THESISES OF THE DOCTORAL (PhD) DISSERTATION

FOOD, ENERGY, AND ENVIRONMENTAL SECURITY FROM SUSTAINABLE DEVELOPMENT PERSPECTIVES IN SELECTED EU COUNTRIES

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1. INTRODUCTION

The delicate balance for our planet's sustainability is under increasing strain. We face the dual challenge of ensuring everyone has access to food and energy, while simultaneously safeguarding the environment for future generations. This challenge intensifies as the world's population surges. By 2050, an estimated 9.7 billion people will significantly amplify the pressure on vital resources like water and land (Guan et al., 2024). Climate change adds another layer of complexity, potentially disrupting agricultural production and resource availability (Riseh et al., 2024).

Our world is facing the complex challenge of ensuring food security for a growing population while protecting the environment and managing our energy resources responsibly. This challenge, known as the Food, Energy, and Environment (FEE) nexus, requires us to understand the intricate connections between these three seemingly separate aspects.

Developing nations face especially acute challenges within the FEE nexus. Limited access to clean water and energy, coupled with dwindling natural resources, threatens their food security (Popp et al., 2014). Striking a balance between economic growth and environmental protection is essential for these countries. A study by Ozturk (2015) suggest that with careful management, economic growth can eventually lead to lower environmental impact, creating a sustainable future. Developed regions also grapple with FEE security concerns. Solutions like promoting renewable energy, diversifying trade partnerships, and adopting sustainable agricultural practices are crucial. Collaboration between governments, scientists, and the public is vital in building a more resilient future for all.

Our journey towards a sustainable future has only just begun. Each step in the food chain, from production to consumption, impacts the others. This interconnectedness highlights the urgency for action, particularly in developing countries. Embracing eco-friendly agricultural practices and promoting responsible resource use are crucial steps in this journey (Wagh et al., 2024). However, the path is not without obstacles. Climate change throws another layer of complexity into the equation, impacting agricultural yields and requiring some countries to explore options like renewable energy or improved trade policies. Additionally, regional disparities in food security exist, with some countries more vulnerable to food price shocks. Addressing these inequalities requires targeted policies that support rural areas and help generate income.

Recent events like the COVID-19 pandemic and the ongoing conflict in Ukraine have significantly impacted global food consumption patterns. The pandemic led to disruptions in food shopping, income instability, and rising food prices, while the war disrupted global food and energy supply chains, further threatening food security in many regions. Extreme weather events like heatwaves and droughts add another layer of complexity to this already intricate challenge (Rabbi et al., 2021b).

1.1. Problem statement and research gap

This research focused on the European Union (EU) context, specifically addressing the challenges to achieving FEE security in EU countries. Prior research hasn't collectively examined this issue within the selected EU region. Furthermore, the examination identified potential "hotspots" where each sector's activities significantly impact FEE security.

Table 1: Analyzing the complex factors shaping FEE security in the EU

	Dimensions	Food	Energy	Environment
Present Status	**Availability**	Doesn't have adequate supply of staple foods like grains, fruits, and vegetables.	Doesn't have adequate supply of clean, affordable, and secure energy sources.	Doesn't have adequate forest, green and pollution-free environment.
	Access	The increase in food prices results in a decrease in individuals' purchasing power.	The lack of accessibility to clean and renewable energy sources.	Resources in EU are less accessible due to the overexploitation of natural resources.
	Utilization	Insufficient nutritional intake and limited dietary diversification	Insufficient measures taken to facilitate the transition towards secure and sustainable energy sources.	The ecology and its biodiversity are in danger due to a lack of adequate protection and restoration efforts.
Resilience	**Vulnerability**	The increasing prevalence of both malnutrition and obesity.	The reduced proportion of renewable energy in the energy mix has resulted in a higher level of dependence on energy imports.	Climate change leads to an increase in temperature, the occurrence of heat waves, floods, droughts, and a decline in food production.

	Sustainability	The EU's plan for food sustainability is designed to protect the environment while ensuring all people have access to nutritious foods.	The low-carbon transition aims for a clean energy future that boosts the economy, sparks innovation, creates jobs, and improves lives.	The European Green Deal aims to supercharge nature, zero out carbon by 2050, decouple growth from resources, and have a toxin-free future.

Source: Barrett (2010a); Borowski & Patuk (2021); Cockx et al. (2015); Friel et al. (2009); Ladha-Sabur et al. (2019); Leisner (2020); Máté et al. (2020a); Mc Carthy et al. (2018a); Monforti & Dallemand (2015); Mostova & Hutorov (2023); Popp et al. (2014); Rabbi et al. (2022a, 2023); Rabbi et al. (2021a); Subramaniam et al. (2020a); Sun et al. (2017a).

Table 1 highlighted the European Union's (EU's) challenges and goals across three key areas: Food, Energy, and Environment. Current shortcomings in the EU include limited access to affordable, nutritious food, a dependence on unclean and expensive energy sources, and environmental degradation. These issues are manifested by insufficient supplies of staple foods and clean energy, alongside deforestation, pollution, and a lack of environmental protection efforts. However, a critical gap exists in the prior research exploring the factors impacting the security and sustainability of FEE systems across European nations. This study addressed this gap by analyzing eight EU member states: Austria, Belgium, Germany, Netherlands, Czech Republic, Hungary, Poland, and Slovakia. While existing studies provide valuable insights, a comprehensive analysis is necessary to understand the specific challenges associated with each factor and its potential connection to achieving the Sustainable Development Goals (SDGs).

