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Assessing the moderating role of technological innovation on food security in poverty reduction within the Visegrad region

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Abstract
The global shift for sustainable development has elicited nations and governments to develop policies to safeguard humankind and the environment. The investigation premised on the poverty reduction within the Visegrad communities (Czech Republic, Hungary, Poland, and Slovakia). The evaluation employed panel data from 2000 to 2022 on the variables of poverty (POV), food security (FOD), foreign direct investment inflow (FDI), economic progress (ECP), population growth (POG), inflation growth (ING), and technological innovation (TIN). Various preliminary assessment of cross-sectional dependence, unit root, and cointegration was evaluated to ensure data reliability and validity. The econometric approach of Cross-Sectional Augmented Distributed Lag (CS-ARDL) model was adopted to study the short- and long-term affiliation. The findings revealed that (a) FOD, FDI, POG, and TIN had a material influence on poverty reduction. (b) However, ECP and ING appreciation poverty rate within the Visegrad region. (c) Again, there was a serial moderating effect of TIN on the affiliation between FOD and POV in the Visegrad region. Furthermore, the Dumitrescu-Hurlin causality test indicated a unidirectional nexus between FOD, FDI, POG, and TIN with POV reduction. While a bidirectional was established on ECP and ING with POV reduction. The outcome serves as a policy and practical supplement to government and institutional agencies in charge of poverty mitigation. The outcome recommend that government should invest in technological innovation to improve food security and poverty reduction to achieve the SDG1 by 2030.

Keywords SDG1, Food security, Technological innovation, CS-ARDL, Visegrad region

1 Introduction

It has been the last decade that the world has leaning toward sustainable development, with special reference to conservation of the environment and the betterment of all living beings. With the global poverty continue to upsurge because of the recent Covid 19, there is the need for policies to combat it. As the world elucidates to achieve a sustainable growth, the core goal has been to reduce poverty. In 2015, the UN SDGs place no poverty as the priority (UN SDGs 2015). It emphasizes the launch of the extreme poverty elimination process without exception for all nations, which provides a base

for implementing inclusive sustainable development. The target is set to 2030, however, the achievement of this has been a failure as the covid-19 has drop nations aback. As illustrated in Fig. 1, the Covid-19 has plagued around 71 million people worldwide into extreme poverty. As a result, this investigation is premises on (a) What is the affiliation between poverty reduction and food security? (b) Is there a nexus between poverty, food security, FDI inflow, and technological innovation? (c) Is there a serial moderation of technology on the affiliation between poverty and food security. To evaluate the investigation, the Visegrad Group which has been an active part of the process to reach this goal (Czech Republic, Hungary, Poland, and Slovakia) was employed.

Considering the framework of the Visegrad region, the past decade has witnessed some achievements and difficulties in achieving SDG1. In accordance with their obligations towards the EU, the Visegrad communities have adopted several policies regarding poverty reduction and social inclusion, as well as economic development plans. Nevertheless, previous literary work has established that food security can be a material component in poverty reduction [1–3]. In Nigeria, [4] examined food security among 120-woman vendors. From the empirical assessment 67.4% fall under the poverty bracket. Again, food security among these woman vendors drop to 64.8%. Cruz-Sánchez et al. [5] indicated that employing food supply, environmental, production, and social factors aid in food security among 2471 municipalities in Maxico to depreciate the poverty figures. A survey in Ghana on male household head established that male household in the cocoa producing areas decrease their poverty levels as food security was not the problem in the area [6].

Achieving a society free of poverty is one of humanity's most basic aspirations. It is clear from international experience that market forces alone will not be enough to eradicate poverty, FDI infusion is essential [7]. According to [8], FDI inflow enhances the level of living in Eastern European, Latin American, and Sub-Saharan African nations. The results highlighted the significant impact of FDI inflow on mitigating poverty in these regions. [9] assert that in today's interconnected world, international investment and

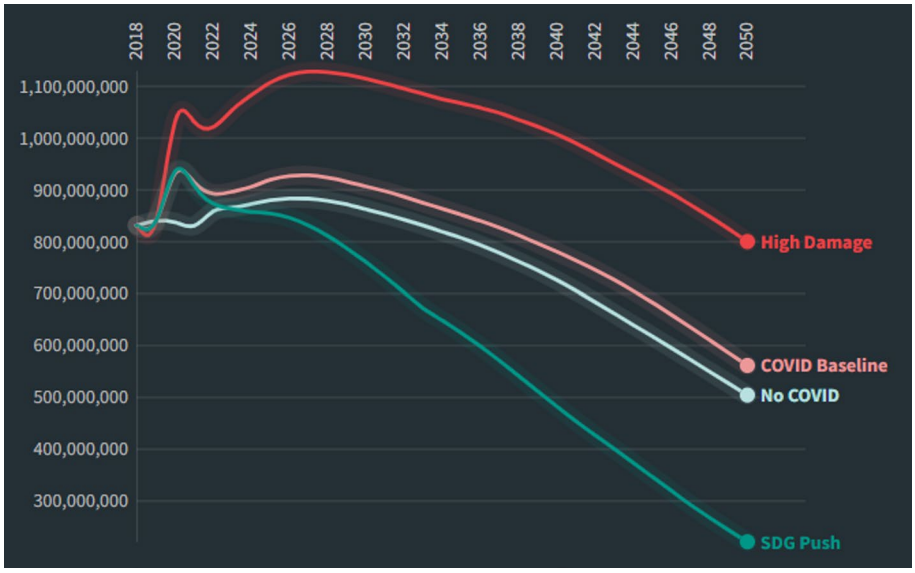

Fig. 1 Impact of pandemic on poverty and its projections up to 2050 under various scenarios. Data source: UNDP SDG Integration (2020)

