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Achieving zero hunger: A global policy lens on food security drivers and income group disparities

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ABSTRACT

Many countries struggle to meet their daily dietary requirements despite numerous attempts to address the existing demand. Consequently, this study collectively analyses the impact of urbanisation, renewable energy, greenhouse gas emissions, population growth, gross domestic product per capita and agricultural land on food production relying on Sen's Entitlement Theory, thus providing insights to resolve the long-standing issue of food insecurity, and support the achievement of the Sustainable Development Goals. The study utilises a stepwise panel ordered Probit model on 146 countries, for the years 1993 to 2023. It further categorises the food production index into three categories of food security as; low, moderate and high, thereby enabling discussion of the likelihood of a country falling into one of the aforementioned food security categories over the years. Urbanisation, agricultural land, and the dummy variables introduced to represent the income groups have been identified to have a significant and favourable relationship with the food production index. In contrast, the greenhouse gas emissions and renewable energy variables have a significantly inverse impact on the food production index. This makes a unique contribution to the existing body of literature, especially by comparing odds over the years, across different food secure categories, countries, and their specific income levels. This study enables policymakers to gain a comprehensive historical perspective on each case. This study further promotes the Sustainable Development Goals, highlighting areas where these goals have been negatively impacted. Additionally, the study discusses optimised investment allocations, agricultural research and development, agricultural technology, climate resilient farming, and sustainable urbanisation planning as solutions for extreme cases.

1. Introduction

Hunger remains a significant global issue in 2023, affecting 733 million people, or approximately one in eleven individuals worldwide. Additionally, 2.33 billion people experience moderate to severe food insecurity, including 864 million who faces high food insecurity (World Health Organization, 2024). In less than a year, over 295 million people in 53 countries faced acute hunger, a 13.7 million increase compared to the previous year (FAO, 2024). With the current economic and climactic pressures, this situation continues to worsen, as 70% of the global population currently resides in countries lacking adequate data to measure progress towards Sustainable Development Goals (SDG) 1 and 2, which aim to eradicate poverty and hunger (World Bank Blogs, 2025).

As a result, understanding the factors influencing food security is imperative, such as urbanisation, which enhances market access, infrastructure, and resilient food systems. Urban and peri-urban agriculture, including rooftop gardens, indoor farming, and community plots, has enhanced local food resilience plays an equally important role. (Srinivasan and Yadav, 2023; Gunapala et al., 2025; Rout et al., 2024). This shift in urbanisation is part of the broader global increase of this factor observed across all income groups, as shown in Fig. 1(a). Further, predictions show that urbanisation will reach 68% by 2050 (UN 2018), and combined with significant population growth, particularly in low (Our World in Data, 2025) and high income countries (Simon, 2024) as shown in Fig. 1(b), which experienced substantial spikes in the late 1990s and mid-2000s, these trends are likely to place increasing pressure on agri-food systems in the future (FAO, 2023; de Bruin et al., 2021).

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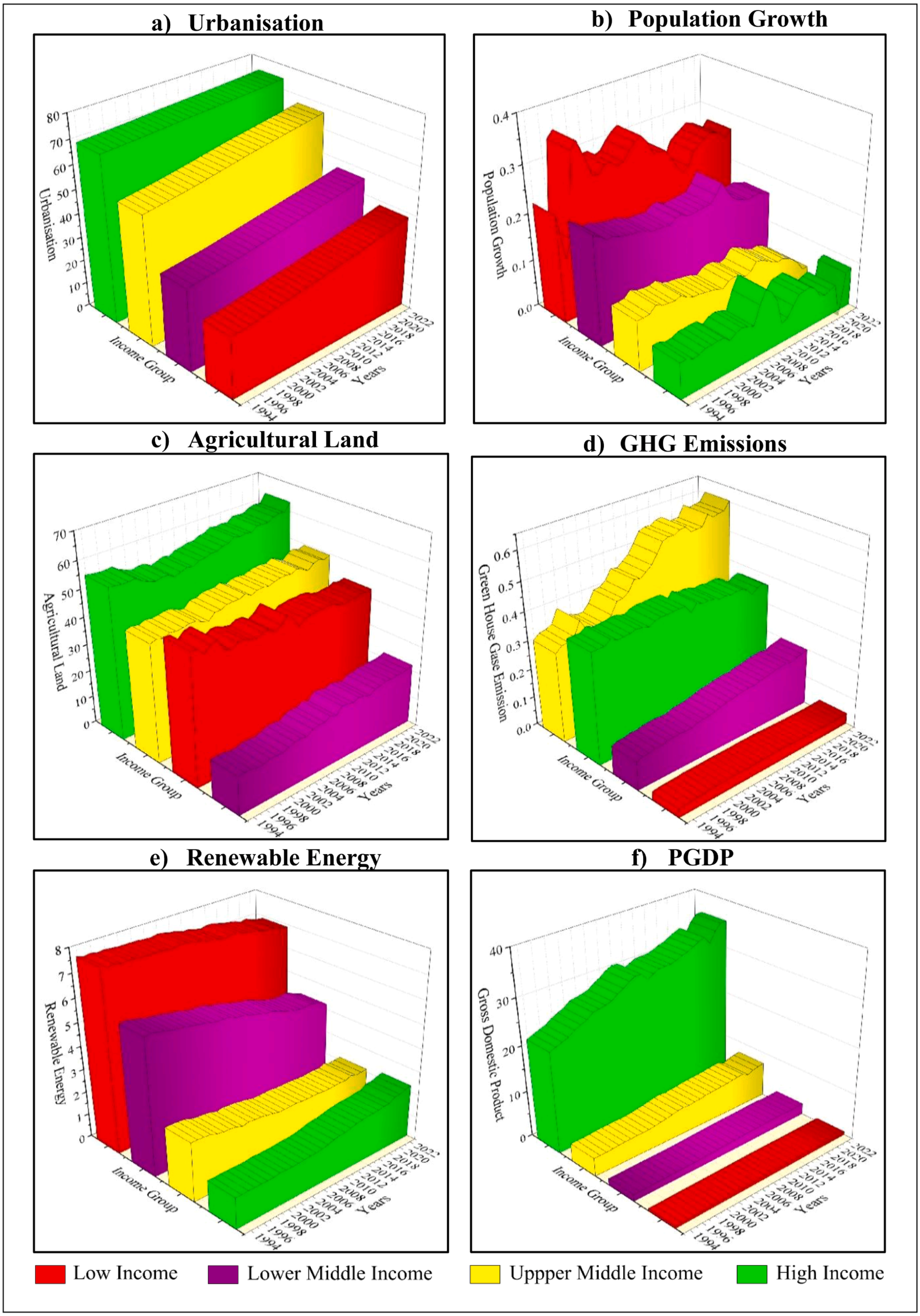

Fig. 1. Averaged variables per income group, 1993 to 2023. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

However, one solution to this issue lies in agricultural expansion, which makes food systems more resilient and about three times more effective than other sectors (The World Bank Group, 2024a). It is predicted that by 2050, the Earth will need to feed 9 billion people using the same land and water resources, and as a response requires a minimal of 70% rise in food production (The World Bank Group, 2012). To meet this demand, fallow lands are now being rehabilitated (Patra et al., 2025), with roughly 1.4 billion hectares of land currently under cultivation (UN, 2025a). However, the success of such initiatives could be complicated by disparities in land expansion, as seen in Fig. 1(c), where a gap of almost 30 hectares is present between lower-middle-income and other countries, likely due to institutional constraints that limit land availability (UN, 2023).

Greenhouse gas (GHG) emissions could also exacerbate this situation by intensifying adverse climate changes such as global warming and natural disasters, thereby reducing food security (UN, 2024; Gobezie and Boka, 2023; Segbefia et al., 2023). This vulnerability, combined with the interaction between emissions from gases such as methane, nitrous oxide, and carbon dioxide (CO_2), presents significant challenges to food security (Lu et al., 2024). The agri-food system as a whole nearly accounts for one-third of global GHG emissions, which accelerates climate stressors like droughts that reduce yields and increase food system vulnerability (FAO, 2022). This is particularly concerning, given that these emissions are rapidly rising in certain regions, such as upper middle-income regions, as shown in Fig. 1(d), where emissions have increased by almost 200% towards 2023, likely driven by industrialisation and economic activities (Dharmapriya et al., 2025).

To reduce these emissions, transitioning to renewable energy must be approached with caution as improper implementation can elevate hunger risks globally by decreasing the daily calorie intake of a person by 43 kilocalories, potentially putting up to 25 million more people at risk of hunger (Hasegawa et al., 2020; Subramaniam et al., 2019). Shifts towards biofuels may negatively impact food productivity by causing deforestation, excessive usage of fertilisers and pesticides, and by competing with resources needed to facilitate shifting consumption habits of a growing population (Kerina and Lauren, 2023), since bioenergy crops require considerably more land than solar and fossil alternatives for energy production, directly competing with food supply and damaging biodiverse ecosystems (Financial Times, 2025). Simultaneously, food systems account for 15% of global fossil fuel consumption, while the petrochemical industry is expanding its markets to reduce reliance on external fossil fuel-based inputs (Arboleas, 2023).

However, renewable energy can also improve food security (Wang et al., 2024a; Yadav et al., 2023) by increasing access to smart irrigation, reducing GHG emissions, stabilising food production in rural areas, reducing grid dependency, improving energy autonomy, and promoting environmental sustainability (Althani et al., 2025; Asamoah, 2020; Gupta, 2025; Mperejekumana et al., 2024a; Mperejekumana et al., 2024b). Despite these benefits, the global adoption of renewable energy, as shown by Fig. 1(e), remains highly uneven, since its usage in lower-middle-income countries has declined to almost 40%. In comparison, it has increased by about 200% in high-income countries, likely due to greater investments in green infrastructure (Global Infrastructure Hub, 2022a; Global Infrastructure Hub, 2022b; IEA 2019).

These disparities in the use of energy, reinforces the need for economic growth fostered by higher gross domestic production (GDP) in developing countries, since it can raise the purchasing power of people (Sun and Zhang, 2021), and reduce food insecurity by approximately 0.78% (Bogmans et al., 2024a), and the proportion of undernourished people by about 0.11% (Bogmans et al., 2024b). As a result, GDP has played a pivotal role in helping vulnerable nations reduce food insecurity by 27.5% in 2024, impacting 313 million people (Lila and Yacob, 2024). However, as shown in Fig. 1(f), significant gaps in gross domestic product per capita (PGDP), nearly 20 million US dollars between high- and lower-income groups, may hinder fair progress in food security.

Recognising these interconnected dynamics, this study aims to collectively evaluate how urbanisation, renewable energy, GHG emissions, population growth, PGDP, and agricultural land influence global food security. In addition, the authors anticipate that the findings of this study will help governments and other institutions assess their progress in food production over time and formulate the necessary policy reforms. This study thereby contributes to existing literature in the following manner:

First, this research introduces a new classification for FPI as low, moderate, and high food security levels, a categorisation not found in previous literature. This facilitates assessing countries' probabilistic likelihood of belonging to each of these pre-determined levels and understanding global food security dynamics. Further, it is expected that the employment of the methodology used would contribute positively to the existing body of literature, since it was not identified as a prominently used methodology in this area of study.

Second, this study examines 146 nations, categorised into high, upper-middle, lower-middle, and low-income countries, to understand the distribution of food security outcomes within each income group. It evaluates the likelihood of countries in each income group falling into one of the three food security levels, showing how food security varies across income brackets.