1.1.1. The aim and objectives of the research

This research also addressed knowledge gaps through its key objectives (detailed in Table 2), which aimed to contribute to developing effective strategies for promoting sustainable development in eight selected EU countries.

Table 2: Research objectives for achieving FEE security

Objective 1:	To investigate the impact of regional disparities on food security across selected EU countries
Objective 2:	To explore how a combined strategy of efficient resource use, sustainable production, improved infrastructure, dietary variety, and minimal food waste strengthens food security and sustainability.

Objective 3:	To analyse and understand the diverse trends and patterns in the EU energy mix.
Objective 4:	To analyse CO_2 emission trends and identify key factors to develop effective mitigation plans.

Source: Author's compilation

Additionally, by examining these critical aspects, the research aimed to gain a comprehensive understanding of the challenges hindering sustainable development in Europe and provide valuable insights for policymakers.

1.2. Research questions

This research simplified these multifaceted issues into a set of well-defined research questions presented in Table 3. This approach aimed to better understand the interdependencies within the FEE nexus and its implications for achieving the SDGs.

Table 3: Research questions aligned with objectives.

Objectives	Research questions
Objective 1	1. To what extent do regional disparities, specifically in urbanization, GDP, consumption patterns, and import dependency, influence food security across selected EU countries?
Objective 2	2. How does a combined strategy of efficient resource use, sustainable production, better infrastructure, dietary variety, and waste reduction impact food security and sustainability?
Objective 3	3. How do EU energy production and consumption patterns impact energy security?
Objective 4	4. What are the main sources and factors contributing to CO_2 emissions?

Source: Author's compilation

1.3. Research process

The dissertation commenced with a comprehensive research background that aimed to elucidate the existing knowledge gap and substantiate the theoretical framework pertaining to the security and sustainability of FEE within European countries. In addition, the comparative performance in relation to the progress of SDGs (2, 7, and 13) was examined throughout the investigation of sustainable FEE development. Furthermore, Figure 1 depicted the research process employed in the study's progression.