commerce are essential drivers of economic growth. Both the host and home countries have gained from FDI inflow, leading to substantial economic growth in the medium to long term. FDI inflow promotes long-term economic growth, which is crucial for achieving these goals [10]. When nations get FDI, it brings cutting-edge technology, specialised knowledge, and financial resources; this helps alleviate poverty, expands healthcare and education opportunities, and promotes environmental sustainability.

Although, empirical investigation has highlighted the significance of food security and FDI inflow in mitigating poverty, there exits literature gaps within the Visegrad region. We included other control variables such as economic growth, inflation, and population in the research. Economic growth-poverty are seen as intertwin with each other to achieve the SDG1. Kicsi et al. [11] revealed that Visegrad region are connected economically to support each other to improve their well-being. Using provincial-level panel data from 2010 to 2020, [2] assessed poverty in China's poorest regions. When economic advancement amounted to7.3%, the 2SLS estimator's empirical results showed that poverty decreased by 8.4%. According to [3], poverty levels in Indonesia have decreased because of individuals' capital growing through financial intermediaries. Additionally, the technological innovation was employed as a serial moderation on the affiliation between food security and poverty mitigation in the Visegrad region.

The evaluation contributes to the ongoing debate the UN sustainable development goals as all the seventeen goals are linked with each other. The research expands the literary work on poverty mitigation within European communities by focussing on the Visegrad region as the region has detailed policies on meeting the SDG1 goals. From the theoretical point of view, the research highlights the material role of sustainable livelihoods frameworks (SLF) in the achievement of the UNSDGs within the Visegrad region which can be applicable to other European and international communities. Again, employing the serial moderation effect of technological innovation, the research adds to the significance sustainability nuanced. The Visegrad region will be able to adopt new technologies for food security and poverty alleviation. Moreover, the variable of economic growth, population growth, and inflation was controlled to contribute to difference in the various region's homogeneity. The investigation employed the second generational econometrics of CS-ARDL to evaluate the affiliation between food security, FDI inflow, technological innovation, economic growth, inflation, and population growth on poverty reduction, thereby, closing the methodological gaps. From the perspective of practical and policy the evaluation provides governments and interested institutions with guidance to mitigate poverty and ways to meet the SDGs by 2030.

The next steps cover the literature reviews, method and econometric strategy, followed by empirical results and discussions. Finally, the conclusions, policies and recommendations were suggested.

2 Literature review assessment

2.1 Food security and poverty

The Food and Agriculture report (2021) established that millions of individuals sleep without food every day. Recent literature has indicated that food security is tied to poverty in SDG1 and SDG2 [1, 12]. The World Food Programme (1996) detailed food access, availability, consumption, and stability as the basis for food security. Their investigation of 169 regions indicated that poverty is high in Africa and South Asia. In Maxico, [5]

investigated food security in 2471 municipalities, using food supply, environmental, production, and social factors as the construct to calculate food security. From nineteen combined evaluation variables, the findings established that about 90% of all the municipalities had secure food security. In one of the high-producing cocoa communities in Ghana, Batame [13] examined the male–female household head and the quality of their food nutrition. The survey outcome revealed that male household head poverty levels were low compared to the female household heads. Likewise, in Sudan, Fadol et al. [14] affirmed that a high percentage of the population is in hunger. The empirical findings were direct to unemployment, culture, and education. They recommended that to meet the SDGs by 2030, 15 million humanitarian aid is needed. UN targets for SDGs in 2030 will not be achieved, and poverty and food insecurity will continue due to recent issues of COVID-19 and climate change.

2.2 Foreign direct investment inflow and Poverty

Foreign direct investment and economic growth have been extensively examined in the Visegrad region; nevertheless, the nexus between FDI and poverty alleviation has garnered comparatively less focus. Janjua et al. [7] contend that in the contemporary interconnected world, foreign investment and trade are fundamental catalysts of economic growth. Both the host and home nations have benefitted from FDI inflow, resulting in significant economic growth in the medium to long term. Islam et al. [10] assert that FDI inflow is an essential instrument for attaining these goals, as it fosters sustained economic growth. FDI inflow can mitigate poverty, provide access to healthcare and education, and foster environmental sustainability by introducing advanced technology, expertise, and financial capital to recipient nations. As referenced by [8], FDI inflow increases the per capita income of individuals within sub-Saharan Africa, Latin America, and Eastern European communities. The results emphasise the significant contribution of FDI inflow in the reduction of poverty among these regions. Employing the FMOLS and DOLS estimates on data from 2005–2021, Kamalu and WanIbrahim [15] examined seventeen emerging communities. The empirical investigation presented a decreasing effect of FDI inflow in these regions on poverty reduction. Besides, Goh et al. [16] stated that for Indonesia to shift poverty and improve the human capital index, FDI inflow in the form of digitalisation is the key. Chukwu et al. [9] conducted an analysis of panel data from twenty-three African economies, focusing on the affiliation between FDI inflow and poverty, as measured by the output of sectoral production. The findings revealed that the FDI inflow effect on poverty alleviation is in the short to medium term rather than a long term. They recommended that proper policies and strategies are needed to mitigate poverty in these regions.

