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How exposed is the Maldivian food system to climate risk? Evidence from a long-term Material Flow Analysis (MFA)

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Abstract

Small Island Developing States (SIDS) are structurally dependent on food imports and vulnerable to climate, market, and geopolitical disruptions. Geographic dispersion, isolation, and exposure to climate extremes further constrain domestic food production. Food and nutrition security (FNS), therefore, remains a critical challenge for island nations. This study conducts the first biomass focussed Material Flow Analysis ($MFA^{biomass}$) for any island nation in the Indian Ocean – the Maldives - from 1976 to 2023. The $MFA^{biomass}$ results are extended with a NOVA-based assessment of ultra-processed foods (UPFs) for 2015–2023. Results reveal a substantial increase in food imports from 0.018 Mt in 1976 to 0.349 Mt in 2023 (+ 1,840%), with import dependency increasing from 19.6% to 77.5%. On a dietary level, the consumption of animal products increased while crops declined. The share of UPFs also increased in the same period, accounting for approximately 26–33% of daily dietary energy intake. Import composition shifted with declines in ready meals and increases in products such as sauces and confectionery, likely responding to declining affordability and health messaging. These trends indicate that the Maldivian food system has evolved toward strong external dependence and changing dietary composition. The current system heightens exposure to climate risks and external shocks, while increasing the prevalence of non-communicable diseases from UPF consumptions. These findings illustrate how import-dependent food systems shape diet quality and long-term socioeconomic vulnerability. Strengthening FNS will require systems-based approaches that combine protection of domestic resources, enhance institutional support for local farmers and fishers, and decrease reliance on imports.

1. INTRODUCTION

Small Island Developing States (SIDS) are a group of 57 islands designated by the United Nations (UNDESA, 2023) uniquely characterized by structural constraints including limited land, geographic dispersion, narrow domestic markets, and high trade dependence (Baldacchino, 2018; Deschenes & Chertow, 2004; Thomas et al., 2020). These constraints restrict domestic production capacity and increase exposure to external shocks, including fuel price volatility and geopolitical crisis (Abdulla, 2023b; Guell et al., 2022; Singh et al., 2022). Climate change further intensifies these pressures through sea level rise and increasing extreme weather, threatening critical infrastructure, livelihoods, and resource availability in islands (Guell et al., 2022; Thomas et al., 2020).

Food systems represent a distinct category of vulnerability within SIDS. Food and Nutrition Security (FNS) is defined by six pillars: availability, access, utilization, stability, and agency (Clapp et al., 2025). In many SIDS, the small size of arable land and freshwater availability limit food production, resulting in heavy reliance on imported foods (Singh et al., 2020; Sonneveld et al., 2021). This dependence has reshaped island diets, as food supplies are increasingly dominated by processed products (Atzori et al., 2024; Oladele et al., 2024; Santos et al., 2019; Vogliano et al., 2021). While these foods may improve availability, they undermine dietary quality and are strongly associated with rising burdens of non-communicable diseases (NCDs) (Haynes et al., 2022; Lin et al., 2018; Palu et al., 2024). At the same time,

reliance on long distance transport and cold chain infrastructure makes food systems vulnerable to disruptions caused by pandemics and shipping delays (Abdulla, 2023b; Allam et al., 2022; Davila et al., 2021). As a result, FNS in SIDS increasingly manifests through compromised utilization and stability, rather than absolute scarcity.

Despite concerns on food security and import dependence, few studies adopt systems-based approaches that link the biophysical structure of food systems with downstream nutrition outcomes. In order to fill this gap, this study adopts a “socio-metabolic research” perspective to examine the food system of an island nation in the Indian Ocean - the Maldives, that faces high exposure to sea-level rise and climate extremes (Moosa et al., 2020). Socio-metabolic research links socioeconomic processes with biophysical flows of materials and energy, offering a system-based framework to quantify resource use patterns (Haberl et al., 2019). Unsustainable patterns of resource use can jeopardise system resilience and accumulate socio-metabolic risk - SMR (Singh et a. 2022). SMR is to islands as circulatory health problems are to humans, both constrain the entity’s ability to withstand significant shocks and changes (Singh et al. 2022).

The study is guided by two key research questions: 1) How exposed is the Maldivian food system to climate extremes and geopolitical shocks, and 2) what are the key drivers that shape the Maldivian food system into socio-metabolic risk, and their potential for resilient futures? To answer these questions, we undertake a diachronic Material Flow Analysis (MFA) for the Maldives, tracing food-related biomass flows across production, trade, and consumption from 1976 to 2023. This is complimented by a NOVA-based classification of ultra-processed foods (UPFs) to extending MFA beyond conventional pressure indicators to explore potential health and nutrition impacts. To our knowledge, this represents the first MFA to explicitly link food metabolism with nutrition indicators.

2. STATE-OF-THE-ART IN FOOD SYSTEM STUDIES ON SIDS

Over the past decades, studies have documented a significant nutrition transition in SIDS, marked by the displacement of traditional diets and reliance on imported foods (Atzori et al., 2024b; Halliday et al., 2023; Marrero & Mattei, 2022; Sievert et al., 2019). Earlier research describes how islands societies historically maintained self-sufficient food systems based on subsistence farming and fishing, producing crops such as taro, breadfruit, and cassava, rich in fiber and micronutrients (Campbell, 2015; Guell et al., 2021; Snowdon et al., 2013; Vogliano et al., 2021) These agroecological systems were adapted to island geographies and unique environmental constraints (Marrero & Mattei, 2022). However, literature attributes their recent decline with trade liberalization and tourism expansion (Schram et al., 2015; Thow et al., 2011; Weis, 2003). Colonial land-use legacies prioritizing export-oriented plantation and cash crops also contributed to soil degradation, further reducing islands’ ability to endure environmental shocks (Douglass & Cooper, 2020; Shepherd & Palmer, 2015).

Some authors have focussed on the changing structure of food imports to show the increasing dominance of UPFs in SIDS (Augustus et al., 2022; Haynes et al., 2020; Santos et al., 2019). Results show

the growing imports of sweetened drinks, instant food, and reconstituted meats high in saturated fat, yet low in essential micronutrients such as vitamins, zinc, and iron (García-Blanco et al., 2023; Liu, 2025; Queiroz et al., 2025). For example, Brewer et al. (2023) demonstrated that in Fiji, unhealthy food have increased fivefold between 1995 and 2018 mainly through sugar and prepared meat. Studies have also highlighted the fact that UPFs often include preservatives and require minimal preparation, making them attractive in islands where cold-chain storage is weak and time pressures are increasing, due in part to urbanization and greater female labour participation (Hawley & McGarvey, 2015; Sievert et al., 2019).

A substantial body of research has linked these nutritional shifts to adverse health outcomes. Diets high in UPFs are strongly associated with non-communicable diseases (NCDs), including obesity (Harb et al., 2023), type 2 diabetes (Levy et al., 2021), hypertension (Oladele et al., 2024), and cardiovascular disease (Nilson et al., 2022). WHO (2023) report that this burden is particularly acute in SIDS, where all ten countries with the highest adult obesity prevalence worldwide are Pacific Island States. Studies have also observed the emergence of a "double burden or malnutrition", where undernutrition coexists with obesity (Atzori et al., 2024; Haddad et al., 2015; Popkin & Ng, 2022). Beyond physical health, research further suggests that the decline in the consumption of fresh contributes to the erosion of indigenous food knowledge systems crucial for social cohesion (Guell et al., 2021; Marrero & Mattei, 2022).

Islands have long been treated as ideal systems within socio-metabolic research due to their small land area and clearly refined system boundaries (Deschenes & Chertow, 2004; Krausmann et al., 2014). Early applications of MFA in islands focused on economy-wide transitions, including studies in Trinket Island (Singh et al., 2001), Iceland and Trinidad and Tobago (Krausmann et al., 2014) and the Bahamas (Martin del Campo et al., 2023), where biomass was embedded as one material category alongside fossil fuels, metals, and minerals. In parallel, global biomass flow accounting studies emerged, establishing methodological foundations for tracing biomass supply and land use (Krausmann et al., 2008; Wirsenius, 2003). More recently, a limited number of studies have isolated biomass metabolism to explicitly examine island food systems. Okoli et al. (2016) conducted the first island-scale biomass MFA focused on agricultural transition in Jamaica, while Rahman et al. (2022) applied biomass flow accounting to four Caribbean islands to assess food localization.