Third, the research includes visualisations that show the percentage change for each independent variable across different income groups, providing a comparative view of how variables change within and between these groups. The heat maps in this study illustrate the predicted odds of countries within each income group falling into low, moderate, or high food security categories over the same period, thus providing a timely overview of the odds.

Finally, this study examines the global impact of socioeconomic and environmental factors on food security, supporting SDG 2- Zero Hunger, SDG 1- No Poverty, SDG 7- Affordable and Clean Energy, SDG 11- Sustainable Cities and Communities, and SDG 13- Climate Action, by providing empirical evidence on food security drivers and strategies for accessing nutritious food. The sections that follow will cover the literature review, data and methodological framework, hypothesis formulation, results discussions, conclusion, and policy implications.

2. Literature review

Understanding how food security is affected by factors such as urbanisation, GHG emissions, renewable energy, population growth, PGDP, and agricultural land use is crucial. As urbanisation accelerated, the human diet faced alterations, along with changes to the methods of food production. It is also essential to evaluate how the harmful effects of GHG emissions may impact food security and the role renewable energy must play in ensuring food security worldwide. Along with this, the rapid increase in population would require significantly larger quantities of food to be produced than ever before, while also necessitating a study on how PGDP can impact food security. Since food is produced on arable land, protecting it and ensuring better farming strategies would ensure that food production is done sustainably around the world. The aforementioned variables have interchanging effects on food security, and by extension, on food production as well. The studies on the relationships between these variables are extensive and must be thoroughly explored to gain a comprehensive understanding of the interplay between them.

2.1. Urbanisation and food security

Urbanisation is the large-scale migration of people from rural areas and towns into urban areas and cities. Over recent decades, this movement has occurred dramatically, with large groups of people relocating from villages to metropolises. Consequently, the total global urban population overtook the total global rural population in 2007 (Hannah et al., 2024). Thereafter, this gap has continued to widen, leading to drastic lifestyle changes, fostering of new cultures, ideas, and behaviours across the globe.

One of the most significant changes in urban lifestyle is the shift in diet, with people requiring more affordable and easily prepared food in larger quantities. Specifically, the demand for dairy products, fish, meat, legumes, fruits, vegetables, and processed foods has increased (FAO, 2023), leading to an overall rise in urban food demand especially in the context of South Asia and Sub-Saharan Africa (de Bruin et al., 2021; Satterthwaite et al., 2010; Kriewald et al., 2019). It is interesting to note that food consumption has changed not only between rural and urban areas, but also between large and small cities (Bren d'Amour et al., 2020). This suggests that even slight variations in dwellings can lead to significant variations in food and nutrition, however it is important that the proportionate increase of urbanisation is comparatively analysed with the available agricultural land as this might not be a larger issue, such as in the case of Sub-Saharan Africa (de Bruin et al., 2021). Consequently, in areas with low food production, urbanisation could be challenging, as urbanised areas require continuous and substantial production to sustain their communities.

The unprecedented rise in the global urban population has created diverse needs in societies, including the rising demand over housing, lack of proper regulations in causing haphazard and disorganised urban planning, leading to untenable urban hotspots (Angel, 2023). A notable example of this is the global growth of slum dwellings, which leads to improper waste management and encroachment of agricultural land most prominently seen in countries such as India (Gumma et al., 2017). Other issues include inefficient land transfers, insecurity in land tenure and land hoarding, which also contributes to this inefficiency (Koroso and Zevenbergen, 2024). This may further distort land prices and weaken the food production of local farmlands leading to food crisis in long run. Improper urban planning could have harmful impacts on the environment (Yu et al., 2024; Jiang et al., 2024). Hence, it is crucial to establish and implement appropriate regulations, ensuring that urban expansion occurs responsibly.

Governments and policymakers can adopt several strategies to enhance food security in urban areas. These include better urban planning, increased investment in urban and peri-urban agriculture (Satterthwaite et al., 2010; Orsini et al., 2013) leading to better market access and improved local employment opportunities, while adopting more intensive, yet sustainable production practices, assists in maximising yields while preserving natural resources and ensuring long term ecological balance. Furthermore, changes to farming labour, land use, and other resources could also enhance food security (FAO, 2023), as these dynamic factors would fit time appropriately. Income and farming diversification, coupled with more focused farming specialisations, could also significantly increase food security (Haile Aboye et al., 2024), with spread risk backed up by agricultural economies of scale contributing to cater beyond the income disparity of the individuals. Conversely, some studies indicate that urbanisation may cause food insecurity, as rapid urbanisation can lead to decreased food production and higher food prices (Abebe, 2024). Nevertheless, implementing more efficient farming practices would reduce wastage caused by farming inefficiencies and help in utilising resources effectively.

2.2. Greenhouse gas emissions and food security

GHG emissions, a primary driver of climate change, continues to rise despite severe warnings and mitigation strategies proposed and implemented worldwide (Hannah et al., 2023). Several studies indicate a negative relationship between GHG emissions and food security (Segbefia et al., 2023; Ajay et al., 2015). One study found that a 1% increase in GHG emissions results in a decrease of 1.2% in food security (Gobezie and Boka, 2023), while another found a positive and significant impact on food availability in the context of Sub- Saharan Africa (Affoh et al., 2022), especially in the long term. This rise in CO_2 further negatively impacts the cereal grain production (Kibria et al., 2023), leading to more price increases (Yan and Alvi, 2022). Food security around the world could be improved by reducing GHG emissions. Multinational corporations and conglomerates would need to make substantial changes to their current processes to facilitate such a shift, which could ultimately benefit both people and the planet.

Climate change, which involves long-term shifts in temperature and weather patterns (UN, 2025b), will also impact food security, led by continuous ignition of fossil fuels. A study conducted in Africa found that under $3^{\circ}C$ warmer climate, Africa's food production could only feed 1.35 billion people, but the continent's population is expected to reach 3.5 billion by 2075, resulting in a deficit in food production for 2.15 billion people. They further note that to achieve food self-sufficiency, agricultural productivity with irrigation alone will not be sufficient (Beltran-Peña and D'Odorico, 2022). Moreover, food security and nutrition are expected to have adverse consequences due to climate change (Mirzabaev et al., 2023). However, climate change could be mitigated by reducing GHG emissions, which would ensure that the environment remains vigorous for food production. Climate change caused by GHG emissions can hinder food security and food production, causing consumption issues around the world. Mitigating the environmental impacts caused by climate change could enhance food security, especially with a rapidly growing population which would demand food in unprecedented amounts.

Temperature is a well-discussed topic in previous studies, where high temperature can result in lower food security. Temperature can decrease grain output (Tehmina, 2022) and can accelerate evapotranspiration from plants and soils (The World Bank Group, 2022) and cause an overall reduction in food security (Hamadjoda Lefe et al., 2024). Although temperature can have several benefits, such as lengthening the growing season or allowing different crops to be grown, it can also make farming more challenging (E.P. Agency, 2025). High temperatures can cause crop yields to fall, pushing many people into poverty. In Africa, the number of people facing poverty due to rising temperatures is estimated to be 43 million (The World Bank Group, 2022). Mitigating GHG emissions would reduce the risk associated with higher temperatures, thereby decreasing the danger posed to food security.

2.3. Renewable energy and food security

Renewable energy is energy derived from naturally available sources that are replenished at a rate higher than they are consumed. Renewable energy generation causes lower GHG emissions than non-renewable energy generation, making it one of the most sustainable and environmentally friendly sources of energy (UN, 2025c). Renewable energy use would reduce the reliance on non-renewable energy sources, such as fossil fuels and coal, which are known to have detrimental effects on biodiversity.

As many studies suggest renewable energy is positively associated with food security (Wang et al., 2024a; Kinda, 2021), while displaying a statistically significant association with agricultural production as well (Qamruzzaman, 2022). Renewable energy was found to have a negative impact on GHG emissions as well (Majeed et al., 2023; Wang et al., 2023; Gielen et al., 2019; Attanayake et al., 2024; Kyire et al., 2025), further contributing to agricultural sustainability (Daoudi, 2025), through renewable energy based cooling technologies (REN21, 2024). This would assist in cost efficient production processes leading to boosts in farmer's income. Moving away from fossil fuel consumption would assist in protecting ecosystems and improving soil and water quality, which would have a positive ripple effect on agricultural production.

However, it is important to highlight that studies have found a mixed relationship between these two variables where, it is positive in the short run, but indicates a negative relationship in the long run (Rehman et al., 2024; Li et al., 2024). Moreover, enhanced energy security with less reliance on imported fossil fuels, economic and social shifts to sustainable development, reduced health risks with cleaner energy production and improved environmental health would act as a positive contributor to food security, while the same would present challenges in terms of resources, costs and economic factors.

The evidence against the negative impacts of renewable energy needs to be taken into consideration as well. Resource competition against agricultural investments (Kurmanov et al., 2025), high initial costs associated with renewable energy (Wang et al., 2024a), increased opportunity cost over land usage in agriculture (Ujjayant et al., 2015), and lack of transitional policies to cushion the impact of the change of energy generation sources would pose a challenge to economies (Lynd et al., 2015), especially across low- and lower middle-income countries. Hence it is important to acknowledge that the deployment in the context of renewable energy should be done with much precaution to ensure that the benefit of renewable energy is maximised both in the short and long run. Additionally, in the context of bio-fuels, land, crops and water utilised for agricultural purposes would be diverted away, resulting in a food-fuel trade off (Rulli et al., 2016), thus creating a higher opportunity cost between the two. Therefore, the decisions of the governments in boosting agricultural production through renewable energy sources should not be compromised by the decision itself, consequently ensuring that the biofuel sources diminish the existent surpluses in natural resources rather challenging food production.

2.4. *Population growth and food security*

The population has increased at such a rapid rate, that it has been difficult for the environment, production, and humans themselves to adjust to this change. After centuries of population numbers being below 1 billion, the number of people in the world has skyrocketed to 8 billion within the last two hundred years (Hannah et al., 2025), where it is expected that this growth will peak at the end of this century. The study of the cultural, demographic and social changes this growth brings is critical to the survival of humanity.

This rapid growth of people requires more resources to meet their consumption needs, giving increasing pressure to the existing food systems. Governments and companies must address this requirement to prevent the increase of global poverty and hunger. One of the most critical factors that arises with population growth is the rise in food production. While food production needs to increase, ensuring food security is equally important. Numerous studies support the notion that the rising population requires a higher level of food production (Schneider et al., 2011; Dossa and Miassi, 2023), ensuring that public and private investments are made continuously (Meyers and Kalaitzandonakes, 2015). However, this increase in resources, funds, and production could have negative consequences for the environment, for example, through the clearing of forest cover for agricultural lands, leading to an imbalance in the environment and impacting the overall biodiversity

Since 1960, food production has grown at a rate of 2.8% per year, while population growth has been 1.9%, with most population growth occurring in developing countries (Byrnes and Bumb, 1998). Countries with a population decline such as Italy and Germany experienced higher levels of food security, while those with rapid population growth experienced worse food security, further contributing to undernourishment, especially in the context of countries such as Niger, Somalia and Sudan (Segbefia et al., 2023; Molotoks et al., 2021; Onwe et al., 2024; Cheeseman, 2016; Kousar et al., 2021; Hall et al., 2017; World Food Program USA, 2024). A similar study found that while rural population growth could increase undernourishment, urban population growth would decrease it. Moreover, the changes in the prevalence of undernourishment mostly impacts long-run changes in the rural and urban population growth (Miladinov, 2023), as it is identified that food security would boost in the long run (Ntiamoah et al., 2023). This highlights the cruciality of a boost in agricultural productivity, which would otherwise cause a spike in agricultural commodity prices and result in higher ecological damage (Ron, 2014, Pimentel, 1991). Positive interrelations between population growth and GHG emissions (Raihan et al., 2025) create stressing situation for food production, especially in the context of low income countries (Lam, 2025). A solution to this crisis is to increase food security by making it available and accessible to everyone. However, with rapidly increasing population, many challenges lie ahead for decision makers, producers and farmers in ensuring equity in making food available to everyone around the world.