2.3 Economic growth and poverty

Economic progress has been considered the factor through which government can calculate the impact of individuals well-being [12, 17]. Policymakers frequently encounter a nuanced equilibrium in striving for two principal aims of economic development: augmented economic growth and diminished poverty. When the per capita income of an economy is high it affiliated with reduction in the level of poverty [18]. Poverty remains a material police subject of the Visgrad region to corroborate with each other to improve their economics and reduce their poverty levels [11]. In reference to Indonesia, Junaidi

et al. [19] indicated that growth in the capital of individual through the financial intermediaries has reduced the poverty levels within the region. Utilizing robust economic approaches, Kitole et al. [20] explored economic growth in Tanzania to achieve the SDG1. The findings from the empirical outcome depicted that government spending, and economic progress are linked to alleviation of poverty between the period 1990–2022. Duan et al. [2] evaluated poverty in impoverished areas of China on a panel data from 2010–2020 on a provincial scale. The empirical outcome from the 2SLS estimator revealed that when economic progress appreciates to 7.3%, it had an affiliation of 8.4% depreciation on poverty. [21] experiment of African communities' economic growth and poverty alleviation concluded that a two-way directional nexus and a triangular affiliation between entrepreneurship, economic progress, and poverty depreciation.

2.4 Technological innovation moderating effect

Technological advancement is quite considered a key factor that helps to improve the affiliation between food security and poverty reduction. These domains have over time coined a common area as central for sustainable development, especially in the backdrop of some of the global issues, including climate change, population, and poverty [17, 22]. Many technological trends, such as digital agriculture, precision farming, and blockchain technology, among others, have been pointed out to play a very important role in boosting food security and reducing poverty levels [23]. Digital agriculture, especially using IoT, has boosted the agriculture industry through enhancement of productivity. According to [24], IoT technology improves the digital and intelligence of the grain industry, which bears strategic importance to the food security of a country. Hence, by adopting and applying these technologies, the farmers will increase their production, hence increase the availability of food, and hence reduce poverty. Sulandjari et al. [25] research indicates that providing agricultural entrepreneurs with advanced technologies significantly improves both the quantity and quality of food produced. This aligns with the findings of [26], who argues that smart farming practices can increase productivity and food security while also addressing the needs of impoverished communities. This perspective is supported by [27], who discuss the importance of Industry 4.0 technologies in achieving sustainable food security. Implementing such innovations, countries can better manage their food resources, thereby addressing both food security and poverty reduction. Therefore, technological innovation was moderated on the affiliation between poverty-food security within the Visegrad region.

2.5 Literary gaps

Indeed, the previous investigation on poverty mitigation has produced different estimates with favourable and unfavourable affiliations with FOD, FDI, ECP, POG, ING, and TIN. The literary work has emphasized that FDI inflow within community improve the economic progress through job creation, education, and health. Similar, empirical inspections have established that population growth and inflation growth are closely linked to the poverty depreciation. As such the variables are controlled in the evaluation. Again, food security and technological innovation have revealed to the way to the target of the SDG1. As such, the serial moderating effect of technological innovation was examined on the affiliation between FOD and POV reduction within the Visegrad communities. Nonetheless, different methods, samples, periods, and variables have been

Table 1 Summary of literatures on poverty reduction

Authors	Economics	Period	Econometric Method	Outcome
[5]	Mexico		Spatial analysis	FOD ↓ POV
[28]	Ethiopia	2014, 2016, 2019	Multinomial logistic regression	FOD ↓ POV
[29]	Nepal	2010–2011	3-Stage Least Square	
[8]	sub-Saharan African, Asian, Latin American and Eastern European countries	1996–2017	3-Stage Least Square	FDI ↑ POV
[19]	Indonesia	2012–2020	OLS and Fixed Effect	ECP ↓ POV
[20]	Tanzania	1990–2022	VAR, VECM, Granger causality	ECP ↓ POV
[30]	China	2012–2018	Fixed effect regression	ICT ↓ POV
[31]	Sub-Saharan Africa	2008–2019	Fixed effect, Driscoll, Two-Stage Least Square	TIN ↓ POV
[32]	China	2007–2018	General Method of Moment	TIN ↓ POV
[33]	India	2009–2010, 2011–2012	Quantile regression	ICT ↓ POV
[34]	sub-Saharan Africa	2010–2019	Dynamic System General Method of Moment	ICT ↓ POV

Note: ↓ decrease poverty ↑ increase in poverty *POV-poverty reduction, FOD-food security, TIN-technological innovation, ECP– economic growth, FDI-foreign direct investment