Existing research on the Maldivian food system has been rather fragmented and siloed but can broadly be grouped into two strands: production and governance-focused studies, and medical-oriented analysis. On the production side, qualitative and sector-specific papers have investigated domestic food production, fisheries management, and emerging climate risks shaping food environment (Abdulla, 2023a; Abdulla et al., 2024; Mohamed, 2024; Van Driessche, 2020). More recent qualitative work has explored lived experiences and "islandness" as a SID-specific lens for understanding food vulnerability (Hassan et al., 2026). Today, these studies have extended to include food characteristics and dietary composition at the retail level, including laboratory-based analysis of fatty-acid profiles and self-reported links between fruit and vegetables consumptions and chronic diseases (Naila et al., 2022; Shareef et al., 2024). While these provide important insights into different aspects of the Maldivian food system, and on SIDS in general, the lack of systems-based studies motivates this research.

3. METHODOLOGY

3.1 Study Area Description

The island nation of Maldives is located in the Indian Ocean, southwest of Sri Lanka (Dissanayake & Jayaratne, 2011). The country consists of approximately 1,190 coral islands grouped into 26 atolls, widely dispersed across an Exclusive Economic Zone (EEZ) of 916,000 km^2 (Stevens & Froman, 2019), of which over 99% is ocean (Republic of Maldives Permanent Mission to the United Nations, 2025). The Maldives is among the lowest-lying countries globally, with around 80% of land area less than 1 meter above sea level, making the country especially exposed to climate impacts (Lahcene et al., 2024; Naylor, 2015). Of an estimated population of 527,799 people (World Bank, 2025), approximately 40% live in the capital city of Malé (Shakeela, 2022). National GDP was approximately USD 7 billion in 2024, with an annual growth rate of 3.5% (World Bank, 2026). Despite its small economic scale, the Maldives is classified as an upper-middle-income country and is the first country in the South Asia to attain this income level (World Bank, 2020b).

3.2 MFA Framework

The overall methodological workflow is summarized in Fig. 1. A national-scale Material Flow Analysis for biomass ($MFA^{biomass}$) was conducted for the Maldives for the period of 1976–2023. The $MFA^{biomass}$ follows conventional Economy-wide Material Flow Analysis (Ew-MFA) guidelines for biomass, as established by Eurostat (2018) and Krausmann et al. (2008). The system boundary corresponds to the political boundary of the Republic of the Maldives. Consistent with Ew-MFA conventions, trade flows include all food entering the country. To adapt the standard $MFA^{biomass}$ framework to an island food-system context, the analysis focuses exclusively on food-related biomass flows, following applications developed by mass balance studies that focused on Caribbean food systems (Okoli, 2016; Rahman et al., 2022). Biomass categories outside of the scope of food provisioning, such as timber, leather, below-ground biomass, and other non-edible materials were excluded from the study. Core indicators include Domestic Extraction (DE), Imports, Exports, Physical Trade Balance (PTB), and Domestic Material Consumption (DMC) (Table 1). Main data sources were drawn from UN Comtrade, FAOSTAT, and FishStatJ. Additionally, all data sources and temporal coverage are summarized in Table 2. Detailed calculation procedures are provided in Supplementary Information S1-S3.

Table 1
Biomass flow indicators used to analyze the Maldives food-system

Biomass Indicators	Description	Equation	Unit
Domestic Extraction (DE)	Total quantity of food-related biomass physically extracted within the national system.	*DE = primary crop harvest + used crop residue + capture fisheries*	Mt yr^{-1}
Used Crop Residues (DE)	Recoverable portion of post-harvest crop that is collected for further economic use	Available crop residues = primary crop harvest × harvest factor Used crop-residues = available crop-residues × recovery rate	Mt yr^{-1}
Import/Export	Food-related biomass entering and existing the national system through international trade	Reported trade data.	Mt yr^{-1}
Physical Trade Balance (PTB)	Net physical dependence measuring trade surplus or deficit	$PTB_{biomass}$=$Imports_{biomass}$-$Exports_{biomass}$	Mt yr^{-1}
Physical Trade Balance per Capita	Net food trade dependence normalized by population	PTB per Capita = $PTB_{biomass}$ ÷ Population	t $capita^{-1}$ yr^{-1}
Domestic Material Consumption (DMC)	Apparent consumption of biomass within the food system	*DMC = DE + Import – Export*	Mt yr^{-1}
Domestic Material Consumption (DMC) per Capita	DMC per person	*DMC* per Capita = DMC ÷ Population	t $capita^{-1}$ yr^{-1}
Import Dependency Ratio (IDR)	Level of external dependence on trade	Import dependence ratio (IDR) = (Imports/DMC)*100	%

Table 2
Overview of the data sources for the biomass flow analysis for the Maldives

Flow/Variables	Data Source(s)	Temporal Coverage
Primary Crop Harvest	FAOSTAT Production Domain	1961–2023
Capture Fisheries	FishStatJ	1950–2023
Used Crop Residues	FAOSTAT Production Domain (derived)	1961–2023
Imports	FAOSTAT Trade Domain (1976–1994); UN COMTRADE (1994–2023); Maldives Customs Services (validation from 2015–2023)	1976–2023
Exports	FAO Trade Domain (1976–1994); UN Comtrade (1994–2023)	1976–2023
Population	World Bank	1976–2023

For the $MFA^{biomass}$, used crop residues were estimated following Krausmann et al. (2008) using harvest factors and recovery rates derived for the South Asia region were applied across the study period. Additionally, grazing livestock was excluded from DE calculations due to its negligible relevance in the Maldivian context. Although small-scale goat and poultry farming exists, the Maldives relies almost entirely on imports for meat and dairy products, and subsistence livestock activity was not captured in FAOSTAT data. This exclusion was validated through expert consultation. It is important to note that not all food entering the domestic system is ultimately consumed. Losses may occur at multiple stages along the food supply chain, including storage, transportation, retail, and household consumption. To contextualize this qualitatively, a food loss and waste estimate was derived from national waste accounts for the Maldives (Maldives Bureau of Statistics, 2021). Reported food waste values were compared against total DMC, yielding an approximate average of 28%. This estimate is used to interpret DMC as “apparent food availability” rather than actual intake.

As UN Comtrade only provides data for the Maldives from 1995 onwards, trade data for earlier years were supplemented using the FAOSTAT Trade Domain to ensure continuity of the time series. Food items include both primary and processed commodities reported under the Harmonized Systems (HS). Items were classified into five broad categories: crops, fisheries, livestock, and animal product, and other processed food products. In cases where trade descriptions or HS codes were ambiguous (e.g. “mixed processed food”, “baked goods”), items were grouped as *other processed food*.

3.2.1 Data Treatment

Some data points exhibited unusually high or low values that could not be explained through literature or expert opinions. These values were treated as data reporting errors or outliers and were addressed by averaging values from the preceding and following years. Examples include anomalous values in

domestic extraction of fisheries in 2004 and import values across all categories in 2016, as well as egg imports (HS 40721) in 2018. Where consistent data were unavailable, multiple-year averages were applied. For example, fish exports for 2023 were based on the average of 2018–2022, and fishmeal feed exports were smoothed using a three-year average. These steps helped reduce the influence of outliers and errors.