2.5. *Agriculture land and food security*

Currently, most of the habitable land in the world is used for agriculture, where croplands comprise one-third of the agricultural land (Hannah and Max, 2024). This is a vast amount of land, and it is being utilised mainly for the consumption purposes of people. Naturally, this extensive use of land causes much concern, increasing the need for thorough evaluation to ensure minimal impact to biodiversity and the planet.

The impact of arable land on food production has been extensively studied, as both factors are crucial for human survival. Studies have found that an increase in arable land leads to higher food production and cereal production (Bambi and Pea-Assounga, 2024), especially in the context of South Asia (Kibria et al., 2023). By increasing the availability of arable land and making it cheaper, more food could be produced, which would help cater for the increasing population as mentioned earlier.

Several factors related to arable land contribute to higher food security. Secure land tenure is found to improve food security (Egerson et al., 2025) along with digital innovation (Ayanwale and Kehinde, 2025), and technological change (Wang et al., 2024b). Countries such as China (Amanda, 2025) and Netherlands (John, 2025) provides the best examples in the use of agritech to the world. While land with more than one acre is crucial for food security, customary and formalised tenure increases food security, whereas tenancy and informal access reduce it (Dagdeviren et al., 2023). Integrating green agro-technology into agriculture could increase grain production and reduce GHG emissions as well (Kibria et al., 2023), with increased forest cover and land restoration (Orou Sannou and Guenther, 2025). Agroforests exhibit better productivity and energy efficiency in land use and food quality

(Pérez-Neira et al., 2023), while farm size and land use also have a significant influence on food security (Adesiyan and Kehinde, 2024). These factors would contribute to long run land use efficiency, while contributing to stable livelihoods of agrarian families.

However, several factors are also found to decrease food security, including large-scale land acquisitions (Mechiche-Alami et al., 2021), current trends in land use (Yu et al., 2025) cropland transfers and losses (Jian et al., 2022), and variations in land demand caused by disparities in food consumption (Lan et al., 2023), as these may create a shortage of resources available for food production. In Kampala, approximately 10% of the urban and peri-urban agricultural land is projected to decline by 2040, resulting in reduced dietary diversity and food security (Hemerijckx et al., 2025). While land productivity gains were projected to rise between 21% and 61%, the observed increase was 31%, which was a slight increase (Patra et al., 2025). It is essential to minimise the impact of these by reducing the usage and, in turn, increasing food security.

Better farming strategies enhance the productivity of arable lands, which would in turn improve food security. Proper usage of fallow lands (Patra et al., 2025) cultivated land restoration (Liang et al., 2024), proper urban-rural integration (Zhao et al., 2025), fragmented and diversified land management (Wu et al., 2025), reallocation of land (Zhu et al., 2025), land allocation to flex crops and producing food crops on marginal lands (Mechiche-Alami et al., 2021), better land use planning (Bousbaine et al., 2017) are essential in ensuring that farming that is sustainable and strategic. These strategies will ensure arable lands are highly rich and efficient for food production.

2.6. *Gross domestic product per capita and food security*

GDP is a crucial indicator of a country's economic growth. While high-income countries reported a per capita PGDP of $ 57,580, low-income countries indicated an average PGDP of $ 2,330 in 2023 (Our World in Data GDP Per Capita, 2023), subsequently highlighting the significant income disparity across the world. Focusing on countries to improve their income has led to an overall rise in living standards, while contributing positively to household food consumption (Tinta et al., 2018) This has led to an increase in food security and food production (Wang et al., 2024a; Abdi et al., 2024; Ceesay and Ben Omar Ndiaye, 2022; Farooq et al., 2024). A prime example of this is China, which is identified as one of the rapidly developing economies and stands out with its food production, reaching approximately four billion tonnes in crops (Journeyz, 2025). China, with an agricultural history dating back to the Neolithic era, continues to cater to its rapidly rising population by investing the increasing national income in agricultural technology and precision farming (Forever Farms, 2025). While countries focus on boosting their GDP, the agricultural industry is also a major contributor to it (Yogi et al., 2025), as seen in countries like Comoros and Ethiopia (The Global Economy, 2025). Further, lower PGDP was associated with food insecurity (Pawlak and Kołodziejczak, 2020).

On the contrary, while GDP is expected to raise food production and security, the rising food demand expected to double by 2050, would trigger a rise in food prices (Fukase and Martin, 2020). However, higher food prices have been identified as a means to encourage food production (Headey and Hirvonen, 2023), thus emphasising the degree to which the rise in prices may influence food security, that needs to be evaluated critically. Economic growth is concurrently associated with a positive contribution to GHG emissions (Dolge and Blumberga, 2021; Obekpa et al., 2025; Pan et al., 2023; Quan et al., 2024; Raihan et al., 2022; Wang et al., 2024c), thus having an inverse impact on food production and overall environmental sustainability in the long run (Fan et al., 2019; Raihan and Tuspekova, 2022). Economic growth was further associated with increased ecological footprints, with suggestions to reduce it, including increased investments in agricultural research and development (Obekpa et al., 2025). GDP has far-reaching impacts not only on food production but also on food demand, prices, and the environment. Increasing food production to cater to this demand while keeping prices and the environmental impacts low is quite a challenge. More food production clears more land area, increasing the adverse effects on the environment, alerting policy makers, economists and institutions to take early precautions in food sovereignty.

2.7. *Amartya Sen's entitlement theory*

Acknowledging the above mentioned literature we can identify that this study is closely linked with Sen's entitlement theory, which states that the roots of famine and hunger is not just reliant on food availability but on entitlements (Nayak, 2005, Sarah, 2025). Consequently, this theory expands to four entitlements as follows;

Production based entitlement is when people rely on food production

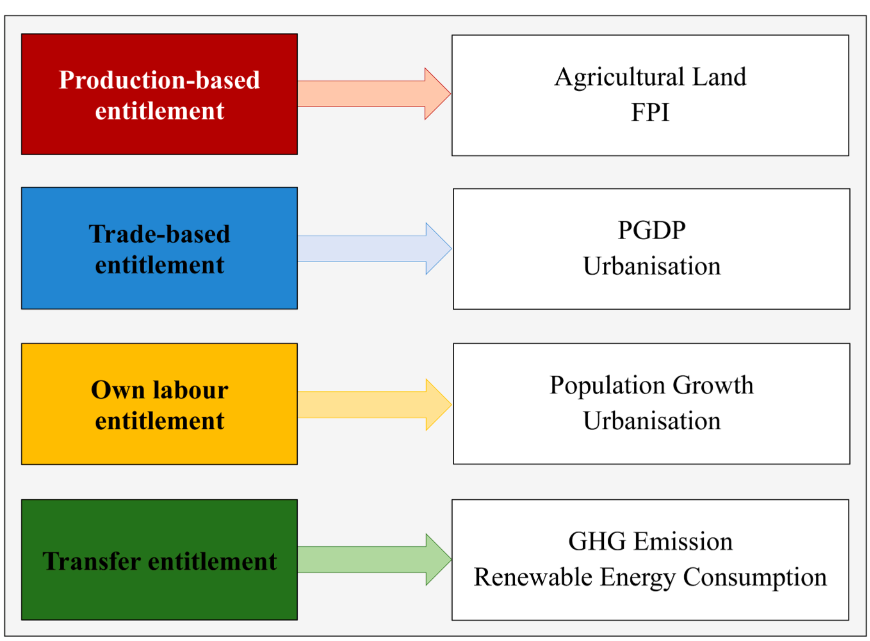

Fig. 2. Mapping Sen's entitlement theory to model variables. Source: Author's compilation.

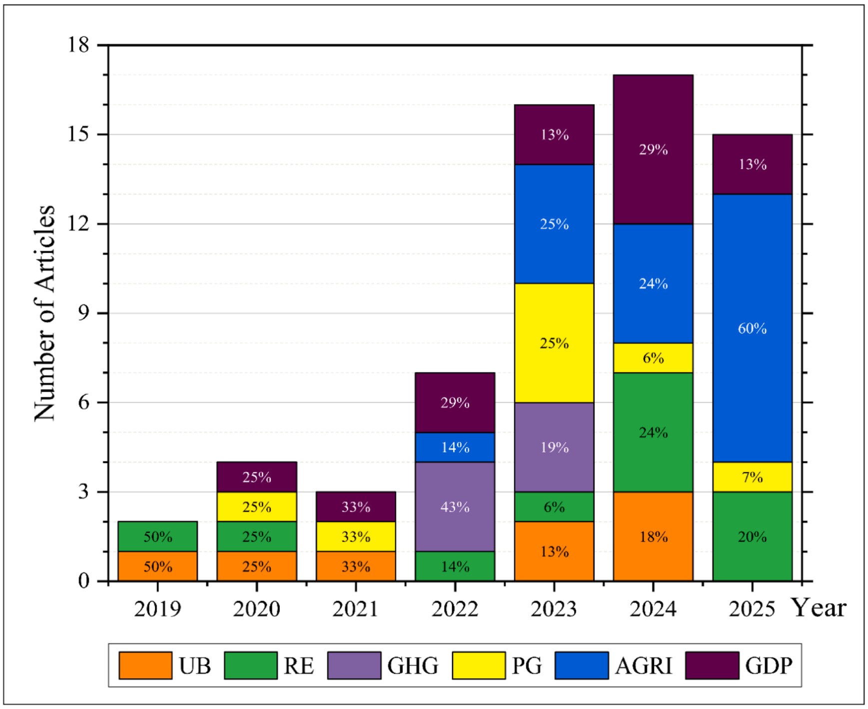

Fig. 3. Distribution of research articles by predictor variables, 2019 to 2025. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

itself, which stands as the core of this study, due to the use of FPI as the dependent variable, though subsistence agriculture may go statistically unrecorded. Trade based entitlement highlights individuals' ability to afford their own food, which when considered across the income groups may vary due to the existence of high-income disparity. Thirdly, own labour entitlement relates the study with consideration of the agriculture land available across the countries, with the net income generated from agricultural sector. Finally, transfer entitlement has been defined, where gifts, aids and remittances play a role. Most low and low middle-income countries may receive aids from governments and institutes to satisfy their food needs, with government investments, especially on the agricultural tech and rural to urban infrastructure would contribute positively to food supply and availability.

Fig. 2 links the Sen's entitlement theory to the conceptual framework by mapping each entitlement category to corresponding variables.

Table 1
Data sources and variables.