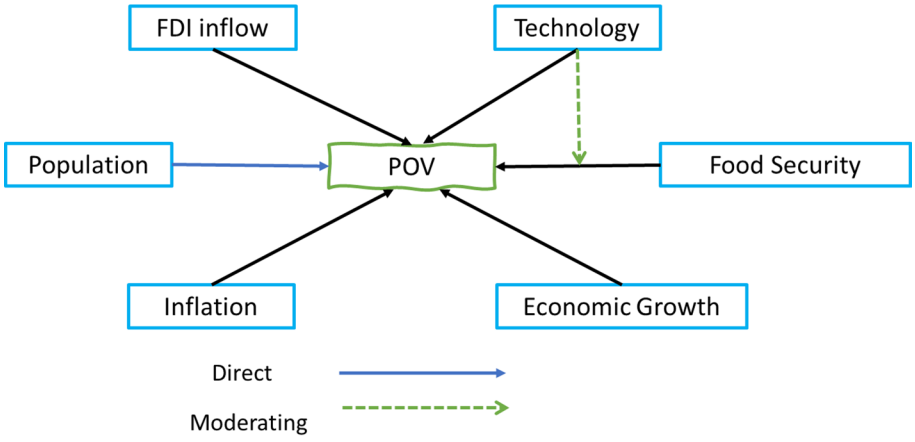

Fig. 2 Model development

employed to investigate the affiliation between these constructs. Again, literary work has been conducted in Europe to explore the determinants of ecological footprint, but not directly in Visegrad region. Additionally, robust econometric models were employed, such as the CS-ARDL, FMOLS, and D-H approaches, to evaluate a vast dataset spanning decades. Table 1 presents the literatures on the studied variables closing the gaps and illustrating the research direction for the current investigation on the affiliation between poverty reduction in the Visegrad region. Figure 2 illustrate the model technique adopted for the investigation.

3 Method and material

The inspection analysis employed annual panel data from verified websites on the Visegrad regions between 2000 to 2022. The group consist of Czech Republic, Hungary, Poland, and Slovakia, the regions were considered due to the regions policies on the formation of the Visegrad group for socio-economic development and policies align with the sustainable development goals. As expressed in the investigation of [35] indicated

that rural communities of the Visegrad region are at risk of poverty. The initial model is developed in Eq. 1.

$$POV = f\left(FOD, FDI, ECP, TIN, POG, ING\right) \tag{1}$$

To ensure uniformity and evaluation consistence, we take the logarithm of all the variables as displayed in Eq. 2. This help reduce the issues of heteroscedasticity in the data making the panel data more homoscedastic. Also, the transformation to log form reduce the problem of outliers and presenting the results in an elastic form for interpretable coefficient between the exogenous and endogenous variables. The serial moderating is presented in $Equ3$ to capture the influence of technological innovation on the poverty mitigation within the Visegrad region.

$$\begin{aligned}\mathrm{InPOV_{it}} = {} & \Omega_0 + \Omega_1 \mathrm{InFOD_{it}} + \Omega_2 \mathrm{InFDI_{it}} + \Omega_3 \mathrm{InECP_{it}} \\ & + \Omega_4 \mathrm{InTIN_{it}} + \Omega_5 \mathrm{InPOG_{it}} + \Omega_6 \mathrm{InING_{it}} + \mathcal{E}_{\mathrm{it}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{InPOV_{it}} = {} & \Omega_0 + \Omega_1 \mathrm{InFOD_{it}} + \Omega_2 \mathrm{InFDI_{it}} + \Omega_3 \mathrm{InECP_{it}} + \Omega_4 \mathrm{InTIN_{it}} \\ & + \Omega_5 \mathrm{InPOG_{it}} + \Omega_6 \mathrm{InING_{it}} + \Omega_7 \mathrm{In}\left(\mathrm{FOD^{*}TIN}\right)_{\mathrm{it}} + \mathcal{E}_{\mathrm{it}}\end{aligned} \tag{3}$$

The coefficient values are depicted as $\Omega_1 - \Omega_6$ with the white noise as $\mathcal{E}_{it}$. The time and country data are presented as $iandt$ for Czech, Hungary, Poland, and Slovakia between 2000 and 2022. POV—poverty, FOD—food security, ECP—economic progress, FDI—foreign direct investment inflow, TIN—technological innovation, POG—population growth, ING—inflation growth. The serial moderation is $\mathrm{FOD} * \mathrm{TIN}$.

3.1 Theoretical assumption

The Visegrad countries employ the Sustainable Livelihoods Framework (SLF) to address poverty and food security by leveraging human, social, physical, and financial capital [36]. The SLF's multi-faceted approach to poverty considers economic variables, social networks, resource availability, and environmental concerns. It identifies livelihood strategies based on capital endowments and external conditions, guiding initiatives to improve agricultural sustainability and productivity in the Visegrad region, ultimately improving food security. Empirical assessment has elucidated that poverty reduction and food security co-move in positive direction [37]. The development of polices on food security is anticipated to alleviate poverty in the Visegrad region. $\beta_1 = \frac{\delta_{FOD}}{\gamma_{POV}} > 1$. The Sustainable Livelihoods Framework is a crucial tool for addressing hunger and poverty in Visegrad, promoting long-term interventions and community resilience through the development of technological innovation technique. Literary works like [25] established that has affirmed that regions incorporate technology into their poverty mitigation plans depreciate the levels drastically. Technological innovation in the productivity and food supply are considered to have a positive influence in poverty reduction. $\beta_2 = \frac{\delta_{TIN}}{\gamma_{POV}} > 1$. Moreover, FDI inflow comes in as a capital inflow to improve the economic progress of the host nations. Tsaurai [3] and Sukhadolets [6] advocate that FDI inflow help in the mitigation of the poverty. Also, empirical outcome asserts that employment and human capital appreciation as associated with inflow of FDI [38]. $\beta_3 = \frac{\delta_{FDI}}{\gamma_{POV}} > 1$. Additionally, economic growth promotes the living standards of the population and per capita increase is affiliated with poverty mitigation especially from developing communities. The removing of poverty within the economy is associated with economic development