3.3 UPF Analysis and Methodological Steps

To extend the $MFA^{biomass}$ to a nutrition-related dimension, a complimentary UPF analysis was conducted for the period 2015–2023. The objective was to quantify the DMC of UPFs in the Maldives and to estimate the associated nutritional indicators relevant for population-level health outcomes. Unlike the conventional $MFA^{biomass}$ described in Section 3.2 which captures total food flows entering the Maldivian economy, the UPF analysis applies a narrower resident-focused boundary to better approximate population-level dietary exposure. This distinction was made possible because import data for the UPF analysis were obtained directly from the Maldives Customs Service, which allows partial distinction between tourism and non-tourism food flows from 2015–2023. To better approximate resident consumption, items such as alcohol and pork products prohibited under Maldivian regulations were excluded. UPFs were identified using the NOVA food classification system, which categorizes foods according to the level of industrial processing (Monteiro et al., 2019). NOVA has been applied in numerous population-level studies to assess diet quality, most commonly using 24-hour dietary recalls or surveys where individual intake data are available (Cattafesta et al., 2020; Dicken et al., 2024, 2025; Koiwai et al., 2019; Martini et al., 2021). However, such intake-based datasets are not available for the Maldives across consistent time periods. Therefore, apparent UPF consumption was quantified using a mass-balance approach consistent with the MFA conventions in 3.2.

All traded food items were classified into NOVA categories 1–4 using HS codes and detailed product descriptions (See S4). Classification primarily followed NOVA definitions and examples provided by Monteiro et al. (2019). Items were coded as NOVA 4 when descriptions clearly indicated industrial formulation or ready-to-eat products (e.g. instant noodles, confectionary, packaged snacks, powdered drink mixes). Moreover, items classified under HS22.02 (non-alcoholic sweetened beverages) such as soft drinks and energy drinks that were not included in the conventional BFA were explicitly incorporated in the UPF analysis, as sugar-sweetened beverages (SSB) constitute a key category of processed food relevant to non-communicable diseases (Oladele et al., 2023; Santos et al., 2019). When the processing level could not be determined with confidence, a conservative approach was applied, and items were assigned to the lowest plausible NOVA category to avoid overestimation of UPFs. The data sources for exports and DE are the same as BFA.

In principle, UPF DMC is defined as:

$$DMC_{UPF} = DE_{UPF} + Import_{UPF} - Export_{UPF}$$

However, since no UPFs exist in domestic extraction, the calculation effectively reduces to:

$DMC_{UPF} = Import_{UPF} - Export_{UPF}$

Food loss and waste were not incorporated into UPF DMC calculations, drawing on expert opinions. UPFs are generally associated with low levels of household waste due to their extended shelf life and high utilization rates among residents. While food loss is generally more pronounced in perishable and minimally processed products due to spoilage during storage and distribution (Parfitt et al., 2010), the majority of food waste in island settings arises from spoilage, expiration, and related forms of degradation affecting the less processed food items.

Outliers for UPF imports for 2016 and 2022 were handled using the same correction approach applied in the BFA, based on averaging adjacent years (t-1, t + 1). As a trade-based analysis, this approach does not capture UPFs produced domestically from minimally processed or processed ingredients. Nevertheless, the method provides a replicable estimate of imported UPFs entering the food system and allows for systematic comparison with biomass flow indicators over time.

3.3.1 Nutritional Proxy Indicators

To estimate the nutritional characteristics of UPF consumption, proxy values for energy (kcal), total free sugar (g), and sodium (mg) were applied to NOVA 4 items using mean values reported by Vergeer et al. (2019). Those proxies were selected due to the absence of product-level nutrient composition data in trade statistics and the lack of national dietary intake surveys for the Maldives. Estimated energy availability from UPFs was compared with total dietary energy supply from FAO Food Balance Sheets, which provide a supply-side proxy for per-capita caloric intake availability. Sugar and sodium estimates were assessed relative to World Health Organization guideline thresholds to contextualize potential nutritional relevance.

3.4 Validation and Field Data Collection

Two rounds of surveys were conducted in August 2025 and December 2025 across six population centres with varying geographic characteristics (Malé–Hulhumalé, Laamu Gan, Addu City, Haa Dhaalu Kulhudhuffushi, Gaafu Alif Thinadhoo, and Gaafu Alif Villingili). Short questionnaires were administered to households across these locations, alongside rapid retail observations in nearby food outlets. The questionnaires focused on household food purchasing behaviours and relative expenditure on fresh foods and ready meals. This component was intended to provide contextual insights into food accessibility across different atoll settings, thereby informing trends visible in the discussion (See S5).

4. RESULTS

4.1 Domestic Extraction (DE)

DE of biomass in Fig. 2 shows a gradual increase across the study period from 0.086Mt in 1976 to 0.170Mt in 2023, representing an overall increase in approximately 97%. DE rose steadily until the early

2000s, peaking at 0.293Mt in 2004. Capture fisheries dominated DE, increasing from 0.035 Mt in 1976 to 0.161Mt in 2023, an increase of nearly 365% and accounting for the majority of total DE in all years. The catch reached its heights in 2005. This peak coincides with the aftermath of the 2004 Indian Ocean tsunami post-disaster recovery efforts towards fisheries, particularly for the tuna industry, and infrastructure rehabilitation for vessels and fishing gears (FAO, 2011). On the other hand, primary crop harvest and used crop residues declines substantially after the mid-2000s, specifically after its peak in 2004 at 0.058Mt. Relative to 1976 levels, local harvest declined by approximately 77%.

4.2 Imports, Exports, and Physical Trade Balance (PTB) of biomass

Net imports in Fig. 3 increased steadily across the timeseries, with aggregate total rising from 0.018Mt in 1976 to 0.349Mt in 2023. Imports of crops and livestock are exhibiting consistent upward trends with no prolonged periods of export nor decline. Import of fisheries products are comparatively small in scale yet increases gradually from nearly 0% until the early 1990s to 0.0045Mt in 2023. Similarly to DE, fisheries dominated the exports with a sharp rise between 2002 and 2005. Exports of crops and livestock products remained minimal across all years. This dynamic is visible in PTB, increasing from 0.006Mt in 1976 to 0.27Mt in 2023, remaining positive throughout the period except for a brief negative value in 1978. Crops dominated the PTB driving the long-term expansion, while fisheries consistently exhibited a negative PTB, reflecting higher export than import volumes. Import Dependency Ratio (IDR) have increased from 19.6% in 1976 to 77.5% in 2023. Same trajectory for all categories is seen in per provisioning adjusted for population, with a slightly compressed magnitude.

4.3 Domestic Material Consumption (DMC) for biomass

DMC represents the actual consumption in absolute and per capita units. In Fig. 4, total food-related DMC increased in absolute terms from 0.09Mt in 1976 to 0.45Mt in 2023 reflecting both population growth and increased import volumes. As for the per capita DMC, crops dominated DMC through the period, with animal products and other processed foods becoming increasingly accounting for a larger share in later years. Per capita DMC more pronounced declining trend in fisheries after the mid 2000s, falling from a peak of approximately 0.38 tonnes per capita in 2006 to 0.18 tonnes per capita in 2023. This is equivalent to an estimated 53% decrease. Applying the estimated average food loss rate of approximately 28% suggests that up to ~ 0.13 Mt of biomass in 2023 may not translate into final consumption.**Fig. 4** Annual aggregate flow of Domestic Material Consumption (DMC), reflecting apparent consumption by both residents and tourists, in absolute (megatonnes) and per capita (tonnes) terms in the Maldives from 1976–2023.

4.4 NOVA 4 (UPF) Analysis Results

Figure 5 presents DMC of UPF in the Maldives from 2015–2023. Absolute DMC of UPF increased slightly over the period, from 0.055Mt in 2015 to 0.058Mt in 2023, despite temporary declines in 2018 and 2021.

Following each decline, DMC rebounded and reached its highest level in 2023. Conversely, per capita UPF decline over the same period, from around 0.13 tonnes per capita in 2015 to 0.11 tonnes per capita in 2023.

Figures 6–7 present the composition and category-specific changes in UPFs, disaggregated across 17 product categories: baked goods and mixes, breakfast cereals, concentrated syrups and flavourings, confectionery and desserts, fats and spreads, ice cream and frozen desserts, infant food, instant/powdered drinks, noodles, processed dairy, processed fish, processed meat, ready meals/snacks, condiments, sugar-sweetened beverages (SSBs), sugar ingredients, and formulations. Total UPF imports increased modestly from 0.0558 Mt in 2015 to 0.0589 Mt in 2023. In 2023, confectionery and desserts, SSBs, and baked goods and mixes were the three largest contributors by volume. In contrast, in 2015, ready meals/snacks were among the top three categories, indicating a shift in the composition of imported UPFs over time.

