production capability on a domestic level and is mostly a computational, supply-driven analysis. Our findings should not be interpreted as predicting real-life situations of malnutrition in India in the future. This research suggests that there could be a severe food shortage soon, which might lead to changes in consumer and producer behaviour as well as market and regulatory interventions like increased trade. The pricing, affordability, and production of food are influenced by several factors, including supply and demand-side measures, commodity prices, commerce, and government policy [38]. For instance, it is anticipated that food costs would rise due to the domestic food scarcity and the projected decrease in the per capita food supply [39,40].

There is a wealth of literature on the interplay between poverty, food insecurity, and agricultural prices. A number of studies find that, since many of the world's poor live in rural areas, food price increases help alleviate poverty in the long run. On the other hand, they only alleviate poverty and starvation temporarily [42]. Commodity imports are projected to rise in India due to the country's inability to fulfill its citizens' complete nutritional demands, which include a balanced intake of calories, protein, and micronutrients. Domestic pricing, farmer income, and the alleviation of poverty are all positively impacted by this cycle [43]. Therefore, it is essential to do further research on the economic aspect of food security in India, specifically focusing on value chain potential and efficiency assessments. This will help us understand how these factors interact with one another and how policy responses may be improved.

In sum, our findings brought attention to several important aspects:

• farm-level output volumes are much lower than the average production worldwide.

• India's agriculture and food policies, which prioritize self-sufficiency, are correlated with low import and export values, which lead to a roughly balanced trade model;

• Inefficiencies in the food system are mostly attributable to the following: harvesting, post-harvest, and distribution losses;

• non-food applications get a modest quantity of calories and fat, but not protein, which is far lower than the world average;

• Since pasture-fed livestock, such dairy cattle, predominate in India, the calorie and protein losses when edible crops are transformed into livestock are minimal. The substantial nutritional benefits of consuming more milk in India imply that this may be a worthwhile exchange of farmland for the supply of high-quality protein.

Based on our research into the Indian food supply chain, we have determined that the most important steps to take to increase food safety are reducing losses during harvesting, processing, and storage, and increasing production of high-quality crops. Not only does this method help find inefficient and wasteful "hotspots," but it also reveals how much of a shift is needed to achieve a target outcome throughout the whole food supply chain. Based on our research, we know that reducing food loss and waste by half is an important step toward improving food security. However, this goal would require substantial investments in infrastructure, education, and the economy. On its own, this would not be enough to guarantee food security in India.

Consequently, ensuring food security in the short and long term requires a concentration on increasing agricultural output. There must be a more thorough evaluation of the possibilities of attaining yields close to 75% AY soon (up to 2030) with the current crop range. To achieve 75% and 90% AY, respectively, for several basic crops, a yield increase of more than 30% and 50% would be necessary (see to S2 Table). Achieving almost maximum yield, or 90% AY, is no easy feat; many industrialized nations still haven't mastered it. To optimize crop choices and prevent negative consequences, it is important to examine the possible constraints of resources and environmental implications required to obtain such yields. Improving water and fertilizer management has the most potential to narrow the yield gap [23].

There are serious worries about India's long-term water security due to the depletion of groundwater supplies caused by agricultural irrigation [43] and especially if the availability of water poses a resource constraint on the achievement of yield. Increases in fertilizer use, which boosts yields, also raises sustainability issues since microbially mediated emissions of nitrous oxide (N2O), a significant greenhouse gas (GHG) source, are a direct outcome of nitrogen fertiliser application to agricultural soils [44]. Therefore, reducing the existing yield gap could come with a heavy carbon footprint.

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