[17]. Xu et al. [39] indicated that government should implement policies that improve the per capita income. We anticipate that economic progress is favourably affiliated with poverty alleviation $\beta_4 = \frac{\delta_{ECP}}{\gamma_{POV}} > 1$. Table 2 display the variables measurement and sources adopted for the estimation the affiliation between the dependent, independent, control, and moderating effect.

3.2 Preliminary tests

The evaluation followed literary works of [41] indicated that when investigating panel data of interconnected regions, it is material to consider factors such as cross-section dependence, unit root evaluation, multicollinearity, and cointegration before selecting the econometric approach to apply to the research.

3.3 Cross sectional dependence and Slope heterogeneity

To effectively simulate interactions among variables with interdependencies across regions, panel data analysis of cross-sectional dependence tests was employed. These CSD exits when the elements of language, culture, migration, and geographical affiliation among the Visegrad communities. Second-generation unit root tests must be utilised for panel data exhibiting cross-sectional dependence, as first-generation tests may yield misleading results. To address variations in individual unit behaviour, appropriate econometric techniques, such as fixed or random effects models, may be employed when heterogeneity among cross-sectional units is acknowledged. We employed three sections of [42, 43], and [4] to develop the mathematical evaluation as displayed below.

$$CSD = \sqrt{\frac{2T}{M(M-1)}} \left(\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sigma_{ij}^{t} \right) \tag{4}$$

3.4 Slope heterogeneity.

To enhance and reduce the cross-sectional environment of the outcome and expound the slop coefficient of the variables result, the slop heterogeneity was adopted. The econometric approach in Eq. 5–6 was developed to inspect this slop parameter.

$$\widetilde{\Delta}\mathrm{SHT} = (M)^{\frac{1}{2}} (2K)^{\frac{-1}{2}} \left(\begin{matrix} 1 \\ M \end{matrix} \widetilde{S} - K) \right) \tag{5}$$

$$\widetilde{\Delta}\mathrm{ASHT} = (M)^{\frac{1}{2}} \left(\left(\frac{2k(T-k-1}{T+1} \right)^{\frac{-1}{2}} \right) \left(\begin{matrix} 1 \\ M \end{matrix} \widetilde{S} - K) \right) \tag{6}$$

Table 2 Variables evaluations

	Source	Acronyms	Measurement Unit
Poverty	[40]	POV	Poverty headcount ratio at societal poverty line (% of population)
Food Security	[40]	FOD	Food production index (2014–2016 = 100)
Economic growth	[40]	ECP	GDP growth (annual %)
Foreign direct Investment	[40]	FDI	Foreign direct investment, net inflows (% of GDP)
Population growth	[40]	POG	Population growth (annual %)
Inflation	[40]	ING	Inflation, consumer prices (annual %)
Technological innovation	[40]	TIN	Proportion of medium and high-tech industry value added in total value added of manufacturing

3.5 Unit root

The assessment instigated various evaluation techniques to check for the stationarity test in the panel data. As illustrated in the cross-sectional dependence outcome, the second-generation unit root of CIPS and CADF was applied in the research. Several investigations have confirmed that CADF and CIPS tests are material for making sure the variables being examined are stationary, which helps to prevent erroneous regression results [41, 44]. The researchers employed the second generational unit test due to the regional affiliation between the Visegrad region which may lead to issues of stationarity in the variables. Also, type 1 error which is associated with traditional unit root (IPS and ADF) estimations are reduced providing a more reliable results for econometric analysis and policy implementations. On food security 39 employed the second-generational unit root with small sample size like our studies.

$$CADF = \gamma x_{it} = \alpha_{it} + \beta_{it-1} + \delta_I T + \sum_{j=1}^{M} \gamma_{ij} \gamma x_{it-j} + \varepsilon_{it} \tag{7}$$

γ denote the inconsistencies among the constructs, x_{it} simulates the variables inspected.

$$CIPS = \frac{1}{M} \sum_{i=1}^{M} \varphi_i \left(M, T\right) \tag{8}$$

3.6 Panel cointegration

The Westerlund cointegration test is a robust methodology for assessing long-term relationships in panel data, particularly when addressing issues of cross-sectional dependence and heterogeneity among units. The [45] test offers various specifications, such as the Ga and Gt methods for heterogeneous slope coefficients, and the Pa and Pt methods for homogeneous coefficients to evaluate the long-term affiliation among the constructs. The equations are displayed as.

$$G_\tau = \frac{1}{M} \sum_{i=1}^{M} \frac{\eta_i}{S.E(\widehat{\eta_i}} \tag{9}$$

$$G_a = \frac{1}{M} \sum_{i=1}^{M} \frac{T\eta_i}{1 - \sum_{j=1}^{k} \widehat{\eta_{ij}}} \tag{10}$$

$$P_\tau = \frac{\widehat{\eta_i}}{S.E(\widehat{\eta_i})} \tag{11}$$

$$P_a = T\eta_i \tag{12}$$

Here the mean for the group assessment is depicted by t $(G_T - G_a)$ and the co-integration is donated by $(P_T - P_a)$.