The largest proportional increases occurred in sugar ingredients (+ 310.4%), breakfast cereals (+ 213.8%), and ice cream and frozen desserts (+ 172.3%), followed by condiments (+ 128.6%) and processed meat (+ 93.4%). Confectionery and desserts also increased by + 66.0%, further reinforcing its position as the dominant UPF category by volume. In contrast, several categories experienced pronounced declines over the same period. Ready meals/snacks decreased by − 69.7%, while noodles showed the steepest reduction at − 95.0%. Formulations (− 72.2%) and processed dairy (− 60.6%) also declined substantially, alongside more moderate decreases in infant food (− 23.9%), fats and spreads (− 18.0%), and instant/powdered drinks (− 14.5%). Baked goods and SSB exhibited comparatively smaller changes, remaining relatively stable over the study period.

Figure 8 summarizes per capita daily availability of UPF-derived energy, free sugar, and sodium in the Maldives between 2015 and 2023. UPF-derived energy availability declined overall, decreasing from 906 kcal/cap/day in 2015 to 780 kcal/cap/day in 2023, while its share of total dietary energy fell from 33.4% to 29.4%. Free sugar availability showed a similar downward trend, declining from 42.8 g/cap/day in 2015 to 36.8 g/cap/day in 2023, contributing between 5.0% and 6.3% of total dietary energy across the period. Sodium from UPFs ranged from 1,702 mg/cap/day in 2015 to 1,465 mg/cap/day in 2023, corresponding to 65–85% of the WHO recommended maximum intake over the study period.

5. DISCUSSION

5.1 How exposed is the Maldivian food system to external shocks?

The $MFA^{biomass}$ results indicate a long-term structural reconfiguration of the Maldivian food system. These findings suggest that the Maldives have become increasingly more vulnerable to external shocks, including climate change and geopolitical disruptions due to its growing reliance on imported foods. Across 1976–2023, the Maldives remained a net importer of biomass throughout the entire time series

with IDR increasing from 19.6% to 77.5% (Fig. 3). The composition of DMC further shows that this increase was driven largely by crop-based flows, particularly staple commodities such as rice and wheat central to the islanders' daily diet. This pattern differs from previous $MFA^{biomass}$ observed in other SIDS, particularly Dominica and Grenada, where rising DMC was accompanied by modest gains in domestic food production linked to recent localization efforts (Rahman et al., 2022). DE and export flows were overwhelmingly dominated by fisheries, representing the country's strongest local production capacity. However, recent trends suggest a divergence between export performance and domestic provisioning. Between 2020 and 2024, domestic fish consumption declined by approximately 3,000 tonnes per year, equivalent to a reduction of 3.3 g/day of animal protein per capita, even when export increased (Abdulla et al., 2024).

This trajectory coincides with a broader reorientation of the national economic base. Following the introduction of the "one island, one resort" model in 1972 (dell'Agnese, 2019), tourism rapidly expanded to contribute nearly three-quarters of GDP (Mallari et al., 2023). Over the same period, agriculture declined sharply, with employment falling from approximately 27% in 1991 to around 11–12% by 2024 (World Bank, 2026a), and GDP contribution dropping from 12.7% in the 1980s to less than 1% today (Mohamed, 2024). Early documents had already identified declining crop production (e.g., coconut) and increasing reliance on food imports, suggesting this transition began early or even before the study period (World Bank, 1980).

Available evidence suggests that food dependence in the Maldives is maintained by both policy framework and prevailing market conditions (Dissanayake & Jayaratne, 2011; Hassan et al., 2026; Van Driessche, 2024). Policies favouring low import duties on essential foods and centralized procurement through the State Trading Organization (STO) have effectively positioned imports as the default mechanism for ensuring national food availability (Ministry of Finance and Planning, 2026; Ministry of Tourism and Environment, 2025; WTO, 2024). Domestic production, by contrast, is limited, seasonal and costly (Asian Development Bank, 2015). These structural constraints, combined with weak market connectivity, generate asymmetric market competition limiting local producers' ability to compete with large-scale imported food products in terms of price and volume (Van Driessche, 2024). Even crops that can be cultivated locally such as cabbage, and watermelon require relatively high input intensity due to poor soils and pest pressures (Abdulla, 2023a), while agricultural inputs including seeds and fertilizers are themselves heavily imported (Maldives Customs Service, 2022), further reinforcing reliance on external supply chains.

The vulnerability of the current metabolic patterns was evident during COVID-19. Tourist arrivals fell by more than 60 percent within months of border closures and GDP contracted by 32 percent in 2020 (Mallari et al., 2023; UNDP, 2023; World Bank, 2020a). As foreign exchange earnings collapsed, food imports increased by 24.9 percent between January and May 2020 despite global supply uncertainty (UNSDG, 2020), underscoring the absence of sufficient domestic substitution. Geopolitical crises further affect food systems, as seen during the 2022 Russia–Ukraine conflict when freight costs intensified inflation in the country (Abdulla, 2023a; Rahman & Rayhan, 2023). More recently, the 2026 U.S.-Iran

conflict highlighted the vulnerability of island economies, with fuel-oil electricity costs for islands projected to rise by 33% following disruptions to global gas flows through the Strait of Hormuz (Ogden & Gumbs, 2026).

Notably, accelerating climate change introduces compounding stress to already limited domestic production. Sea-level rise is projected to reach up to 0.9 meters by 2100 (World Bank, 2024a), increasing exposure to flooding. Saltwater intrusion and shallow aquifers threaten cultivation on low-lying islands where freshwater are scarce (Corwin, 2021; Mazhar et al., 2022). Similarly, rising temperature and altered precipitation patterns further destabilize yields through intensified pest pressures and fungal outbreaks in tropical settings (Cilas et al., 2016; Gerken & Morrison, 2022; Seidel et al., 2024). Additionally, stronger storms disrupt planting cycles and increase packaging damage and post-harvest losses, particularly for perishable crops grown in outer atolls that require hours of transport to Malé (Shahbazi et al., 2025).

Fisheries, which account for majority of the DE are subjected to the same risks. The Maldives ranks first in projected fisheries exposure in the Indian Ocean, with potential declines in catch ranging from 17 to 100 percent under different emissions scenarios (World Bank, 2024a). Ocean warming and expanding low-oxygen zones alter pelagic ecosystems and contribute to taxonomic shifts in tuna distribution, affecting catch stability (Dueri, 2017; Erauskin-Extramiana et al., 2019). Comparable tuna-dependent SIDS in the Pacific are projected to experience declines of tuna catch by 26 to 37 percent within three decades (FAO, 2024), indicating that highly specialized island fisheries economies face intensified climate risk. These pressure also operate alongside existing threats, such as overfishing and illegal catch (Lindley, 2025).

Besides susceptibility to external shocks, food distribution within Maldives is also problematic. Food imports must pass through centralized hubs in Malé before reaching outer atolls, often without reliable cold-chain infrastructure. In tropical conditions, spoilage and microbial contamination may occur even before products reach final market points, increasing systemic inefficiencies, as well as susceptibility to foodborne illnesses (Shewfelt & Prussia, 2022; Tort et al., 2022). In 2024, it was estimated that the Maldives generated the highest reported food waste globally and substantially above large economies such as the United States (World Population Review, 2026). The majority of this waste is transported to Thilafushi, an artificial island designated for landfilling since 1997 (Kapmeier & Gonçalves, 2018), with food and yard waste comprising roughly 80% of the total stream, increasing risk of fire (Kapmeier & Goncalves, 2016).

5.2 Insights from the Nutrition Analysis

The findings further suggest that the food-system vulnerability in the Maldives extends beyond external supply shocks and include nutrition risks associated with increasing exposure to imported processed foods. Our nutrition estimates show that UPFs contributed approximately 26–33% of total daily energy availability over the study period. For comparison, UPFs accounted for 21.5% of total energy intake in Fiji (Palu et al., 2025) and 40.5% in Barbados (Harris et al., 2021). Estimated free sugar availability from UPFs alone exceeded the WHO “ideal” recommendation of < 5% in all years, while sodium availability

averaged roughly 74% of the WHO recommended maximum (2000 mg/day). While the current UPF consumption levels in the Maldives remain moderate compared to other islands, current dietary patterns are close to or already exceeding recommended thresholds.