Variable	Acronym	Measurement Unit	Source
Food Security	FPI	Food Production Index (2014–2016 = 100)	(The World Bank Group 2024)
Urbanisation	UB	Share of the population living in urban areas	(Our World in Data, 2024a)
Renewable Energy Consumption	RE	Percentage of total final energy consumption	(The World Bank Group 2024)
Greenhouse Gas Emissions	GHG	Tonnes of CO_2 equivalent	(Our World in Data, 2024b)
Population Growth	PG	Annual percentage change in population size	(The World Bank Group 2024e)
Gross Domestic Product per Capita	PGDP	GDP per capita (constant 2015 USD)	(The World Bank Group 2024e)
Agricultural Land	AGRI	Agriculture Land (% of land area)	(The World Bank Group 2025)

Source: Authors' compilation.

Production of an individual's own produce in their own land links production-based entitlement to the study. Followed by PGDP and urbanisation that signals an individual's ability to purchase produce, where population growth, especially in rural context and urbanisation signals individuals who work for produce. Transfer entitlements could come in form of subsidises and remittances encouraging sustainable production.

In reviewing the literature relevant to this study over the past 6 years, reveals the distribution of the predictor variables discussed across studies as depicted in Fig. 3. This clearly shows that the number of studies on independent variables in recent years has increased, thus emphasising the importance of the topic this study addresses. Despite such extensive studies, food security remains a significant issue that needs to be addressed continuously. The segment below reports the results and discussion of the model, thus providing insights for governments and institutions.

3. Data and methodology

3.1. The data

The dataset utilised consists of 146 countries, which were formed due to the existence of comprehensive global data. This study spans from 1993 to 2023, capturing a panel dataset comprising countries worldwide. Statistical data was gathered using the "World Bank" and "Our World in Data", and cubic polynomial estimation was used in filling any missing values for 2022 and 2023. Table 1 provides an overview of the variables used, including their abbreviations and respective data sources, while Appendix 1 provides the dataset utilised in the study.

3.2. The methodology

The objective of this study is to estimate the odds of a nation being categorised as low, moderate or high food secure. Model selection between the full and the stepwise specification was guided by Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC),

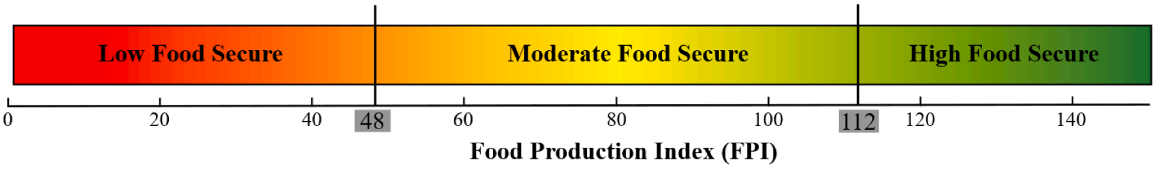

Fig. 4. FPI categorisation. Source: Authors' compilation based on the data source (The World Bank Group 2024c).

where it was identified that stepwise specification yielded lower AIC and BIC values as shown in Appendix 2. Hence, stepwise panel ordered probit model was used to derive the probabilities over 31 years for each country. The authors took the initiative in categorising the variable FPI into three categories as mentioned above. Fig. 4 visually presents the categorisation of FPI, with 48 and 112 being the thresholds between the food security categories. Previous literature influenced the categorisation of FPI into three groups (Macalou et al., 2023). Software OriginPro (2024) and Inkscape (Inkscape, 2025) was used in compiling the visualisations for this study.

The equation following stepwise is depicted in Eq. (1)

$$FPIC_{it}\ (1,2,3) = X_i(\beta_1 UB + \beta_2 RE + \beta_3 AGRI + \beta_4 PGDP + \beta_5 LI + \beta_6 LMI + \beta_7 UMI)_{it} + \varepsilon_{it} \tag{1}$$

Where:

$FPIC_{it}$ (1,2,3)	The latent dependent variable together with the defined category levels
$\beta_{1,2,..6}$	Coefficients of the independent variables
UB	Urbanisation
RE	Renewable Energy
AGRI	Agricultural Land
PGDP	Gross Domestic Product per capita
LI	Low-income dummy variable
LMI	Lower-middle-income dummy variable
UMI	Upper-middle-income dummy variable
ε	Standard error term

Fig. 5 presents the overall procedure followed in generating the insights of the paper. The study began by identifying the research gap, whereby the research questions and objectives were formulated to address the problem. A critical literature review was conducted to support the authors' claims, followed by preliminary visualisations. Proceeding to the empirical analysis, the categorisation of FPI was done followed by heteroscedasticity and multicollinearity check, which is presented through Appendix 3. It was identified that the data was free of multicollinearity but was heteroscedastic. A stepwise panel ordered probit model was adapted, whereby population growth and PGDP were dropped due to their insignificance.

The final model was summed up with the inclusion of income groups as dummy variables, followed by an analysis of the percentage change of the variables, and a trend analysis of the odds of each country through a heat map. Finally, policies were recommended to overcome existing low food security instances, especially quoting examples form success cases.

4. Results

This section summarises the percentage change of the independent variables, along with the panel ordered probit results generated in the context of the global perspective, portraying how each variable impacts the likelihood of a country being food secure.

4.1. Preliminary analysis

Preliminary analysis of the percentage change in renewable energy consumption suggests that high-income countries have mostly attempted to adapt to renewable energy consumption over the years, with low-income countries exhibiting the highest volatility, primarily due to their high sensitivity to external shocks and resource constraints, which necessitates policy frameworks and international aid. Fig. 6 illustrates a notable increase in renewable energy consumption around 2020 and 2021, primarily due to fluctuations in energy demand during the COVID-19 pandemic.

With more than 50% of the world's population living in urbanised areas, Fig. 7 shows that high-income countries have experienced the highest growth in recent years. However, it has not always been the same; the 2010s show that lower-middle-income countries experienced higher growth in urbanisation, resulting from industrialisation and globalisation across those countries.

Rising GHG emissions have always been an issue that governments and institutions are trying to tackle. Fig. 8 illustrates that these attempts to minimise GHG emissions have resulted in much lower changes in growth in recent years. COVID-19, similarly to renewable energy consumption, impacted GHG emissions, resulting a sharp downward spike as economies shut down in 2020.

Fig. 9 portrays the growth of agricultural land over the years. Low-income countries have maintained their growth in agricultural land, despite the COVID-19 pandemic having a positive impact on agricultural land, thus increasing growth across all income groups. While in various instances, there has been a negative growth in the agricultural land for high income countries, the adverse impacts increased in 2014 mostly due to policy reformations and rising use of corn in ethanol production (Mumm et al., 2014) However, this rise is very minimal when compared to the boost in agricultural land in low-income countries in the same year.

4.2. Panel ordered probit results

Moving forward with the probit results, Appendix 4 provides the initial results generated before running stepwise. Table 2 presents the results incorporating the model's sensitivity to differences across income groups after stepwise, thus assisting in predicting more insightful probabilities across nations, with identifying it as the preferred specification.

The analysis adapts dummy variables representing the income groups and follows a stepwise panel ordered probit model to assess the odds of a nation falling into a food security category of low, moderate or high. The study excludes the high-income category when setting the dummy variables to avoid perfect multicollinearity, leading to a summarisation of 17 sub-hypotheses related to FPI and the estimated results.

Hypothesis 1a. A rise in urbanisation significantly reduces the odds of

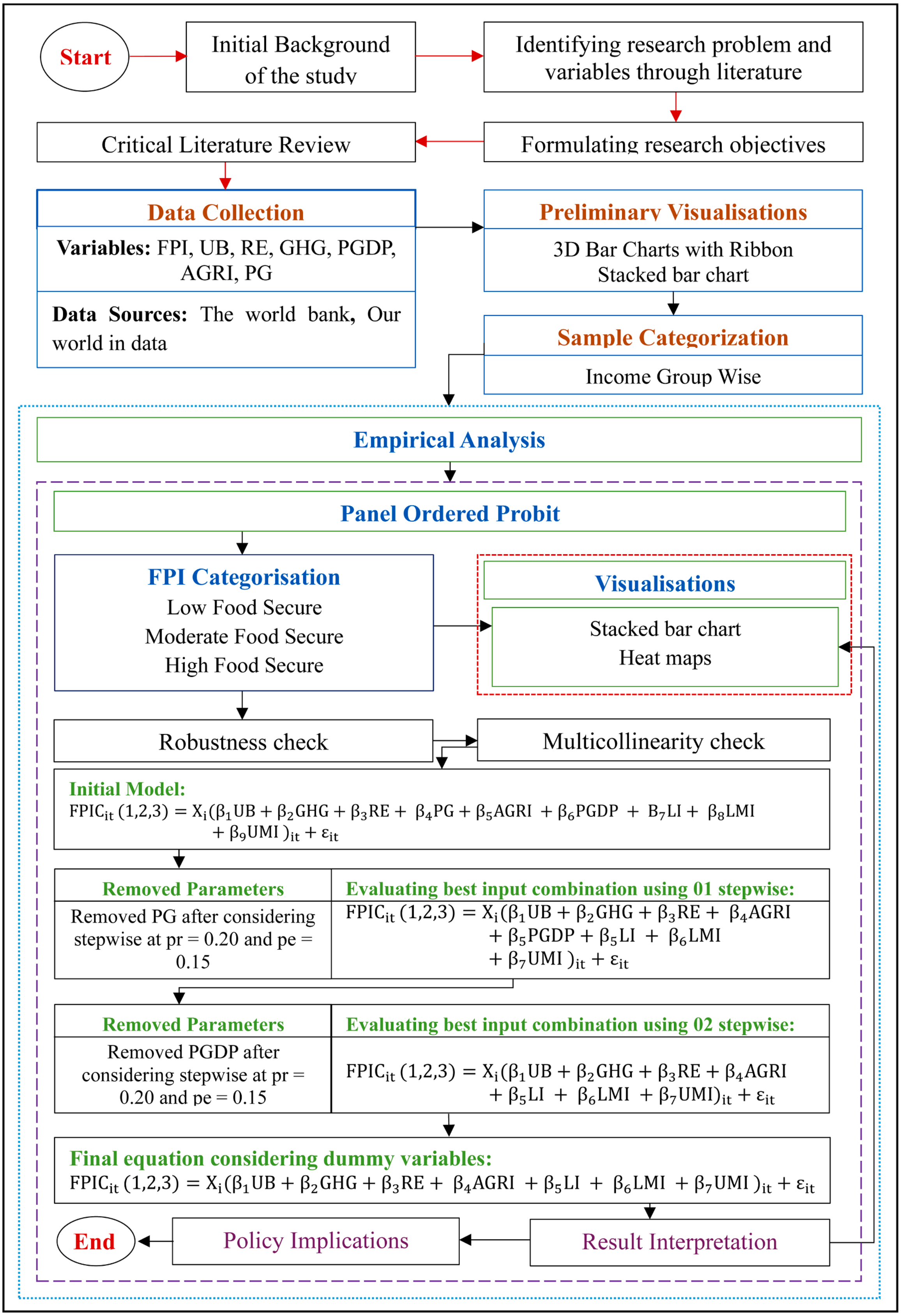

Fig. 5. Data and methodology flow diagram. Source: Authors' compilation.