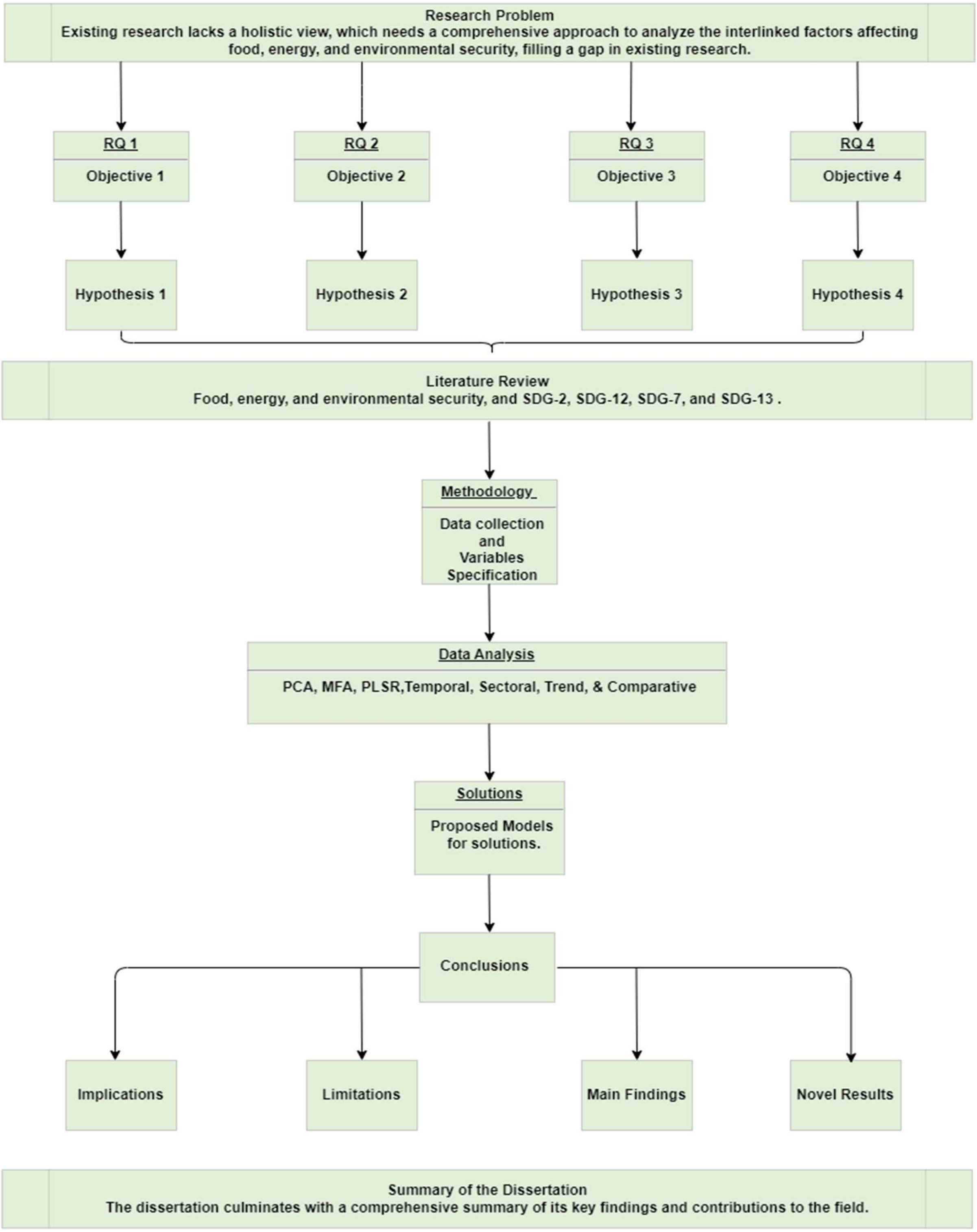

Figure 1: The research processes.

PCA: Principal Component Analysis; MFA: Multiple Factor Analysis; PLSR: Partial Least Squares Regression

Source: Author's compilation

1.4. Structure of the thesis

This thesis tackled the complex interplay between FEE security, demanding a holistic approach. It explored the interconnectedness of these domains through the lens of specific SDGs (2, 7, 12, 13) and built upon existing research by:

- **Reviewing existing literature:** Examining individual security domains, uncovering gaps, and justifying further research.
- **Employing robust methodology:** Justifying the research design, data collection, and analysis techniques used.
- **Developing a novel framework:** Integrating concepts from each domain to understand how factors like climate change and energy production impact their stability.
- **Presenting insightful findings:** Analyzing data to identify patterns, trends, and relationships between variables.
- **Proposing solutions:** Incorporating three unique models to offer practical insights and potential strategies for enhancing security in these areas.
- **Contributing to the field:** Summarizing key findings, proposing future research directions, and providing a comprehensive reference list.

Overall, this dissertation aimed to deepen our understanding of the interconnectedness between food, energy, and environmental security and offer practical solutions for addressing the challenges they pose.

2. METHODS AND METHODOLOGY

2.1. Methods and data collection

This investigation dived into FEE security in selected EU countries. It explored both challenges and opportunities related to these critical issues. The research painted a comprehensive picture, leveraging quantitative and qualitative data, aligned with relevant SDGs. This SDG lens allowed for deeper insights and evaluation of findings. Ultimately, the research aimed to guide effective and targeted actions towards achieving sustainability goals.

Investigating the link between food security and SDG 2 (Zero Hunger) and 12 (Responsible Consumption and Production) in **Study 1 (food security)** required a robust methodology capable of handling complex relationships between numerous interconnected variables. Unlike simpler regression methods that might struggle with such intricate data, Partial Least Squares Regression (PLSR) proved ideally suited for this task. PLSR facilitated the simultaneous analysis of two sets of variables: those directly related to food security and those associated with the SDGs. This comprehensive approach enabled us to not only identify key factors influencing food security but also critically assess their connection to achieving the relevant SDGs.

The PLSR model captures the relationships between the X and Y variables through a combination of outer and inner components. The outer components represent the variation within each block (X and Y) individually, while the inner components capture the latent variables that explain the shared variance between them. This complex interplay can be mathematically expressed as:

Consider a scenario for analyzing a dataset that consist of I observations and J variables, denoted by the X block. Here, x_{ij} represents the i-th observation for the j-th variable, and the matrix X_{IxJ} has dimensions IxJ. Furthermore, $X^{(j)}$ indicates the j-th column of matrix X. Similarly, let's suppose there is another dataset with the same number of observations as Y and K variables, where Y_{IxK} denotes the i-th observation for the k-th variable, and Y_{IxK} forms a IxKmatrix.

The outer relation for X block is:

$$X_{IxJ} = \sum_{l=1}^{L} t_{Ix1}^{(l)} \cdot {p'}_{1xJ}^{(l)} + E_{IxJ} = TP' + E \qquad (1)$$

The outer relation for Y block is:

$$Y_{IxK} = \sum_{l=1}^{L} u_{Ix1}^{(l)} \cdot {q'}_{1xK}^{(l)} + F_{IxK} = UQ' + F \qquad (2)$$

Consider two error matrices, E (of dimension IxJ) and F (of dimension IxK). Additionally, we have two "score" matrices, $t^{(l)}$ and $u^{(l)}$ (both IxL), representing scores for X and Y, respectively. These matrices can be further decomposed into column vectors: $t^{(l)}$ (of dimension $Ix1$) for T and $u^{(l)}$ for U, where l represents the l-th column (and there are L columns in total, indicating the number of latent components).

Similarly, we have two matrices, P' (of dimension LxJ) and Q' (of dimension LxK), containing "loadings." These can also be expressed as row vectors: $p'^{(l)}$ (of dimension $1xJ$) for P' and $q'^{(l)}$ (of dimension $1xK$) for Q'. Here, l again refers to the l-th row (out of L total rows). The prime symbol ($'$) denotes matrix transposition.