Another key finding is the divergence between absolute and per-capita DMC UPF (Fig. 5). Between 2015 and 2023, absolute import volumes and total DMC remained stable to increasing, while per-capita availability declined modestly from 0.13 t to 0.11 t per person per year. During the same period, the national population increased by nearly 23% (World Bank, 2026b). Population growth likely contributes to this compression, but demographic change alone does not fully explain the trend, suggesting behavioural and socioeconomic drivers.

Two plausible drivers appear to shape this compositional shift. First, affordability pressures and evolving food purchasing behaviours may be altering the form of UPF consumption rather than outright elimination. Consumer Price Index (CPI) data from 2021–2023 show price increases in selected convenience products, while some fresh foods fluctuated in price (Maldives Bureau of Statistics, 2023). At the same time, our survey findings indicate a continued move toward commercially mediated food consumption, with respondents reporting greater reliance on restaurants and takeaways today (62.4%) compared to a decade ago (55.1%), alongside a decline in home cooking (34.8% to 22.2%). The decline in certain ready-made UPF imports may therefore reflect substitution toward processed food assembled domestically or in restaurants, rather than a genuine reduction in these foods. Second, expanding public health messaging has coincided with this adjustment. Since 2017, sugar taxation, dietary guidelines, school-level energy drink restrictions, and NCD action plans have increased visibility of unhealthy diets (Ministry of Health, 2017, 2023; WHO, 2025). In our survey, 97% of respondents reported greater exposure to messaging discouraging UPFs primarily via social media and television. The apparent decline in per-capita DMC should therefore be interpreted cautiously. Reductions in heavier UPF categories may coincide with increases in lighter yet energy-dense products (e.g., sauces, desserts), which contribute less by weight while delivering comparable or greater sugar and sodium loads.

The nutritional implications of this shift can be interpreted within the Maldives' existing health burdens. In terms of Disability-Adjusted Life Years (DALYs), NCDs account for roughly 78% of total disease burden (World Bank, 2011). Leading causes include cardiovascular disease, stroke, diabetes, and kidney disease (WHO, 2024). Between 2000 and 2020, adult obesity prevalence increased by 179%, and childhood obesity by 364.3% despite tobacco and alcohol use declining (WHO, 2024). Importantly, these health burdens operate alongside other drivers, including high physical inactivity, growing car-centricity, and climate-related heat stress that may further constrain outdoor activity and exacerbate respiratory risks (Gordon-Strachan et al., 2025; Ministry of Health, 2023; World Obesity, 2026),

Moreover, diet-related NCDs translate into measurable economic costs. Government health expenditure increased from 8.8% in 2000 to 18.2% (+ 106.8%) by 2021 (WHO, 2024), indicating rising fiscal pressure. Meanwhile, the health sector faces workforce shortages and reliance on foreign medical professionals (Mallari et al., 2023), with capacity constraints under escalating NCD demand, particularly for rural

residents dependent on travel to Malé or overseas care (Suzana et al., 2015). In 2019, overweight and obesity were estimated to cost approximately US$65.9 million in the Maldives, equivalent to 1.2% of GDP with nearly 70% attributable to indirect costs such as absenteeism (World Obesity, 2024). Projections suggest that this burden could reach 3.1% of GDP by 2060 if trends persist.

Global evidence further supports the potential labour productivity decline from deteriorating diet quality. NCDs such as diabetes are consistently associated with lower hours worked and premature mortality (Chaker et al., 2015; Fu et al., 2009; Zhao et al., 2023). In Pacific SIDS, cardiovascular disease alone has been projected to account for over 40% of lost economic output (Hou et al., 2022), while Barbados report approximately US $75 million annually in work inefficiency linked to diet-related illness (World Bank, 2024b). For small island economies heavily dependent on service sectors such as tourism, these chronic disease can erode economic resilience, particularly when compounded by climate-related labour productivity losses (Gordon-Strachan et al., 2025). While imported UPFs may appear economically efficient in the short term through affordability and convenience, these gains may be offset by downstream healthcare and productivity loss.

The burdens arising from this configuration are unevenly distributed across geographic areas. Households in outer atolls are further disadvantaged by infrequent transport and prioritization of vegetable imports toward urban Malé (UNDP, 2014), increasing reliance on shelf-stable foods with lower cold-chain requirements such as UPFs. Limited access to fresh food has implications for maternal diets and breastfeeding practices, especially for neonatal nutrition and NCD risks later in life (Ben-Avraham et al., 2023; Capra et al., 2025; Oliveira et al., 2022). Women, who are disproportionately responsible for food preparation and childcare, face increasing time pressures due to labour participation, conditions that can make UPFs more attractive (Ameye & Glatzel, 2025; Buksh et al., 2023; Hashan et al., 2020; Ruel et al., 2017). FNS may further exacerbate gender inequalities through domestic violence, particularly where women have limited influence over household food purchasing decisions (Chegere, 2024; Lentz, 2018).

6. CONCLUSION: WAYS FORWARD

This study assessed the vulnerability of the Maldivian food system to external shocks by developing one of the first food-focused $MFA^{biomass}$ outside the Caribbean context. It found that the Maldives food system is highly vulnerable to both external shocks and nutrition insecurity due to its heavy reliance on imported foods and increasing exposure to UPFs. The results indicate that the biomass metabolism has undergone a structural shift: while food imports have ensured caloric availability, the composition of foods entering the system is shifting toward processed products and sustained exposure to elevated levels of sodium and sugar. From a FNS perspective, this transition suggests that greater food availability does not necessarily translate into improved diet quality. Instead, it reflects a complex configuration in which import dependence, environmental vulnerability, and changing consumption patterns interact to shape food access and dietary utilization. The current profile therefore signals accumulating SMR, systemic vulnerability to future shocks, including climate change impacts on

fisheries, geopolitical disruptions affecting global supply chains, and economic volatility influencing food prices.

Initiatives such as AgroNat programs and emergency cultivation plots introduced during the COVID-19 pandemic (FAO, 2025) illustrate emerging efforts aimed at strengthening local production, but these interventions appear largely reactive. Strengthening long-term resilience will require more proactive strategies, including climate-resilient local agriculture, improved storage and distribution infrastructure to reduce food losses, and diversification of food supply channels.

For an isolated nation with limited land, complete food self-sufficiency may be neither biophysically feasible nor economically desirable. However, strategic prioritization within the food system remains possible. Protecting the fisheries sector represents one of the most important leverage points (Birchenough, 2023; Pouponneau, 2023). Marine foods provide both economic value and essential nutrients, particularly omega-3 fatty acids associated with reduced cardiovascular risk (Jamioł-Milc et al., 2021; Xia et al., 2025). At the same time, subsistence production in outer atolls continues to function as a dietary buffer and social anchor (Maldives Bureau of Statistics, 2019). Practices such as indigenous food cultivation, kinship-based food exchange, and intergenerational transmission of traditional knowledge reinforce social cohesion and can strengthen collective capacity for disaster recovery (Alexeyeff, 2010; Marrero & Mattei, 2022; Campbell, 2015b).

Supporting decentralized small-scale production and emerging innovations such as hydroponics and rooftop farming as well as improved intra-atoll transportation could enhance food access. Circular nutrient recovery through anaerobic digestion from all sectors could further support local production while reducing dependence on imported fertilizers (Areeshi, 2022; Singh et al., 2020). Finally, addressing the growing influence of UPFs will require structural policy responses, including restrictions on marketing to children and fiscal measures targeting sugar-dense imports. While important data gaps remain, particularly regarding local production and nationally representative dietary surveys, the use of largely open-access datasets demonstrates the potential for replicable food system analyses in data-scarce island contexts.

By providing a systemic assessment of food flows and vulnerabilities, this study contributes to advancing Sustainable Development Goal 2 (Zero Hunger) through improved understanding of food and nutrition security dynamics in the Maldives. The findings also highlight linkages with other SDGs, including SDG 3 (Good Health and Well-being), underscoring the importance of integrated food system strategies in vulnerable island contexts. Such insights call for coordinated, cross-sectoral approaches to strengthen resilience, improve diet quality, and support sustainable development pathways in small island states.