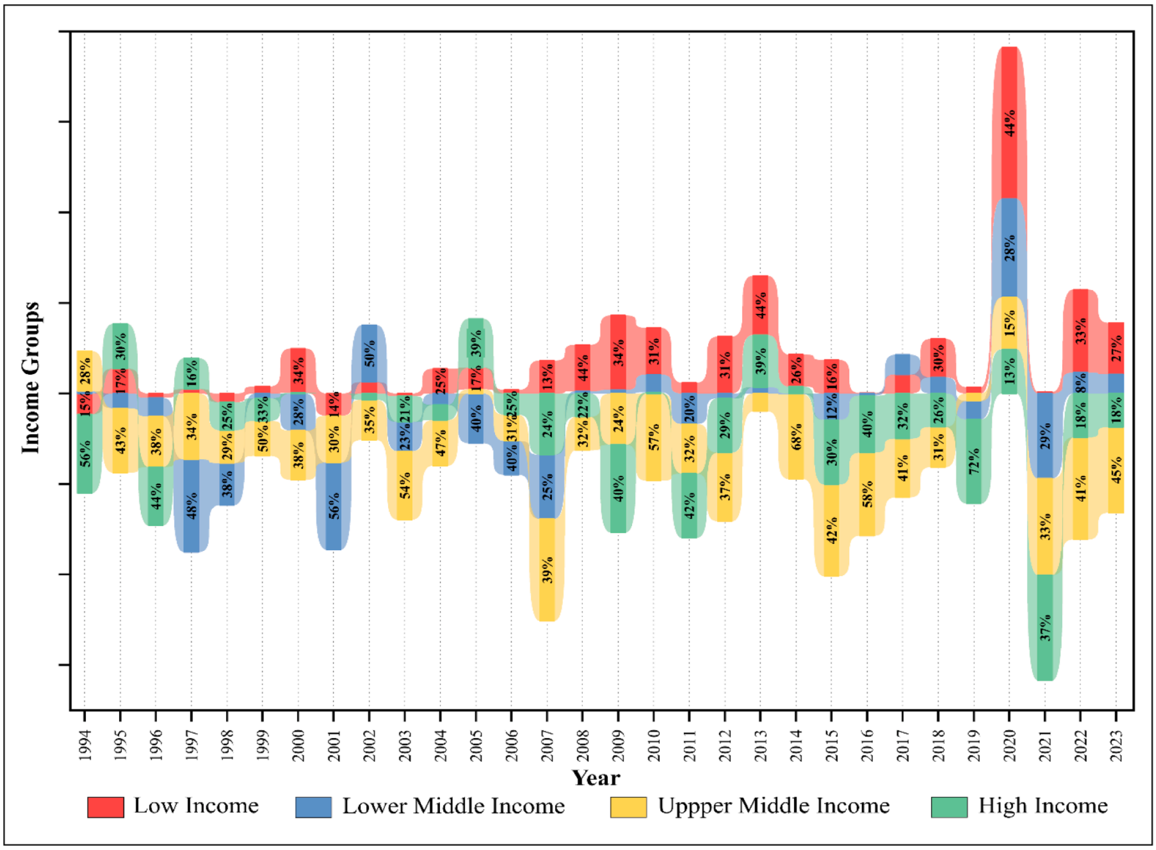

Fig. 6. Percentage change in renewable energy consumption, 1994 to 2023. Source: Authors' compilation based on the data source (The World Bank Group 2024d).

a nation being categorised as low food secure. This explains that when urbanisation increases by 1% the likelihood of a country being categorised as low food secure falls by approximately 1%, considering that it is significant at 1%. While urbanisation has been expected to have either a positive or negative sign, the empirical results support the latter. Improved infrastructure facilitating better access for food (Szabo, 2016), diversifying diets and improving income levels leading to healthy food consumption (Cockx and Boti, 2025, Tacoli, 2017) would contribute to enhancing the food security levels across urban areas and keep in line with SDG goal 11 of Sustainable Cities and Communities.

Hypothesis 1c. When urbanisation rises, the likelihood of a country being categorised as highly food secure rises at a significance of 1%. As a result, with every 1% rise in urbanisation, the probability of a country being categorised as highly food secure rises by 1.3%. This is supported by market-oriented farming practices (Braamhaar et al., 2025), which have been adopted by countries such as China and the US, and by government incentives provided to farmers in countries like India and Sri Lanka to enhance their food production.

Hypothesis 2a. Most countries in the present world tries to adapt biofuels into their electricity generation mix to minimise the greenhouse gas emissions, pollution and resource depletion caused by non-renewable energy sources. However, relying too heavily on renewable energy would introduce uncertainty and lead to rising food prices (Hasegawa et al., 2020), negatively impacting food security and promoting irresponsible consumption and production. Consequently, findings reveal that the odds of a nation being categorised as low food secure rise by approximately 4.6% when renewable energy consumption increases by 1%.

Hypothesis 2b. On the contrary, the possibility of a country being highly food secure significantly falls by approximately 6%. This could occur as natural resources, such as land and water, in their early stages of transitioning into renewable energy, would create an opportunity cost against agricultural land. At the same time, the improvement in renewable energy in the short term may not be matched by policy restructuring to ensure that food systems are aligned with the renewable energy supply, thus creating a gap between them.

Hypothesis 3a. Agricultural land is an area that most governments focus on nowadays. While agricultural land can be increased physically by clearing forests, it can also be improved by boosting farming efficiency. Most institutions would select the latter due to the larger GHG emissions associated with land clearing. As a response, with a percentage improvement in the agricultural land used, the possibility of a country being low food secure falls by approximately 0.06%, thus indicating a positive relationship between agricultural land and FPI as expected.

Hypothesis 3b. Simultaneously, when agricultural land rises by a percentage, a country's food security rises by 0.07%. This is further exacerbated by the crop-specific agriculture adopted by governments to ensure dietary requirements are met (Wu et al., 2014). Countries such as India focus on crops like rice, wheat, and pulses to maximise their agricultural production. However, the soil must not be over-strained, thereby ensuring that local ecosystems are not harmed, and that food production is sustained in the long run.

Hypothesis 4a. Results indicate that with 1% rise in PGDP the likelihood of a country being categorised as low food secure falls by 0.03% at 5% of significance. This is because as PGDP rises the average household income is boosted, thus encouraging people to reach for better standards of living. This is further enhanced by improved safety nets

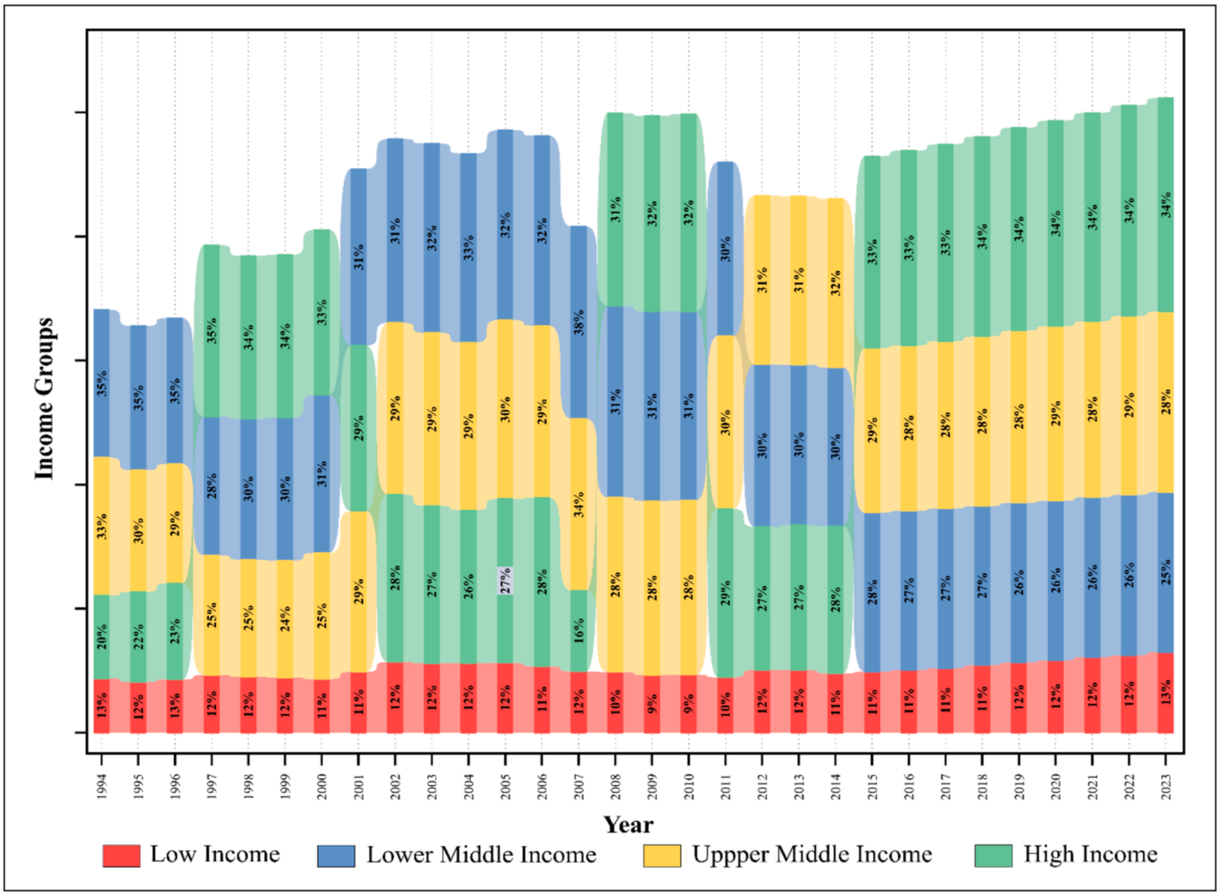

Fig. 7. Percentage change in urbanisation, 1994 to 2023. Source: Authors' compilation based on the data source (Our World in Data, 2024a).

such as higher savings, thus making families and individuals less vulnerable to external shocks such as sudden inflation fluctuations or climate changes.

Hypothesis 4b. On the contrary, the likelihood of a country being categorised as high income rises by 0.3% when PGDP rises by 1%, thus indicating a positive relationship. This is led by increased investments on infrastructure that may improve the access and availability of food, followed by increased investments on agricultural technology that would boost local farming and strengthen the local foods systems. This would therefore act as a safety net against imports, as countries avoid over relying on it.

Hypothesis 5a. This significantly signals that being a low-income country is likely to reduce the likelihood of being categorised as low food secure by approximately 57%. This could likely be due to the economic dominance of the agricultural sector in most low-income countries, such as Malawi, where around 76% of its employment comes from agriculture, and an overall 59% of people in low-income countries work in agriculture (Feed The Future, 2025). This, positively contributes to increasing household food availability and utility, thereby improving the worsening conditions of food security over the years.

Hypothesis 5b. A country falling into the categorisation of low-income is likely to have a lower likelihood of approximately 16% of falling into the moderate-income category. While this is significant at 10%, it is essential to acknowledge that the predicted probabilities indicate that most low-income countries fall into the moderate-income category.

Hypothesis 5c. Results surprisingly indicated that being a low-income country would raise the likelihood of being categorised as highly food secure by 73% at a significance of 1%. Subsidies provided by governments and other institutions, along with a focus on agriculture and increased employment in the sector, may contribute to this percentage. However, many low-income countries cannot take advantage of the resources available to satisfy their dietary needs due to the unavailability of proper distribution systems, inadequate storage, poor climatic conditions, and lack of contingency plans to act during natural disasters. In addition, the lower income per head, while engaging in agriculture, would lead to strict spending on nutritional food, thus creating a gap between food security and income groups.