3.7 Regression advocate

The application of the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model in estimating long-term nexus variables such as poverty, food security, FDI inflow, technological innovation, economic growth, and population growth is

particularly advantageous due to its ability to address cross-sectional dependence and heterogeneity inherent in panel data. The CS-ARDL model, developed by [46] extends the typical ARDL framework to accommodate these complexities, providing more reliable estimates of both short-run and long-run elasticities [41, 44]. This model is especially relevant in contexts where the relationships among the variables are expected to vary across different cross-sectional units, allowing for a more nuanced understanding of the dynamics and interaction effects. To ensure the findings are robust and reflective of the underlying economic realities, thereby enhancing the policy implications derived from such analyses the CS-ARDL was employed to evaluate the long-term affiliation between poverty, food security, FDI inflow, technological innovation, economic growth, and population growth in the Visegrad region.

$$\Delta POV_{it} = \varphi_{it} + \sum_{j=1}^{n} \varphi_{it} POV_{i,t=j} + \sum_{j=0}^{n} \backprime \varphi_{it} X_{i,t=j} + \sum_{j=0}^{1} \backprime \varphi_{it} \overline{Z}_{i,t=j} + \mu_{it} \tag{13}$$

$\overline{Z}_t = (\Delta POV_{it}, \overline{Z}_t)$ Comprises the CST mean average and its components X_{it} Exhibit the distinctiveness of individual independent variables $FOD, FDI, ECP, TIN, POG, ING.$

3.8 Model selection justification

In order to calculate results on the affiliation between FOD, FDI, ECP, POG, ING, and TIN on POV we employed the CS-ARDL. Previous literary work of Zheng et al. (2025) research the BRICS economy adopting CS-ARDL technique with limited sample size and years. However, the dynamic common correlated effect was utilized as a robustness check. Similarly, Segbefia et al. (2023) investigated food security within the regions of Nigeria, Ghana, Kenya, Zimbabwe, and Tanzania for the period 1990–2021. The researchers used the CS-ARDL model and checked it the AMG and CCE-MG technique. In addition to the CS-ARDL model, we applied the Pool Mean Group (PMG) as sturdiness check to account for the limitation in the panel data set of this research just as previous literatures. The PMG technique can hand both short and long run estimation when the data have issues of cross-sectional dependency, endogeneity, and slope heterogeneity just like our study (Klomp and Haan, 2013).

3.9 Granger causality

Though the CS-ARDL technique accounts for the long- and short-term changes in the variables and the adjustment speed, the direction of influence of one variable to another is not properly explained. The [47] causality test is a robust statistical method used to investigate causal relationships in panel data, particularly when addressing cross-sectional dependence among units. This test allows for heterogeneous coefficients across different cross-sections, making it suitable for diverse economic contexts. The econometric equation is present below.

$$Y_{it} = \alpha_i + \sum\nolimits_{m=1}^{M} \psi_i^m, Y_{i(m-t)} + \sum\nolimits_{m=1}^{M} \lambda_i^m, Z_{i(m-t)} \tag{14}$$

Such that m illustrates the segment of the lag, ψ_i^m displays the model's autoregressive.

Table 3 Descriptive statistics

	POV	FOD	TIN	FDI	ECP	POG	ING
Mean	12.504	97.148	43.739	6.958	3.124	−0.071	3.675
Median	12.550	96.885	45.625	4.077	3.568	−0.043	2.852
Maximum	22.500	116.250	59.446	106.498	10.832	1.571	15.100
Minimum	5.900	74.660	26.078	−40.085	−6.597	−2.489	−0.874
Std. Dev	3.385	8.284	8.943	16.004	3.015	0.438	3.364
Skewness	0.122	0.019	−0.289	3.421	−1.045	−1.907	1.588
Kurtosis	2.824	3.004	1.914	20.782	4.907	15.754	5.642
Jarque–Bera	3.345	4.605	5.805	1391.735	30.701	679.278	65.411
Prob	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VIF	2.566	1.305	2.204	1.499	1.849	2.838	1.944

Table 4 Cross sectional dependence

	Pesaran Scaled L-M	Breusch-Pagan L-M	Bias-Correlated Scaled L-M
POV	4.192 (0.000)	21.435 (0.000)	4.456 (0.000)
FOD	6.723 (0.000)	49.778 (0.000)	12.638 (0.000)
FDI	11.294 (0.000)	45.123 (0.000)	6.493 (0.000)
ECP	9.998 (0.000)	40.634 (0.000)	6.089 (0.000)
POG	9.480 (0.000)	38.840	6.119 (0.000)
ING	10.286 (0.000)	41.632 (0.000)	6.089 (0.000)
TIN	6.983 (0.000)	30.188 (0.000)	5.059 (0.000)