Declarations

Conflict of Interest Statement: The authors declare no conflict of interest.

Data Availability Statement: All primary datasets used in this study are publicly accessible from the following repositories: FAOSTAT; UN Comtrade, World Bank, and World Health Organization. The dataset used or the nutrition analysis are provided by the Maldives Customs Service. All data generated during the analysis, as well as the document and spreadsheets needed to replicate the figures and tables, are provided in the Supporting Information that accompanies this article.

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Figures

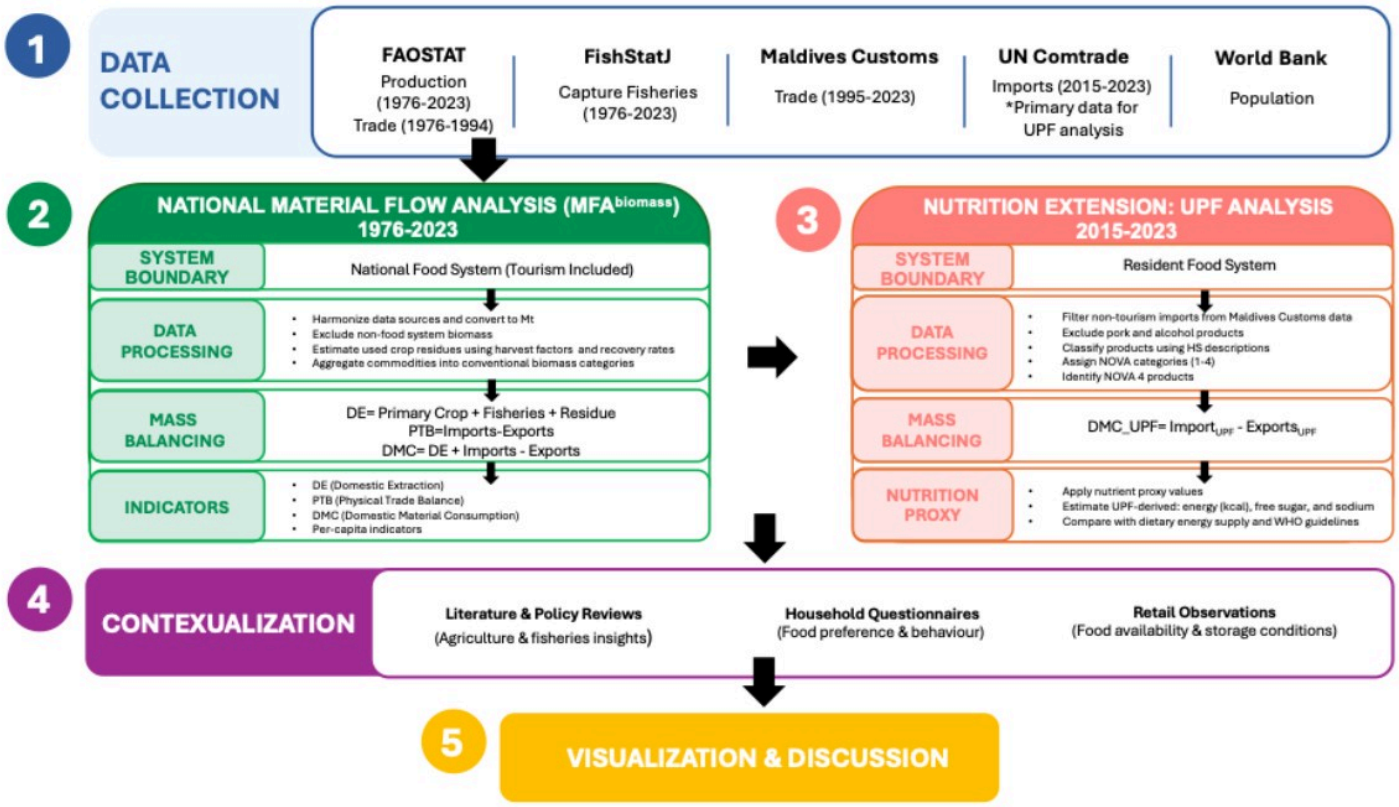


Figure 1

Overview of the study design and methodological workflow

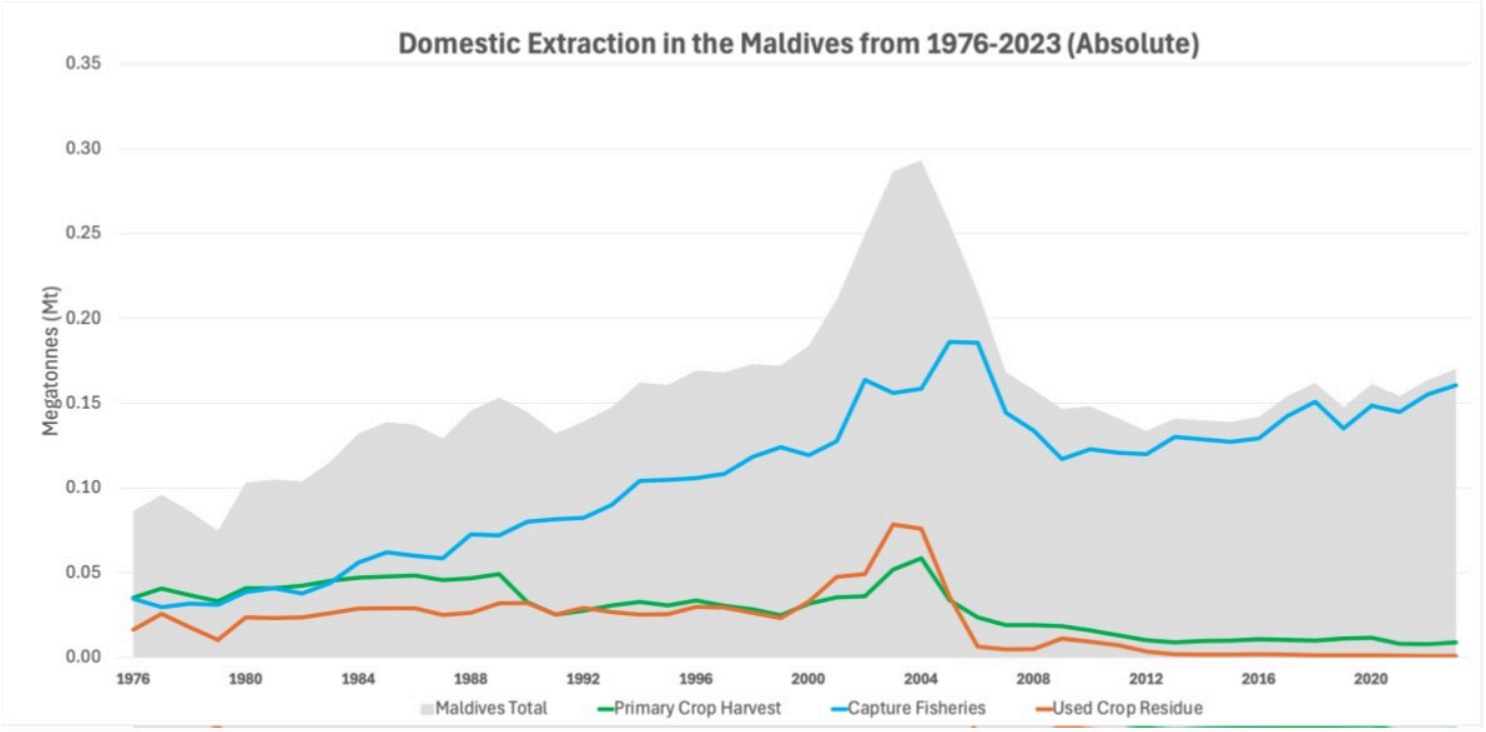


Figure 2

Domestic extraction of biomass in the Maldives from 1976-2023 in absolute values (megatonnes)