This explains the relationship between error matrices, score matrices, loading matrices, and their corresponding vector representations. It emphasizes that these elements play a role in representing scores for X and Y.

$$T_{IxL} = \sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot W'^{(j)}_{1xL} = XW' \qquad (3)$$

and

$$t_{Ix1}^{(l)} = \sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot w_{j,l} \qquad (4)$$

The weight matrix for the variables in the X block is denoted by $W'^{(j)}$, where each entry $w_{j,l}$ represents the weight of the l-th latent component on the j-th variable.

The X-scores are also used to predict the variables in the Y block. In this case, the formula (4) replaces $u_{Ix1}^{(l)}$ from formula (2) with $t_{Ix1}^{(l)}$. This indicates that the X-scores are used as predictors for the Y block variables.

$$Y_{IxK} = \sum_{l=1}^{L} \left(\left(\sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot w_{j,l} \right) \cdot q'^{(j)}_{1xK} \right) + G = XW'Q' + G \quad (5)$$

The Partial Least Squares Regression (PLSR) technique analyzes data by first reducing the predictor variables (X) to a set of principal components (PCs). These PCs, represented by factor scores ($t^{(l)}$), are then used to predict component scores ($u^{(l)}$) derived from the dependent variable (Y). Finally, the predicted Y component scores are used to estimate the original Y values.

PLSR's key strength lies in its ability to maximize the relationship between the factor scores of the predictor and dependent variables ($t^{(l)}$ and $u^{(l)}$, respectively). It achieves this by strategically selecting X -scores that best correspond to the Y-scores, ensuring a strong pairing between the latent independent and dependent variables (Garson, 2016). Herman Wold's pioneering Nonlinear Iterative Partial Least Squares (NIPALS) method (Wold, 1975) is used to calculate the components of PLS. Geometrically, the NIPALS approach involves projecting the original X matrix onto a plane defined by the scores of the X components. This projected data is then correlated with the Y values (Wold et al., 2001). A common visualization technique involves plotting the corresponding columns (representing dimensions) of the W' weight matrix and the Q' loading matrix on the same coordinate system. This visualization helps to illustrate the associations between the two sets of variables.

The analysis employed Tanagra 1.4.50 software (Rakotomalala, 2005). To guarantee the generalizability of the models, a cross-validation technique was implemented, splitting the data into 75% for training and 25% for testing. The models' performance was assessed using R-squared change and Root Mean Squared Error (RMSE).

In order to assess how sustainable development influences food security, a specific set of indicators was selected. The table (Table 4) summarizes these relevant indicators for various aspects (accessibility, availability, quality, stability, and Sustainable Development Goals) of food security in the listed European Union countries. The table also provides details like the timeframe (2012-2019), data sources, abbreviations used, and explanations for how each indicator is measured.

Table 4: Measurement of variables for assessing food security in the context of sustainable development

Pillar		Period	Indicator	Source*	PCA component	Abbreviation	Measurement	Previous Literature
Food security block (Y) /dependent variables/	Food accessibility	2012-2018	Gross Domestic Product (GDP) per capita	EIU	PC1	gdppercapita	US$ at PPP** per capita	(Campi et al., 2021; Marino & Pariso, 2020)
		2012-2018	Road infrastructure	EIU	PC4	roadinfra	Score (0-4) 4 = best	(STEWART, 2003; Wenban-Smith et al., 2016)
		2012-2018	Port infrastructure	EIU	PC1	portinfra	Score (0-4) 4 = best	(STEWART, 2003; UN, 2020)
		2012-2018	Rail infrastructure	EIU	PC1	railinfra	Score (0-4) 4 = best	(STEWART, 2003)
	Food availability	2012-2018	Urban absorption capacity	EIU	PC2	urbabsorb	GDP (% of real change) - period of urban growth	(Wenban-Smith et al., 2016)
		2012-2018	Volatility of agricultural production	EIU	PC3	volagrprod	Standard Deviation (0-1)	(Campi et al., 2021)
		2012-2018	Political stability	EIU	PC2	polstab	Score (0-100) 100=best	(Campi et al., 2021)
		2012-2018	Food loss	FAO	PC4	foodloss	Waste/supply (ton)	(Bodirsky et al., 2020; UN, 2020)