Hypothesis 6a. Most individuals living in lower-income countries tend to face rapid urbanisation; however, countries such as India, Vietnam and the Philippines have been able to sustain their urban growth with proper urban planning and optimised spending on city growth. This is substantiated by the results, as a lower-middle-income country would have an inverse but significant likelihood of being categorised as low food secure, as the odds fall by approximately 44%.

Hypothesis 6c. In expectation of economic growth, stability and income parity, most low-income countries conduct food programmes and obtain aid from organisations such as the United Nations (UN), especially during natural catastrophes, thus maximising their effort in closing the food shortage existing. Hence, a lower-middle-income country has a higher probability, approximately 56%, of being categorised as a higher food-secure country. However, due to the larger-scale disparity between communities and gender, as well as rising food prices, the impact of these efforts is minimised, thus explaining the results that indicate the majority of lower-middle-income countries are in the moderate-income category.

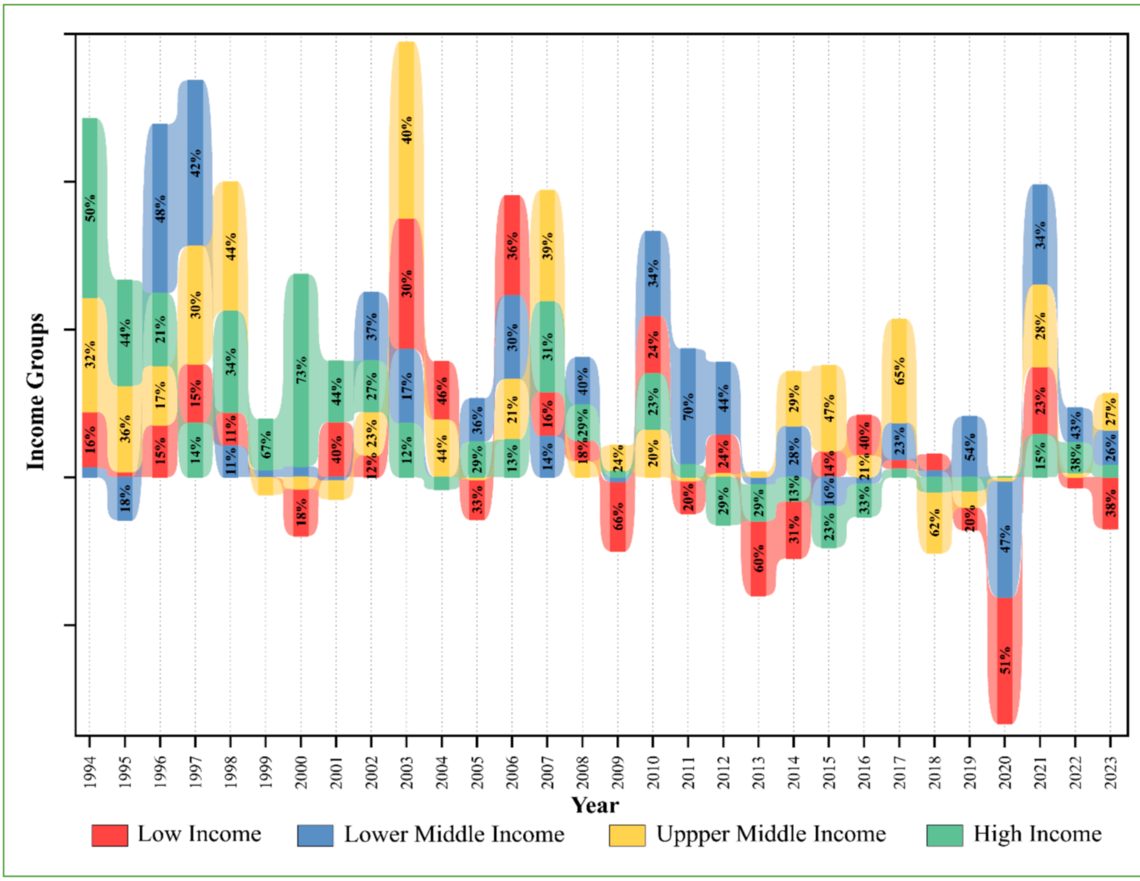

Fig. 8. Percentage change in GHG emissions, 1994 to 2023. Source: Authors' compilation based on the data source (Our World in Data, 2024b).

Hypothesis 7a. Upper-middle-income countries indicate an inverse likelihood of 15.6% of it being categorised as low food secure at a significance of 1%. This is increased by greater dietary diversity, optimised investments in newer technologies and planned sustainable urbanisation plans. A notable example of this is Argentina, which not only produces for its own community but also exports its produce to other countries (The World Bank Group 2024b).

Hypothesis 7b. The probability of an upper-middle-income country being categorised as highly food secure would rise by 20% approximately. Most upper-middle-income countries focus on improving their economic sustainability, accordingly, Erdogan (Erdogan, 2022), has identified that food production indeed makes a positive contribution to the economy. Furthermore, proper regulations, backed by sufficient funding, help upper-middle-income countries maintain their levels of food security.

4.3. Robustness checks

As elaborated above population growth and GHG emissions were dropped with stepwise due to their insignificance despite the availability of sound literature to reason the addition of those two variables to the model. Consequently, an outlier test at 5% was conducted on FPI which is the dependent variable, and on the two explanatory variables which were dropped due to insignificance, including: population growth and PGDP. Here it was identified that the signs and the significance remained the same thus validating the drop of the variables through stepwise. The results obtained after outlier tests is presented through Appendix 5. Additionally, a 10-fold cross validation was run on validation the model accuracy, where the model showed an improvement from 52.65% to 53.23% upon proceeding with stepwise. This indicates a feasible accuracy, considering it is a trichotomous probit model.

In summary, the results presented above support many findings and challenge others, further assisting interested parties to gain a fresh and updated perspective on how various global factors impact food production.

5. Discussion

The discussion utilises the probabilities computed by the model, as mentioned above. It tends to provide a holistic view of the country's global perspective on food security, giving special attention to the income groups to which the nation belongs. The figures illustrated below show how the likelihood for each country changes yearly over the period from 1993 to 2023. The figures follow a gradient of red, yellow, and green, thus representing low, moderate, and high, food security respectively, with the detailed statistics being provided through Appendix 6.

Fig. 10 portrays that most high-income countries have had a higher likelihood of being categorised as moderately food secure across the years 1993 to 2023. Soaring food inflation, fragile food systems, varying climate, and wars (Ministry Of Agriculture in Guyana, 2025) have increased the likelihood of Guyana being categorised as low food secure. Proper agricultural plans and regulations set by its government have assisted Guyana in slightly reducing the odds of being food insecure towards the end of the considered period. The rising cost of living and over-reliance on food imports, which account for 90% of its domestic consumption, (Barbados Environmental Conservation Trust, 2020) have driven Barbados to have higher odds of experiencing low food security over the years. In addition, Antigua and Barbuda faces a much more serious situation, with the probability of being food insecure having risen in recent years. Rising food prices, contributed to by Hurricane

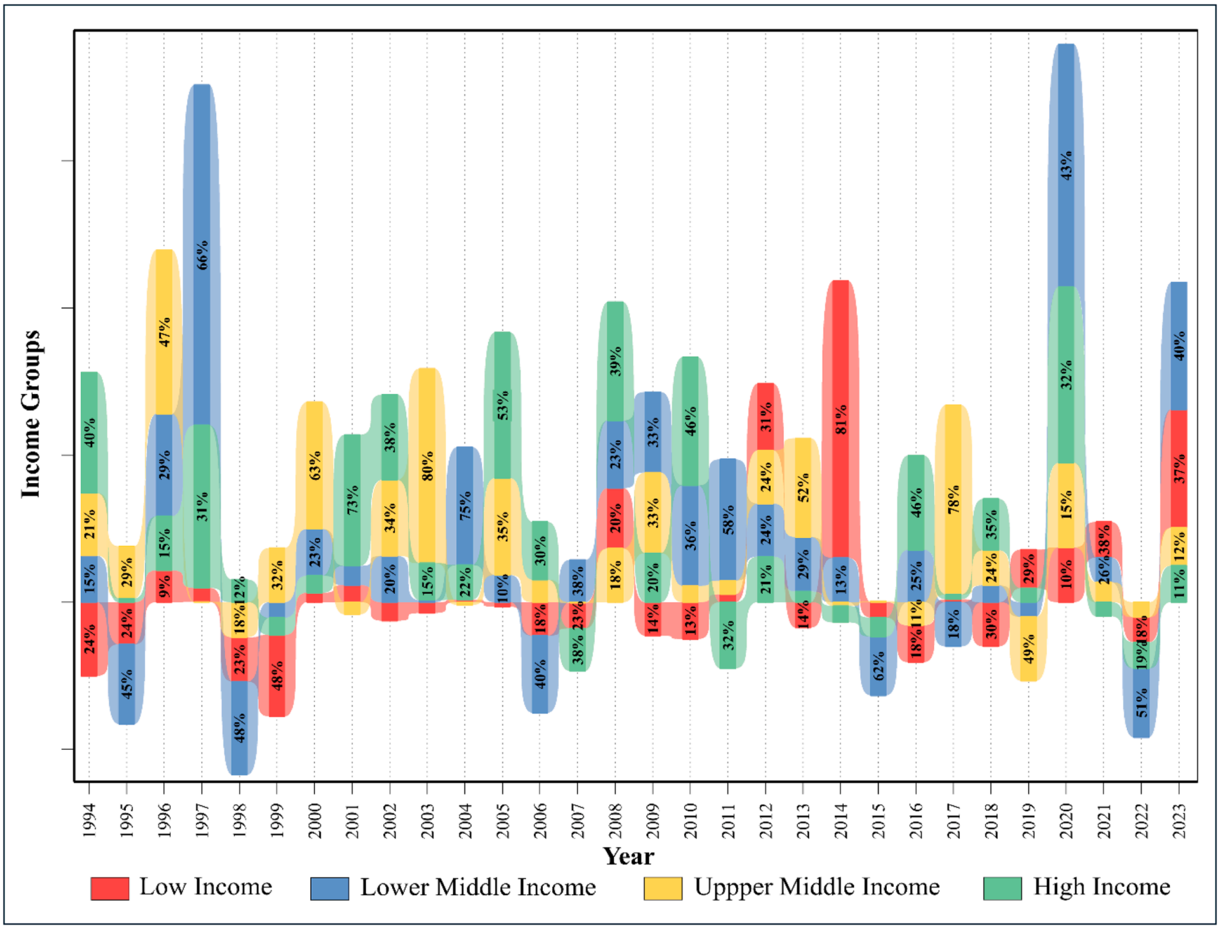

Fig. 9. Percentage change in agriculture land, 1994 to 2023. Source: Authors' compilation based on the data source (The World Bank Group 2025).

Table 2
Panel ordered probit model, estimated results with marginal effects (pr = 0.20 and pe = 0.15).

Variable	Estimate	Robust SE	Marginal Effects (in percentages)		
			Low food secure	Moderate food secure	High food secure
UB	0.089***	0.021	-0.009***	-0.003	0.012***
RE	-0.405***	0.106	0.042***	0.011	-0.053***
AGRI	0.054***	0.021	-0.006***	-0.002	0.007***
GDP	0.026**	0.013	-0.003**	-0.001	0.003**
LI	5.576***	1.203	-0.572***	-0.159*	0.731***
LMI	4.295***	0.949	-0.441***	-0.123	0.563***
UMI	1.524***	0.558	-0.156***	-0.044	0.200***
Ancillary Parameters					
$\hat{\gamma}_1$	6.057	2.042			
$\hat{\gamma}_2$	9.93	2.142			
Wald Chi^2	45.2				
Log Pseudolikelihood	-2063.69				
No. of observations	4526				

Note: The coefficients presented above represent marginal effects with the significant levels as follows, * significant at 10%, ** significant at 5%, and *** significant at 1%.
Source: Authors' compilation using (StataCorp, 2021) .