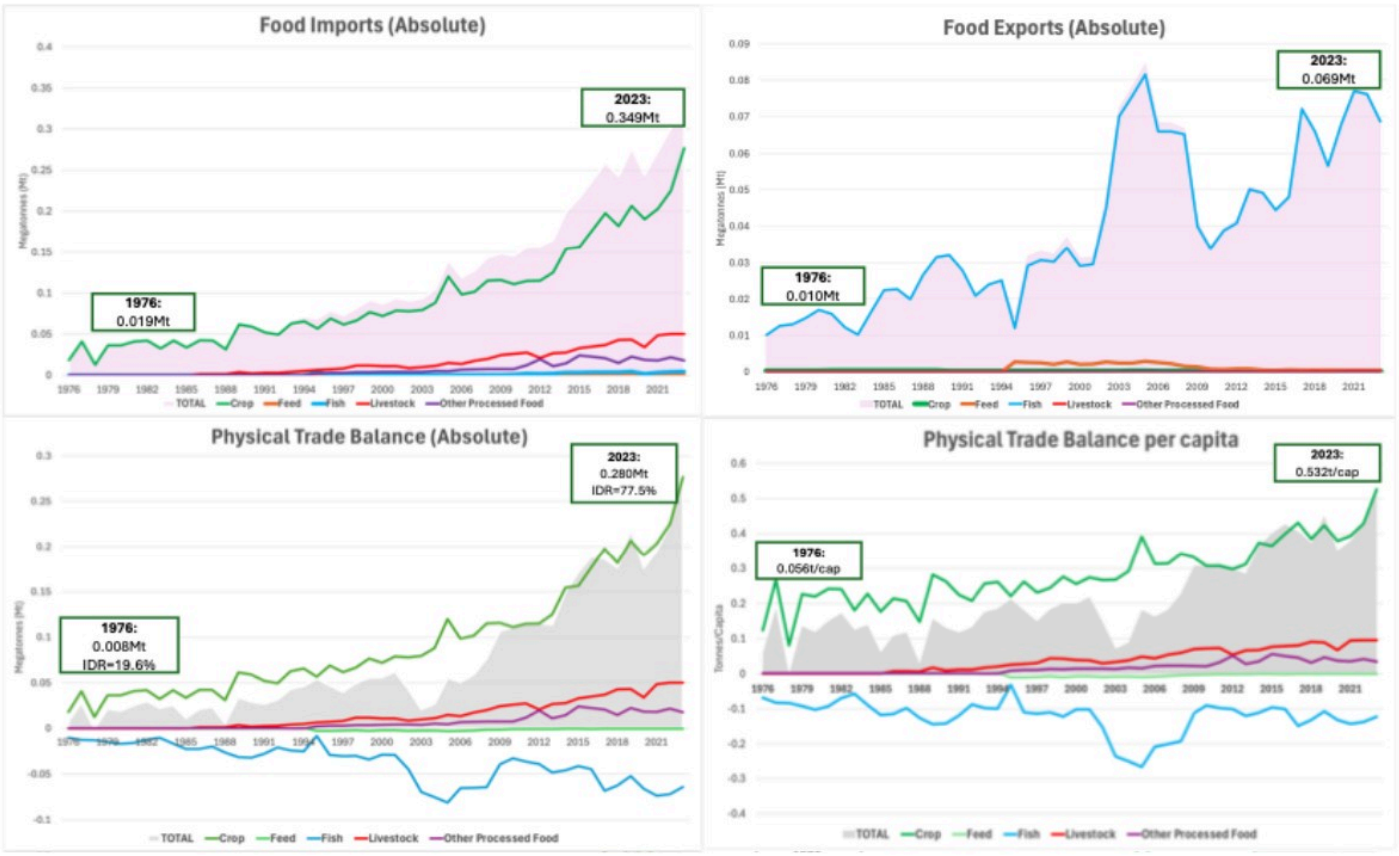


Figure 3

Net trade volumes and annual aggregate flows of Physical Trade Balance (PTB) in both absolute and per capita terms (1976-2023)

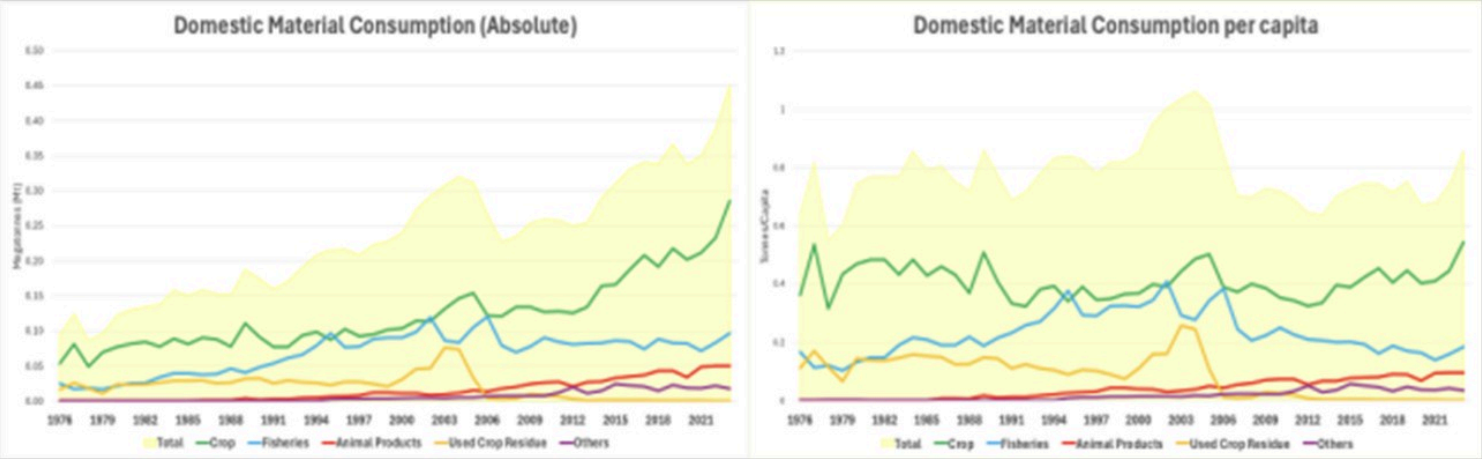


Figure 4

Trends in absolute and per capita domestic material consumption of ultra-processed foods from 2015-2023 in the Maldives