4 Empirical results

As encapsulated in Table 3 the descriptive estimation and the multicollinearity (variance inflation factor—VIF) to check for the variable's average means, normality and independence. The mean value estimates are POV (12.504). The implication is that the Visegrad communities' poverty alleviation is at low. This is attribute to the current polices imitated in the region policy. For instance, Czech Republic achieve a lowers poverty rate stand at a point of 7.4% and the Slovakia at a point of 12.5% establishing the regions desire to achieve a sustainability development gaol 1. Additionally, food security had a mean average of 97.148, the results implied that Visegrad communities can meet their food security target at the rate of 97.148 in the SGD1 target. Similarly, technological innovation had a mean figure of TIN (43.739), the implication is that Visegrad communities can developed innovation targeting at food security and poverty depreciation at a rate of 43.7%. Again, other mean values are as follows FDI (6.958), ECP (3.124), POG (– 0.071), and ING (3.675). furthermore, the variables skewness and kurtosis indicate that the variables have no outliers and as such provide the basis for significance interpretation and further research. To ensure the variables are not multicollinear, the VIF estimation values are affirm in literary work of [48] and [41] depicting that the values are less than 5 as a rule of thumb. Therefore, the variables of POV, FOD, FDI, ECP, POG, ING, Causality outcome and TIN findings indicates that no multicollinearity exits among them.

4.1 Cross sectional dependence

To ensure that the indicators studied here are independent, we employ cross-section and slop heterogeneity tests. [42, 43] and [49] results are displayed in Table 4, along with their corresponding significance levels. Due to its great significance, the distribution shows that it is independent. Furthermore, the interconnection between the indicators

Table 5 Panel unit root

	CADF		CIPS	
	Level	**1st Difference**	**Level**	**1st Difference**
POV	−0.416 (0.339)	53.315 (0.000)	−0.154 (0.439)	−5.859 (0.000)
FOD	−1.506 (0.066)	−7.594 (0.000)	−2.361 (0.009)	−15.400 (0.000)
FDI	−4.771 (0.000)	−7.359 (0.000)	−4.609 (0.000)	−14.182 (0.000)
ECP	−5.017 (0.000)	−7.914 (0.000)	−5.024 (0.000)	−16.639 (0.000)
POG	−0.368 (0.357)	−2.520 (0.006)	−1.174 (0.120)	−4.528 (0.000)
ING	−0.056 (0.478)	−2.785 (0.003)	−0.391 (0.348)	−2.389 (0.009)
TIN	0.227 (0.589)	−5.974 (0.000)	−0.003 (0.499)	−7.172 (0.000)

Value in () are significance levels

Table 6 Panel cointegration evaluation

	Z-statis	***P* value**
G_T	−7.456***	0.000
G_a	2.841	0.349
P_T	−9.223***	0.000
P_a	3.907	0.753

*** display the significance level @ 5%

and the variables that depend on them is shown by the slope heterogeneity. The favourable levels of independent and dependent affiliation across the variables are highlighted by the Δ^ and Δ^adjusted.

4.2 Panel unit root

To ensure the variables are stationary in the panel, the two most verifies second generational unit root test of CIPS and CADF was employed. Table 5 illustrated outcome of the order level for POV, FOD, FDI, ECP, POG, ING, and TIN within the Visegrad regions. The outcome estimation shows that FDI and ECP were at I (0) for all the two evaluations. The results depicted that all the parameters were in the first order I (1) for the two estimations of CIPS And CADF. This affirms for long-term co-movement of the variables in the Visegrad region.

4.3 Panel cointegration evaluation

To confirm a long-term affiliation between poverty, food security, FDI, economic growth, population growth, inflation growth, and technological innovation between Visegrad areas, the inquiry goes through a cointegration evaluation of Westerlund assessment (Table 6). There was a long-term nexus and cointegration between the variables throughout the research period, as indicated by the cointegration coefficient and P-values Gτ and Pτ. The next step was to employ the CS-ARDL model to assess the variables affiliation. We employed the cointegration test of Kao (1999) as a diagnosis estimation for Westerlund cointegration considering the insignificant p. values which may affect the long run estimation and model selection. Table 7 present Kao outcome of long run cointegration between the dependent variable (POV) and independent variables (FOD, FDI, ECP, POG, ING, and TIN). The probability values for all statistics are significantly less than 5%, providing a sturdiness evidence of cointegration. The estimation outcome established a strong evidence of cointegration among the variables, as all the test statistics (Modified Dickey–Fuller t, Dickey–Fuller t, Augmented Dickey–Fuller t,

Table 7 Kao cointegration

Series	Statistics	Probability values
Modified Dickey–Fuller t	− 18.045	0.000
Dickey–Fuller t	− 22.237	0.000
Augmented Dickey–Fuller t	− 12.888	0.000
Unadjusted modified Dickey–Fuller t	− 34.069	0.000
Unadjusted Dickey–Fuller t	− 25.435	0.000