Omar and COVID-19 (The Borgen Project, 2021), significantly contributed to its odds of being categorised as low food secure. Although governments have introduced various projects to mitigate this issue, they appear to be less effective.

Moving forward to Fig. 11, the upper-middle-income countries, it can be identified that Argentina, Mongolia, Mexico, South Africa, and Ukraine has continuously improved its likelihood of being highly food secure over the years, backed by their targeted policies and emphasis on nutritional diversity (Cecilia et al., 2022). However in the case of Ukraine it is important to acknowlede that the ongoing conflit with Russia started in 2023 may severly afftect their food production levels hence bringing forth concerns in thier long maintained self suffieciency. Policy reforms, focused funding and modernising agriculture in the cases of Albania, Guatemala, Namibia, Peru, Indonesia and Thailand contributed to improve food security coming to recent years. China, starting around around 1998 improved its likelihood of being categorised as moderate good secure while coming to 2021 this changed to high food secure. The adoption of improved technology in agriculture,

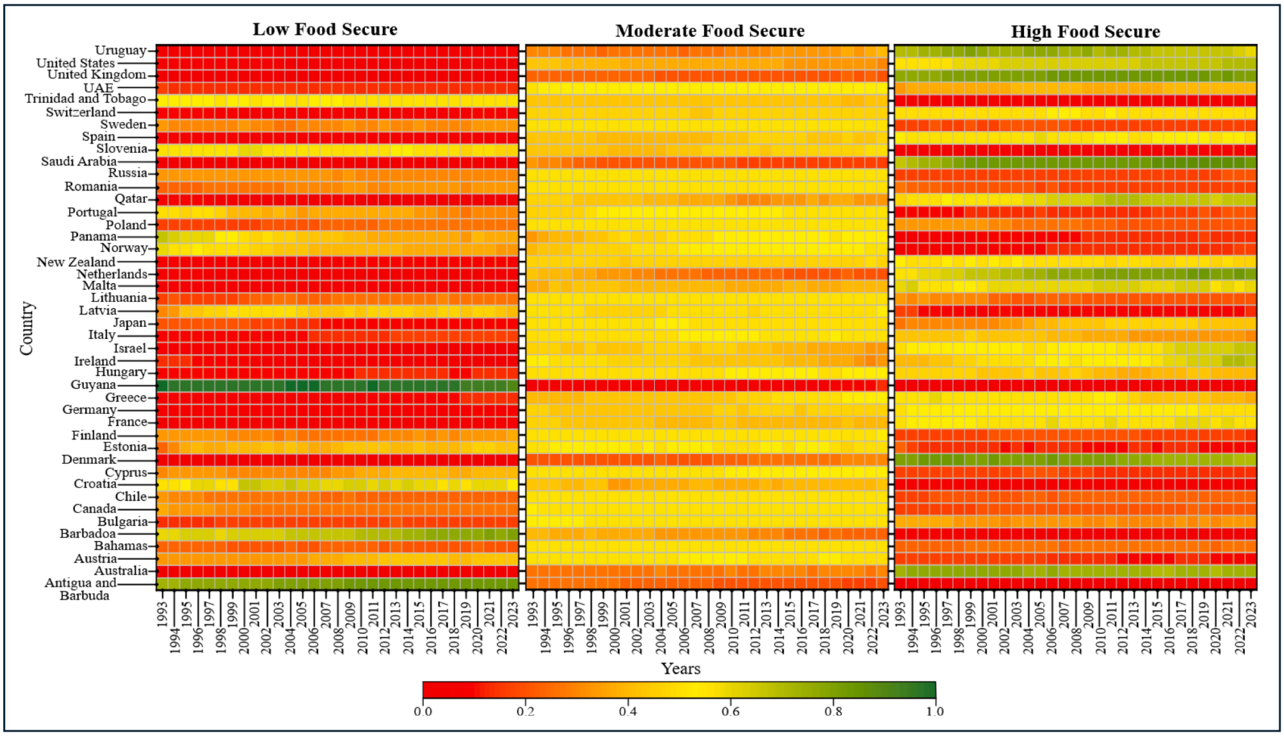

Fig. 10. Predicted probabilites for high-income countries, 1993 to 2023. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

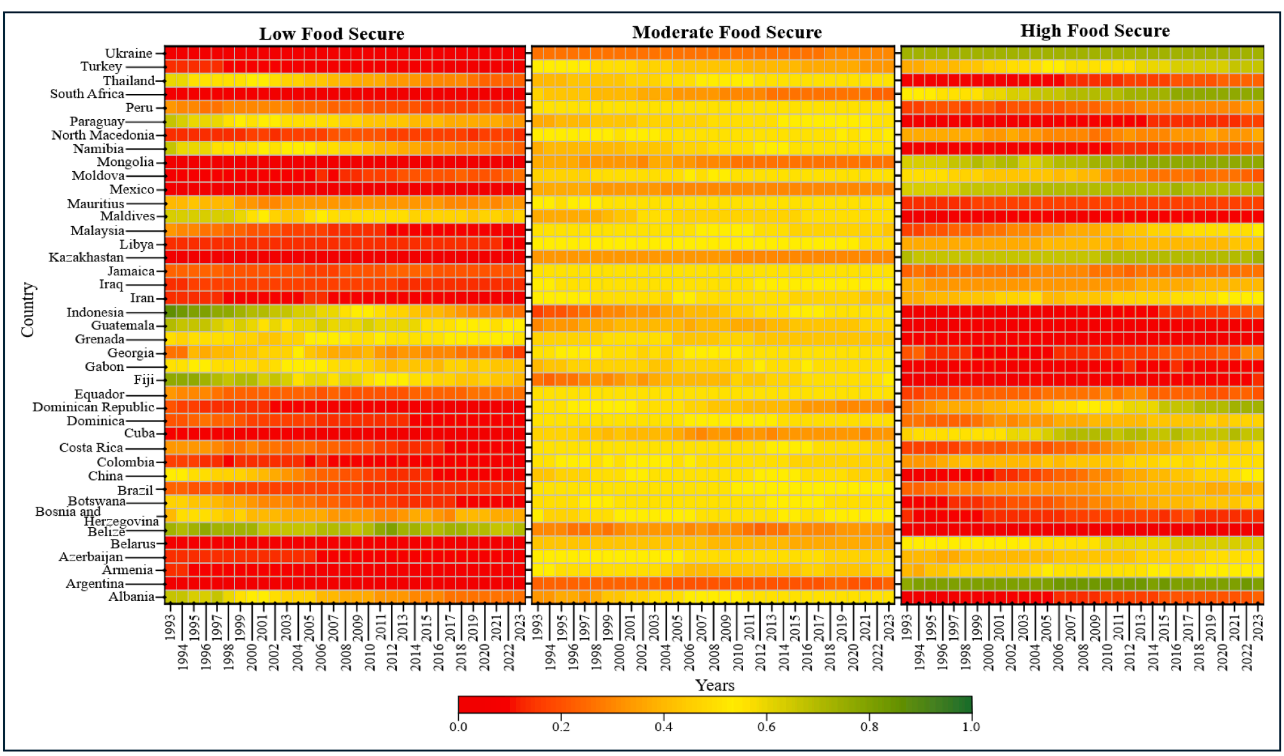

Fig. 11. Predicted probabilities for upper middle-income countries, 1993 to 2023. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

advanced infrastructure, crop specialisation by geography, and policy reforms in employment, food consumption, and production (Kevin et al., 2024) have assisted these countries in overcoming the food shortages they faced over the millennium.

Fig. 12 graphically displays that Tunisia, and Lebanon have continually had higher odds of being highly food secure, where Tunisia is recognised as a fully self sufficient country (FAO, 2025a) and where in the case of Lebanon agriculture is the main source of income for the rural

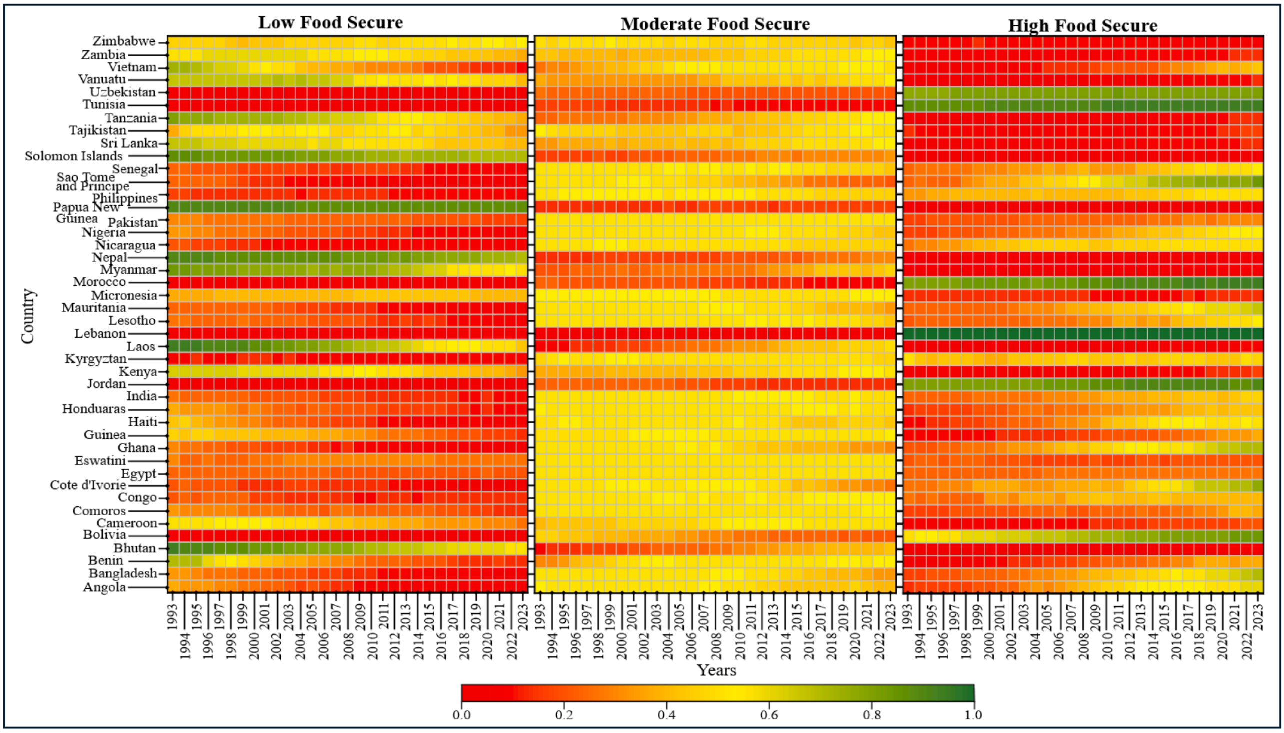

Fig. 12. Predicted probabilities for lower middle-income countries, 1993 to 2023. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