	Food quality	2012-2019	Diet diversification	FAO, EIU	PC4	dietdiv	% (Percent)	(Bodirsky et al., 2020; Johnston et al., 2014)
		2012-2019	Protein quality	EIU	PC1	proteinqual	Score (0-100) 100=best	(Campi et al., 2021)
		2012-2019	Average food supply	FAO	PC1	avefoodsupply	Kcal/person/day	(Campi et al., 2021)
	Food stability	2014**-2019	Severe Food Instability	FAO	PC3	foodinst	% of the total population	(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018)
		2012-2017**	Safe Drinking Water	FAO	PC3	safedrink	% of the total population	(Young et al., 2021)
		2012-2016**	Prevalence of Obesity	FAO	PC3	prevobesity	% in population (above 17 years)	(Bodirsky et al., 2020)
Sustainable Development Goals block (X)/ independent variables/	SDG 2 and SDG 12	2012-2018	Public expenditure on agricultural R&D	EUROSTAT	PC3	Agric R & D	Score (1-9) 9 = highest	(Campi et al., 2021)
		2012-2019	Agricultural Factor Income	EUROSTAT	PC1	AFI	% (2010=100 %)	(European Commission, 2019)
		2012-2019	Poverty proportion	EIU	PC2	povprop	% under global poverty line ($3.2/day)	(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018)
		2012-2019	the area under organic farming	EUROSTAT	PC2	orgfarm	% of the total utilized agricultural area	(de Backer et al., 2009; Rounsevell, M.; Fischer, M.; Rando, A. T. M.; Mader, 2018)
		2012-2017**	Ammonia emission from agriculture	EUROSTAT	PC1	ammemis	tonne	(de Backer et al., 2009)
		2012-2018**	Harmonised risk indicator for pesticides	EUROSTAT	PC2	HRI1	% (2011-2013 average =100%)	(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem

								Services, 2018)
		2014-2017**	Rate of obesity	EUROSTAT	PC4	obesity	%	(Bodirsky et al., 2020)

[1] *Notes: * EIU: Economist Intelligence Units* (European Intelligence Units, 2021)*; EUROSTAT: Statistical Office of the European Union* (Eurostat, 2020b)*; FAO: Food and Agricultural Organization* (FAO, 2020)*; **: missing data were estimated from OLS regression.*

This study examined how sustainable development practices influence a nation's food security. It focuses on Sustainable Development Goals (SDGs) 2 and 12, creating a framework to analyze food security and sustainable development together.

Three key aspects were used to evaluate food security: affordability (FAF), accessibility (FAC), and quality (FQ). Affordability considers a country's economic ability to buy food during both stable and volatile times, including factors like income and food spending. It also analyzes how import tariffs and reliance on external sources affect vulnerability to price changes.

Building on this foundation, the second study (**energy security**) focused on energy production and consumption data from 2010 to 2021. Here, the researchers utilized a Trend and Comparative Analysis approach to gain a comprehensive understanding of energy security dynamics over the past decade. This rigorous approach involved a Trend Analysis of energy in eight EU countries. Specifically, they delved into the electricity landscape using World Bank (WB) data on both electricity demand and generation. To effectively represent and analyze this data, the researchers employed various mathematical tools and visualizations.

First, key variable (D_{ij}) was electricity demand for country i in year j defined. Here G_{ij} was electricity generation for country i in year j. The number of countries was represented by n (here, n = 8). Afterwards, summary statistics were utilized to gain insight into each country's electric energy profile.

The following formula was used for the summary statistics:

$$\bar{D}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} D_{ij}$$

Mean electricity demand was denoted by $\bar{D}_i$. Average demand for each country was calculated by summing demand across all years (N_i) and this was divided by the number of years. Hence, the standard deviation of electricity demand can be calculated as follows:

$$\sigma_{Di} = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(D_{ij} - \bar{D}_i\right)^2},$$

where σ_{Di} indicates deviation of demand around the mean. Minimum ($D_{min,i}$) and maximum electricity demand ($D_{max,i}$) defined the range of demand for each country. Similar calculations were applied to statistics for electricity generation $\left(G_{ij}\right)$, where minimum and maximum electricity generation was denoted by $G_{min,i}$ and $G_{max,i}$.

Finally, to understand the data clearly $Bar\ Plot(i) = \overline{D}_i\ and\ \overline{G}_i$ were created for each country, displaying both the mean electricity demand $\overline{D}_i$ and generation $\overline{G}_i$. This allowed for quick comparisons and identification of potential trends across all countries.

By combining mathematical expressions with clear visualizations, this analysis provided a comprehensive understanding of the electricity demand and generation landscape within the selected EU countries. In addition, to create the trend lines for the examination of the energy consumption trend in eight EU nations using data from various sources the following mathematical formulas and equations were used:

For each energy source j in the dataset, a linear trend line was fitted using the ordinary least squares regression method. This resulted in the following linear equation:

$$y = mx + b$$

The normalized energy consumption is denoted by y, x denotes the year, m denotes the slope, indicating the rate of change (positive for an increase and negative for a decrease) in consumption over time, and b represents the baseline level of consumption. Trend lines can provide insight into the direction and magnitude of energy consumption shifts.

A Comparative Analysis of renewable energy consumption across countries provided an insightful view of the EU energy landscape. This comparison allows policymakers to identify opportunities to diversify their energy mix and prioritize investments in sectors with the greatest growth potential.