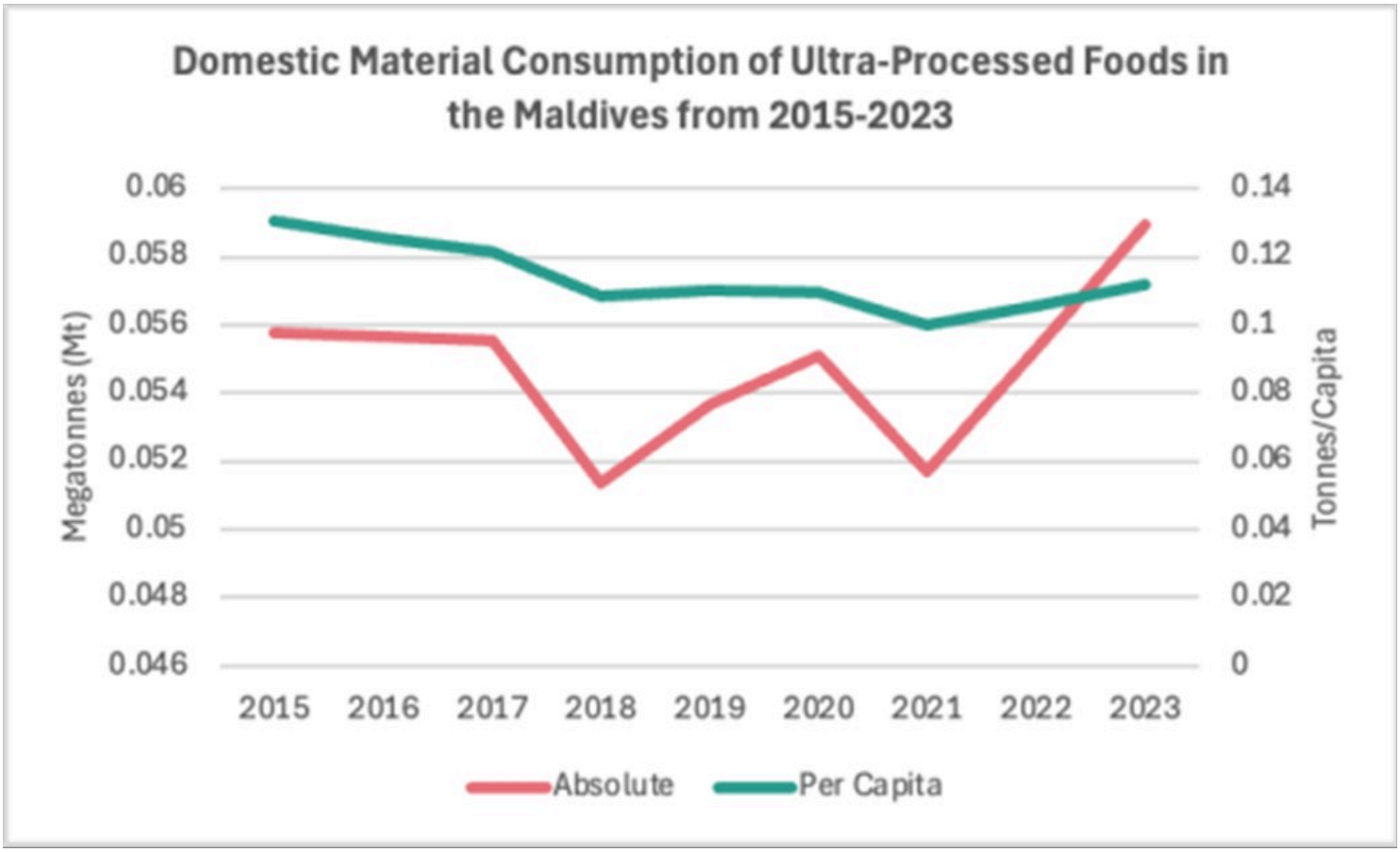


Figure 5

Annual trends in the composition of ultra-processed foods in the Maldives in megatonnes (Mt) from 2015 to 2023.

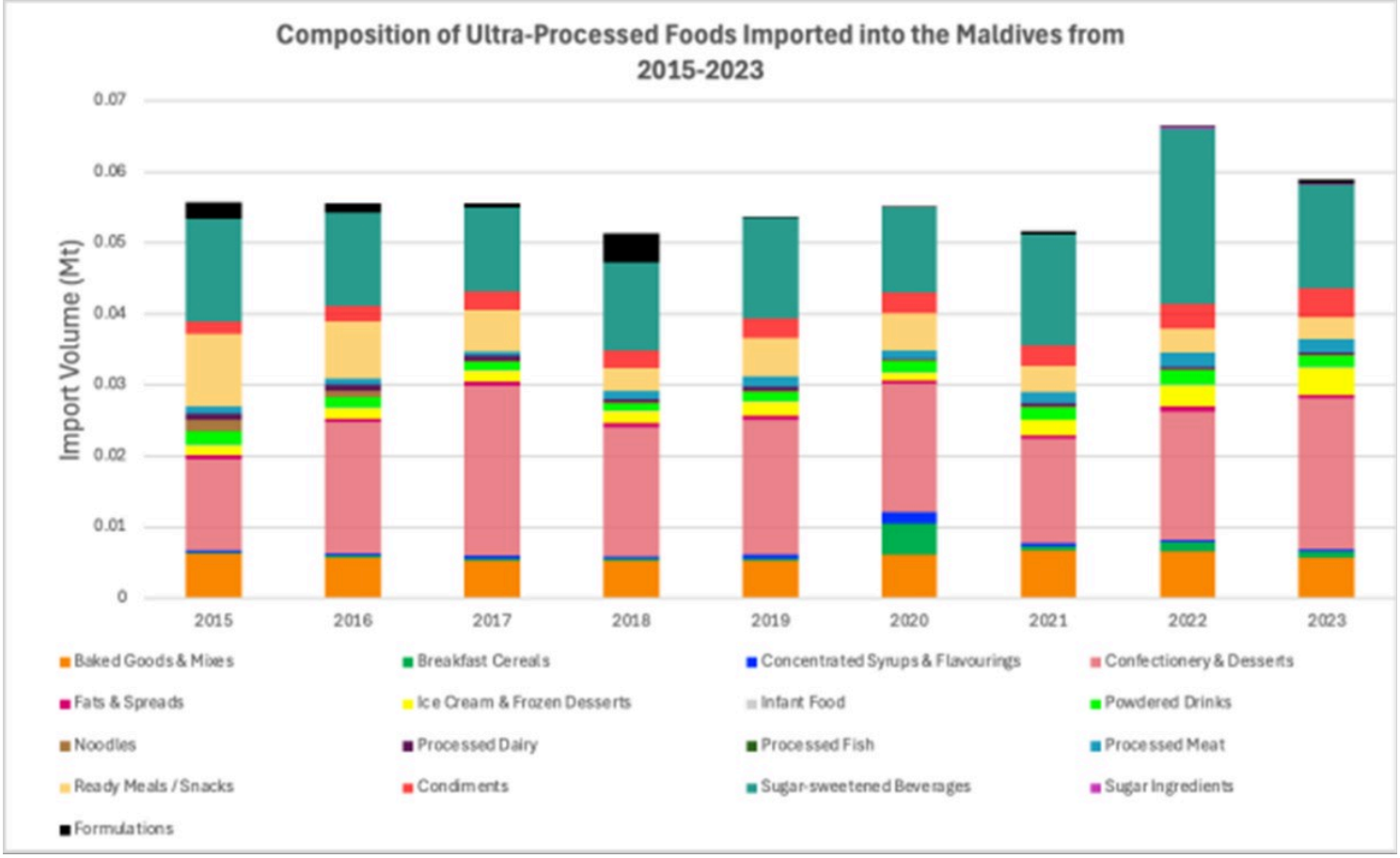


Figure 6

Category-specific changes in ultra-processed food imports into the Maldives in megatonnes (Mt) from 2015-2023

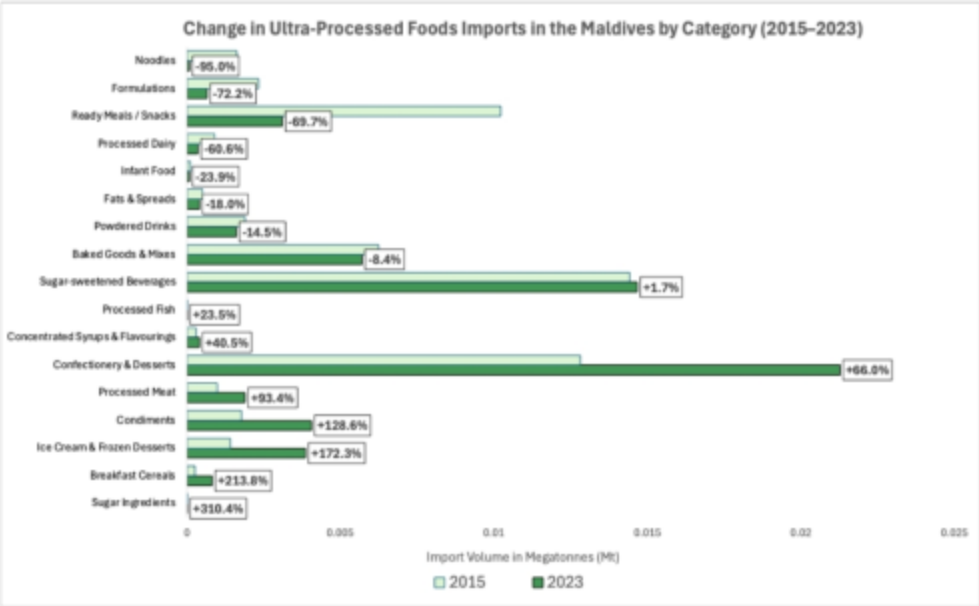


Figure 7

Category-specific changes in ultra-processed food imports into the Maldives in megatonnes (Mt) from 2015-2023



Figure 8

Per capita daily availability of energy, sugar, and sodium from ultra-processed foods in the Maldives from 2015-2023