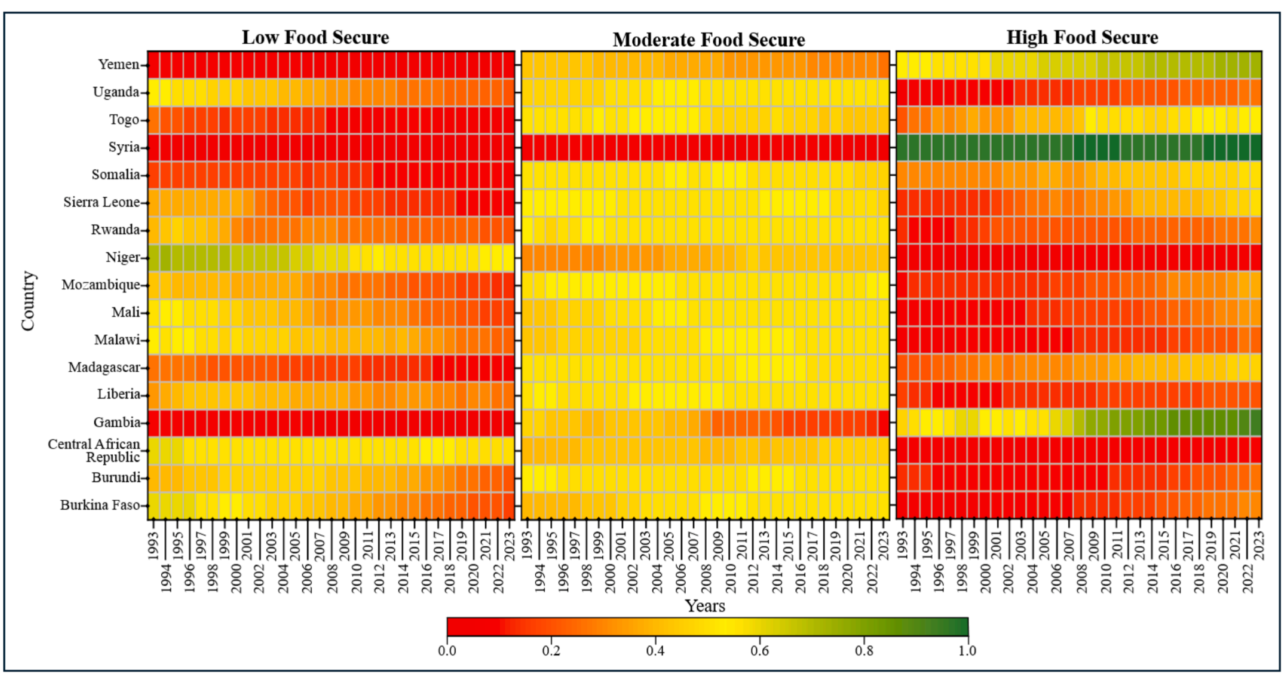

Fig. 13. Predicted probabilities for low-income countries, 1993 to 2023. Source: Authors' compilation using (OriginLab Corporation 2024) and (Kosiński et al., 2025).

areas (U. Guide, 2025) . In the case of Papua New Guinea, though the main contributor of their economy is agriculture, the results still indicate a higher likelihood of being categorised as low food secure, ersulted due to poor infrasturcture in storage and supplying the agricultural products (Teddy, 2024) to the relevant people at the relevant time. Further, majority of this country over-rely on subsistence agriculture whereby the true picture of the self sufficiency on food may not be revealed.

When considering the Fig. 13, Yemen and Gambia have succeeded in improving the probability of being food secure in recent years. The extremely low average rainfall in Yemen has made it difficult for them to improve their food production (Climates to Travel, 2025) Initially, they have improved their food production levels from the extreme lows that it was before. Major interventions from the UN and World Bank has assisted Yemen to strengthen their food security levels (The World Bank

Group, 2023). Around 50% of the Gambia's food needs are met by local food production (African Development Bank Group, 2023), while the country primarily relies on subsistence farming, (FAO, 2025b) hence recording a higher likelihood of being food secure. It is essential to highlight that the food security levels of most low-income countries have improved over the years, where this improvement is clearly diplayed through Niger. However, the UN identifies that 63% of low and low-middle-income countries lack financing for food (Bartosz, 2024). Together with worsening climate conditions worldwide and rising inflation rates, the efforts made by institutions to improve food security have had a minimal impact.

Hence, considering the current global situation, policies must be reconstructed to take into account technological advancements, as well as the environmental and economic conditions of individual nations. Ensuring that policies are aligned towards the SDGs' it is necessary to focus on the effectiveness of the policies and the fundings that would be made in the years ahead.

6. Conclusion and policy implications

The study adopts a global perspective on food production, thereby evaluating the likelihood of a nation falling into one of the three pre-determined categories of food security. Results computed indicate that while urbanisation, agricultural land and GDP have a significant positive impact on FPI, renewable energy consumption is predicted to have considerable inverse implications. In addition, the dummy variables relative to the income groups introduced to the model shows a significant positive impact on FPI.

Adapting from the best examples across the world, countries such as Netherlands focus on sustainable urbanisation and effective urban planning which creates balanced environment encouraging agricultural growth, whereas countries such as Lebanon could restructure their urbanisation process, automatically aligning with SDG goal number 11: Sustainable Cities and Communities. Further, agriculture subsidy restructuring, and climate resilient farming methods in New Zealand can be adapted by countries such as Papua New Guinea, Guyana and other countries in the African and Asian regions facing critical climate conditions.

China presents the use of emerging technologies in the use of agriculture, such as precision farming, and advanced biotechnology thus providing pathways to overcome the Neo-Malthusian future with improved agricultural efficiency. Though this might not be the most feasible option for the low- and lower middle-income countries considering the large investments involved, countries in the high- and upper middle-income category such as Antigua and Barbuda, Barbados and Belize could definitely consider this approach. This would assist in achieving their SDG goal 9, while mainly ensuring that goal 2 of Zero Hunger is undoubtedly attained.

Although most countries have established policies and regulations to promote food security through their governments and other institutions, the results indicate low effectiveness of these policies. Hence, these long-standing policies must be restructured in consideration of the dynamic climatic, technological, and social conditions.

7. Limitations and future research

This study utilises FPI as a measure of food security, although past literature supports its usage, it still lacks complexity in capturing all four pillars of food security. Hence this leaves out potential for future researchers in constructing a more inclusive and extensive set of secondary data in measuring all the four pillars of food security. Furthermore, the categorisation of FPI at thresholds of 48 and 112 is solely due to the author's preference. The study overlooks the gap in studying the changes in the results if the threshold points change. Additionally, it is important to highlight that renewable energy is measured as a percentage of total final energy consumption, whereby the study avoids evaluating the impact of different components of renewable energy on food security. This opens potential for future researchers to evaluate this aspect further.

While the study aims to assess the impact of income levels on food production, it may not be the only qualitative factor to consider when building the final model. In addition, the study tries to fit in all 146 countries in one model, hence bringing forth limitations in applying country-specific effects. Additionally, the results derived from stepwise could contradict with the literature evidence hence essentially highlighting the cons of using this method, though at the same time it is employed with the expectation of improving the model fit econometrically.

Supporting information

Appendix 1: Dataset
Appendix 2: AIC and BIC estimation and selection criteria
Appendix 3: Multicollinearity and heteroscedasticity of initial model
Appendix 4: Probit results prior running stepwise
Appendix 5: Post-outlier sensitivity analysis
Appendix 6: Predicted probabilities
Figure captions and descriptions

Figure #1: Averaged variables per income group, 1993 to 2023

This figure provides a 3D overview of all the predictor variables across the income groups across the years 1993 to 2023. The values of all countries belonging to the respective income group, for the respective year is averaged to derive the values per year. Red represents low-income countries, purple represents lower middle-income countries, yellow represents upper middle-income countries and green represents high-income countries.

Figure #2: Mapping Sen's entitlement theory to model variables

This figure simply maps the Sen's entitlement theory to the conceptual framework of the study, thus depicting its relevance. Red represents production-based entitlements, blue represents trade-based entitlements, yellow represents own labour entitlements, and green represents transfer-based entitlements.

Figure #3: Distribution of research articles by predictor variables, 2019 to 2025

This figure provides a detailed analysis of the literature utilized in the study, while the frequency of the predictor variables identified in the previous studies are presented as a percentage of all articles identified per year. Orange represents urbanisation, green represents renewable energy consumption, violet represents GHG emissions, yellow represents population growth, blue represents agricultural land and purple represents GDP

Figure #4: FPI categorisation

This figure depicts the categorisation of FPI with 48 and 112 being marked as thresholds. Red represents lower food security, yellow represents moderate food security and green represents high food security.

Figure #5: Data and methodology flow diagram

This figure provides a summary of the whole study.

Figure #6: Percentage change in renewable energy consumption, 1994 to 2023

This figure provides the percentage change of renewable energy consumption compared to previous year across the income groups. With the percentage change per year being depicted from the highest to the lowest orderly. Red represents low-income, blue represents lower middle-income, yellow represents upper middle-income, and green represents high-income.

Figure #7: Percentage change in urbanisation,1994 to 2023

This figure provides the percentage change of urbanisation compared to previous year across the income groups. With the percentage change per year being depicted from the highest to the lowest orderly. Red represents low-income, blue represents lower middle-income, yellow represents upper middle-income, and green represents high-income.

Figure #8: Percentage change in GHG emissions, 1994 to 2023

This figure provides the percentage change of GHG emissions compared to previous year across the income groups. With the percentage change per year being depicted from the highest to the lowest orderly. Red represents low-income, blue represents lower middle-income, yellow represents upper middle-income, and green represents high-income.

Figure #9: Percentage change in agricultural land, 1994 to 2023

This figure provides the percentage change of agricultural land compared to previous year across the income groups. With the percentage change per year being depicted from the highest to the lowest orderly. Red represents low-income, blue represents lower middle-income, yellow represents upper middle-income, and green represents high-income.

Figure #10: Predicted probabilities for high-income countries, 1993 to 2023

This heat map portrays the predicted probabilities of all the high-income countries adapted in the study, across the three categories of food security and across the years 1993 to 2023. Red represents the lowest likelihoods, yellow represents moderate likelihoods and green represents the highest likelihoods of falling into a certain category.

Figure #11: Predicted probabilities for upper middle-income countries, 1993 to 2023

This heat map portrays the predicted probabilities of all the upper middle-income countries adapted in the study, across the three categories of food security and across the years 1993 to 2023. Red represents the lowest likelihoods, yellow represents moderate likelihoods and green represents the highest likelihoods of falling into a certain category.

Figure #12: Predicted probabilities for lower middle-income countries, 1993 to 2023

This heat map portrays the predicted probabilities of all the lower middle-income countries adapted in the study, across the three categories of food security and across the years 1993 to 2023. Red represents the lowest likelihoods, yellow represents moderate likelihoods and green represents the highest likelihoods of falling into a certain category.

Figure #13: Predicted probabilities for low-income countries, 1993 to 2023

This heat map portrays the predicted probabilities of all the low-income countries adapted in the study, across the three categories of food security and across the years 1993 to 2023. Red represents the lowest likelihoods, yellow represents moderate likelihoods and green represents the highest likelihoods of falling into a certain category.

CRediT authorship contribution statement

Nirmani Pulle: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Prasad Sampath:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Data curation. **Sarah Perera:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation. **Dinuli Wijayaweera:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ruwan Jayathilaka:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2026.101409.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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