The calculations of the total consumption for each type of renewable energy across all countries were as follows:

- Total Renewables Consumption = ∑ (Renewables Consumption for each country)
- Total Solar Consumption = ∑ (Solar Consumption for each country)
- Total Wind Consumption = ∑ (Wind Consumption for each country)

The Comparative Analysis can be represented by the following equations:

Percentage of Renewables Consumption =

$$\frac{\text{Total Renewables Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}}\ X\ 100\%$$

Percentage of Solar Consumption =

$$\frac{\text{Total Solar Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}} X\ 100\%$$

Percentage of Wind Consumption =

$$\frac{\text{Total Wind Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}} X\ 100\%$$

This robust mathematical framework, underpinned by a tailored set of equations, enabled a comprehensive assessment of fossil and renewable energy consumption throughout selected European countries. Applying this model to real-world data highlighted the substantial contributions of renewable energy to the energy mix of eight EU nations. Matlab R2023b provided the computational power to perform these insightful calculations.

To understand how food and energy production and consumption affect the environment, **Study 3 (environmental security)** focused on the combined environmental and climate change effects of major carbon dioxide (CO_2) emitters from different sectors. Data for this study was sourced from the official database of the Food and Agriculture Organization of the United Nations (FAO) between 2010 and 2021(FAOSTAT, 2021).

In the Temporal Trend Analysis, the dataset was grouped by year to facilitate the analysis. The mean values for each variable were calculated for each year, providing a snapshot of the average emissions levels over the entire dataset. Temporal trends were visualized through line plots, allowing for a clear depiction of how emissions from different variables evolved over a specified timeframe. The formula used in the analysis was as follows:

$$Average_{V_i}(t) = \frac{1}{N_j} \sum_{j=1}^{N_j} D_{ijt}$$

Here V_i represents the emissions from eight different variables, for example, On-firm energy use, Agrifood systems waste disposal. The emission value is represented by D_{ijt} for variable V_i. The number of countries is denoted by N_j and t indicates the year. The X-axis represents the year from 2010 to 2021. The Y-axis represents the average emission value ($Average_{V_i}(t)$) for variable V_i in the *t-th* year. If the trend was upward then $Average_{V_i}(t)$ increased over the years, this indicated a positive temporal trend. The downward trend was indicated by a decreasing $Average_{V_i}(t)$ value and it indicated a negative temporal trend.

To understand the sources of greenhouse gas emissions in the European Union, a sectoral analysis was conducted. Emissions were categorized (e.g., energy, industry, agriculture), and their contributions were quantified by summing emissions across EU countries. Percentages were calculated to show each sector's proportional share of the total emissions. A pie chart visually depicted the distribution, aiding in identifying dominant contributors. This analysis helped to identify key sectors for targeted emission reduction strategies, ultimately contributing to a cleaner EU.

$$Total\ EmissionsV_i = \sum_{j=1}^{N} D_{ij}$$

Here, V_i represents emission from food production, process, and consumption stages. N represents the total number of countries and D_{ij} represents the CO_2 emission value for each country. The emission value was transformed into a percentage using the following formula:

$$PercentageV_i = \frac{Total\ EmissionsV_i}{Total\ Emissions} X\ 100$$

While the total emissions data provided a comprehensive picture, converting it into percentages offered a clearer understanding of emission rates across different countries. This analysis was facilitated by the Matlab (version R2023b) software package.

Moving on to **Study 4 (FEE security)**, which focused on Food, Energy, and Environment (FEE) security, the chosen variables underwent thorough empirical testing to confirm their impact on selected EU countries' FEE security levels. This approach was informed by the insights gleaned from previous empirical studies. This study delves into the intricate connections between food security, energy use, and climate change. To achieve this, Multifactor Analysis (MFA) was employed to examine a broad spectrum of variables. MFA, a technique pioneered by Thurstone (1931) and further developed by Escofier & Pages (1994), is particularly adept at analyzing sets of correlated variables that can be naturally grouped. Its strength lies in its ability to handle complex relationships within and between these categories of variables.

The Visegrád Group (V4), comprising the Czech Republic, Hungary, Poland, and Slovakia, stands as a pivotal alliance within Central Europe. These four nations, along with Austria, Belgium, Germany, the Netherlands, and Switzerland, often find themselves grouped together due to their intertwined economic ties and shared concerns. This shared analysis was founded on the close economic connections and similar interests these countries share.

Table 5: Explanations of indicators for food security, energy utilization, and climate change

Pillar	Period	Indicator	Source*	Abbreviation	Measurement
Climate change	2012-2017	Air pollution	W.B.	air_pollution	Micrograms per cubic meter
	2012-2018	CO_2 emission (Cropland)	W.B., FAO	co2_crop	Gigagrams
	2012-2018	CO_2 emission (Grassland)	W.B., FAO	co2_grass	Gigagrams
	2017-2018	Soil erosion	HWSD	soil_erosion	Score (1-4) 1 = best
	2017-2018	Forest area	W.B.	forest_change	% of the total land
	2012-2018	Temperature rise	EIU	temperature_rise	Score 0 = least vulnerable
Energy usage	2012-2015	Energy intensity level	W.B.	energy_int_level	Megajoule at PPP** GDP
	2012-2018	Renewable electricity output	EUROSTAT	ren_electric_output	% of total output
	2012-2018	Renewable energy consumption	EUROSTAT	ren_energy_cons	% of the final energy
	2012-2018	Final energy consumption from biomass and renewable waste	EUROSTAT	final_energy_cons	Thousand tons of oil equivalent

Food affordability (FAF)	2012-2018	Food consumption as a share of household expenditure	W.B.	food_consump	% of total household expenditure
	2012-2018	Gross Domestic Product (GDP) per capita	EIU	gdp_per_capita	US$ at PPP** per capita
	2012-2018	Agricultural import tariffs	WTO	agr_imp_tarif	% (Percent)
	2012-2018	Food import dependency	FAO	food_imp_depend	% (Percent)
Food accessibility (FAC)	2012-2018	Average food supply	FAO	food_supply	Kcal/person/day
	2012-2018	Volatility of agricultural production	EIU	agr_prod_vol	Standard Deviation (0-1)
	2012-2018	Urban absorption capacity	EIU	urban_absorb	GDP (% of real change) - period of urban growth
	2012-2018	Population growth	W.B., EIU	population_growth	% (Percent)
	2012-2018	Road infrastructure	EIU	road_infra	Score (0-4) 4 = best
	2012-2018	Port infrastructure	EIU	port_infra	Score (0-4) 4 = best
	2012-2018	Political stability	EIU	pol_stab	Score (0-100) 100=best
	2012-2018	Public expenditure on agricultural R&D	EIU	pub_exp_agrrd	Score (1-9) 9 = highest

	2012-2018	Food loss	FAO	food_loss	Waste/supply (ton)
Food quality (FQ)	2012-2018	Diet diversification	FAO, EIU	diet_divers	% (Percent)
	2012-2018	Dietary availability of vegetal iron	FAO	diet_veg_iron	Mg/person/day
	2012-2018	Dietary availability of animal iron	FAO	diet_anim_iron	Mg/person/day
	2012-2018	Protein quality	EIU	protein_qual	Score (0-100) 100=best

[1] *Notes: * EIU: Economist Intelligence Units* (European Intelligence Units, 2021)*; EUROSTAT: Statistical Office of the European Union* (Eurostat 2020)*; FAO: Food and Agricultural Organization; HWSD: Harmonized World Soil Database; WB.: World Bank* (The World Bank, 2020)*; WTO: World Trade Organization* (WTO, 2020). ***: Purchasing Power Parity.*

Multifactor analysis (MFA) utilized a two-step approach for data exploration and visualization. In the first stage, each data block, represented as a rectangular matrix with dimensions (I x J), where I denote the number of observations and J denotes the number of variables, undergoes Principal Component Analysis (PCA). This analysis aimed to identify underlying patterns within each block. Subsequently, the information extracted from each PCA is normalized using the square root of its first eigenvalue, ensuring data comparability across different blocks (Abdi et al., 2013). The second stage involved performing a global PCA on the normalized data. This final step allows visualization of observations in a lower-dimensional space, typically two-dimensional (2D), with factor scores representing the coordinates of each observation.

In this specific investigation, five (T)datasets, referred to as "blocks," were analyzed. Each block comprised a rectangular data matrix denoted by $(I \times J[t])$, where I represents the number of observations and $J[t]$ represents the number of variables in the t-th block. All data matrices were preprocessed by centering and normalizing, denoted by $X[t]$. Additionally, each observation was assigned a "mass," reflecting its importance and directly proportional to its weight. This information was stored in a diagonal matrix M with dimensions $(I\ x\ I)$. Merging the normalized blocks resulted in a new, combined data matrix, denoted by Z $(I \times T)$, referred to as the global data matrix (Escofier & Pages, 1994).

The singular value decomposition of the global data matrix Z is then estimated using a standard PCA.

$$Z = U\Delta VT \text{ } with \text{ } UTU = VTV = I,$$

In singular value decomposition (SVD) of matrix Z, the diagonal matrix containing the singular values is denoted by Δ, while U and V represent the left and right singular vectors, respectively. The formula for calculating global (F) factor scores can then be expressed as:

$$F = M - 1/2U\Delta,$$

Where each horizontal row represents a single observation, and each vertical column represents a specific characteristic or measurement of that observation. This is a common way to organize data, allowing for easy comparison and analysis of different observations across various aspects.

2.2. Analytical procedures

Effective data analysis acted as a strategic cornerstone for research, uncovering the data's nature and outlining methods for its collection, evaluation, and interpretation. This ensured the study's significance and impact. Analyzing historical data was crucial for understanding long-term trends and predicting their future implications on critical issues like food security, allowing us to proactively address challenges and achieve the Sustainable Development Goals (SDGs). A range of software tools was employed to analyze the data presented in Table 6 below.

Table 6: Methodological approaches for data analysis

SL No.	Research objectives	Data analysis strategy	Software Used for Analysis
1.	To explore food production, consumption, and DMC efficiency for sustainable food security.	▪ Multiple Factor Analysis (MFA) ▪ Principal Component Analysis (PCA)	PAST and R
2.	To evaluate SDG indicator impact on sustainable food security.	▪ Global space and partial analysis ▪ Partial Least Squares regression (PLSR)	R and Tanagra

3.	To analyse and understand the diverse trends and patterns in the EU energy mix.	▪ Trend Analysis ▪ Comparative analysis	Matlab
4.	To analyse CO_2 emission trends and identify key factors to develop effective mitigation plans.	▪ Temporal trend analysis ▪ Sectoral Analysis	Matlab

Source: Author's compilation

3. CONCLUSIONS

3.1. Implications

This research revealed the intricate link between FEE security, emphasizing the impact of actions at all levels, from individual households to international partnerships. Interventions in one area can cascade into others, highlighting the need for comprehensive and coordinated strategies. For instance, large-scale energy projects might affect local biofuel plants and regional environmental security. Similarly, global trade regulations can influence regional agricultural production and distribution networks.

The research also unveiled discrepancies in European countries' energy transition efforts, with some leading in renewable energy adoption while others fall behind. Tailoring solutions to each country's specific needs is key, focusing on expanding renewable energy capacity, strengthening cross-border energy grid connections, and fostering regional cooperation. The study identified technology and system integration as crucial drivers for advancing renewable energy integration and enhancing energy efficiency. The research further identified targeted strategies for reducing CO_2 emissions in the agri-food sector, emphasizing the importance of energy efficiency and sustainable practices across the entire supply chain. Collaboration among policymakers, producers, retailers, and consumers is crucial for implementing comprehensive solutions, including consumer education, and incentivizing sustainable practices. Continued investment in research and development of innovative technologies is critical for emission reduction and building resilience in the food system.

3.2. Limitations and Future Research Directions

The study's limitations stem from methodological choices and variable selection. The arbitrary selection of key variables introduces bias, particularly omitted variable bias. Additionally, the study's broad scope necessitates numerous indicators, potentially hindering representativeness. Future research should employ a multidisciplinary approach encompassing economics, circular economy, sustainability, resource management, and climate theories. This comprehensive approach is crucial for developing accurate indicators reflecting global realities and future trajectories.

Further research is crucial to overcome these limitations and move forward. Deep dives into specific regions facing significant challenges, like the V4 countries, can provide a clearer understanding of their unique circumstances. Analyzing existing policies and exploring their potential for adaptation or transfer across the EU can lead to more effective solutions. Investigating innovative solutions in areas like renewable energy and sustainable agriculture offers promising avenues for addressing identified challenges.

3.3. Main findings of the study

Instead of taking a simplistic view of FEE security, as has been done in the past, the dissertation focused on the nuances essential for delving into the relationships between FEE and other social, economic, and environmental factors. The examination concluded that the various aspects of food security are expected to have varying effects on the different parts of SDGs. Specifically, the following findigs were discovered:

Table 7: Empirical findings aligned with research hypotheses of the study.

Sl. No	Findings	Supporintg Hypothesis
01.	The study on food security in selected EU countries revealed a regional disparity and identified challenges in access, affordability, and quality. Urbanization and economic factors affect access, while consumption habits and import reliance impact affordability. Diet quality, including protein intake, is also a concern.	The finding provides evidence that food security is indeed linked to regional disparities, higher urbanization, and (implicitly) economic growth, supporting Hypothesis 1 (H1).
02.	This research proved food security and sustainability demand a strategy focused on efficient domestic material consumption (DMC), sustainable intensification, upgraded road, rail, and port infrastructure, dietary diversity, and waste reduction.	The research finding highlights specific strategies that contribute to the core elements of Hypothesis 2 (H2): efficient production, better infrastructure, diverse diets, and reduced waste. By implementing these strategies, we can achieve a more sustainable food future.

03.	The study demonstrated a 204.34% increase in renewable energy consumption from 2010-2022. This growth underscores the effectiveness of sustainability policies and investments in accelerating the shift towards a greener energy sector.	The growth in renewable energy consumption is seen as a positive step towards a more diverse energy mix. This alignment with the core concept of Hypothesis 3 (H3) strengthens the hypothesis.
04.	This research revealed that household food consumption is the primary driver (24.8%) of food-related CO_2 emissions in selected European countries, followed by on-farm energy use (18.5%) and food transportation (13.8%).	The finding strongly supports Hypothesis 4 (H4) by highlighting that several stages within the food system, heavily influenced by food production practices and energy consumption patterns, are significant contributors to CO_2 emissions.

Source: Author's compilation

3.4. New and novel results

Enhancing interconnection and regional cooperation can address these hurdles by facilitating resource exchange and grid stability. Aligning national strategies with EU goals, while respecting individual circumstances, is crucial. Additionally, investing in technological innovation, system integration, and smart grids enables greater flexibility and integration of renewables. The research novel results were as follows:

Table 8: Novelty: contributions of the research

1.	The findings succinctly captured how SDGs 2, 7, and 13 influence FEE security across the selected EU countries, stressing the need for regionally tailored policies to address these interconnected challenges.
2.	The research explored a novel energy transition concept based on energy security pillars and RePowerEU principles, aiming to achieve carbon neutrality.
3.	An integrated FEE model was developed and linked to SDG 2, 7, and 13, seeking dual security and sustainability.
4.	Th investigation led to the development of a novel framework that seamlessly integrates sustainability dimensions with FEE security considerations.

Source: Author's compilation

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Total IF of journals (all publications): 32,846
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