Table 8 CS-ARDL model estimation

	Model 1		Model 1 (Moderating -TIN)	
	Coeff	Stand.Error	Coeff	Stand.Error
Long-term				
FOD	0.296***	0.126	0.548***	0.241
FDI	0.614***	0.145	0.488***	0.171
ECP	− 0.426*	0.268	− 0.275*	0.103
POG	0.081***	0.011	0.069***	0.018
ING	− 0.310***	0.123	− 0.029**	0.009
TIN	0.403***	0.169	0.537***	0.223
FOD*TIN->POV	–	–	0.762***	0.289
Short-term				
FOD	0.720***	0.283	0.542***	0.141
FDI	0.534***	0.164	0.714***	0.293
ECP	− 0.410***	0.109	0.311***	0.088
POG	0.016***	0.005	0.131***	0.031
ING	− 0.122***	0.041	− 0.139***	0.067
TIN	0.376***	0.171	0.476***	0.154
FOD*TIN->POV	–	–	0.681***	0.176
ECT (− 1)	− 0.519	0.000		

Note: *, **, *** illustrates at 10%, 5%, 1% respectively

Unadjusted modified Dickey–Fuller t, and Unadjusted Dickey–Fuller t) are significantly negative and accompanied by probability values close to zero.

4.4 CS-ARDL estimation

Table 8 presented the econometric evaluation of the cross-sectional augment distribution lag after confirming the results from the cointegration test. The outcome in the findings include the long and short run estimates on POV, FOD, FDI, ECP, POG, ING, and TIN (see model 1 and 2). As illustration in Table 6, the findings show that in the long and short term FOD had a favourable material influence on poverty reduction in the Visegrad community. For instance, 1% appreciation in food security cause a 29.6% and 72% depreciation in poverty within the Visegrad region. The findings support the investigation work of [48] assessment of food security within selected African regions. They recommend that proper food security policies and human capital development can reduce waste of food and improve the livening standard of the populace. This was affirmed in [14] experiment in Sudan employing the integrated food security phase classification. The outcome established that inflation, lack of money, and unemployment contribute significantly food insecurity.

In addition, the investigation delved into the influence of foreign direct investment inflow on poverty reduction. The empirical outcome indicated positive material effect of FDI on POV. With a Coeff figure of 0.614 (61.4%) in the long term and 0.534 (53.4%)

in the short term among the Visegrad region (see Model 1). The inspection highlight is that FDI inflow into the region help to improve the alleviation of poverty. The results support the pervious literary work of [10] and [7] that FDI inflow can mitigate poverty, provide access to healthcare and education, and foster environmental sustainability by introducing advanced technology, expertise, and financial capital to recipient nations. Chukwu and Adewuyi [9] analysed panel data from twenty-three African economies, examining the correlation between FDI influx and poverty, as indicated by sectoral production output. The findings indicated that the impact of FDI influx on poverty reduction is observed in the short to medium term rather than in the long run.

On the evaluation between evaluation between economic progress and poverty reduction, the CS-ARDL outcome shows an inverse affiliation between ECP and POV. With 1% appreciation in the economic progress cause an uprise in 0.42.6% and 41% in the poverty rate for long and short term respectively (model 1). The Visegrad region have the most rural population with populace living below the minimum wage rate. Though the economy is stable, high rent cost and electricity affect the standard of living. Duan and Liu [2] assessment of China rural poverty alleviation indicated that funding for poverty reduce the level by 8.4% and contribute to the appreciation of economic development by 7.3%. Similarly, in the context of 42 region in Sub-Saharan Africa, Asongu and Eita [50] empirical investigated the nexus between economic growth and poverty for the period 1980–2019. Employing the robust quantile regression the research depicted that poverty and inequality distribution of income is tired to economic growth. Therefore, to meet SDG1 target by 2030, Visegrad much direct resources and policies to improve the living standards of the population through adoption of renewable energy and technologies to improve the rural economy and the agricultural sector.

Again, in model 1TIN had a material affiliation in the depreciating the rate of poverty in the Visegrad communities. With a 1% upsurge in TIN resulted in a 40.3% and 37.6% decrease in POV rate in the long and short term respectively. Literary work has indicated that technological innovation boosts the productivity of economy and aid in the decreasing of poverty [23]. Therefore, Visegrad region can decrease their poverty rate by employing technological approaches in the form digital agriculture with the introduction of IOT in the production of lines. Similarly, in the context of 31 provinces in China, [51] indicated that financial technologies can help improved in the poverty levels in the provincial poverty reduction programs. The serial moderating role of TIN on the affiliation between POV and FOD was presented in Table 8 model 2. The empirical findings from the CS-ARDL estimation show that TIN had a positive moderating effect on the affiliation between FOD and POV. With a Coeff value of 76.2% and 68.1% for the long and short term respectively (FOD*TIN- > POV). The implication is that Visegrad communities can improve their food security and reduce poverty levels through the adoption of technological innovation practises [48]. Sulandjari [25] research indicates that providing agricultural entrepreneurs with advanced technologies significantly improves both the quantity and quality of food produced. With the EU green deal project and adoption innovative approaches Visegrad region can developed technologies that will improve the production of agricultural produce and limit waste and resources. Prior evaluation work in Nigeria on process innovation and sustainable poverty depreciation through the ARDL model estimation indicated that both the long- and short-term poverty level was decreased through efficient implementation of process innovation into food security

[22]. Likewise, Susan et al. [52] investigated 153 regions for the period 2016–2020 on the nexus between technology and poverty reduction. The empirical estimation affirmed that technology innovation served the catalyst to reducing poverty in African and Asian regions. Finally, the R square value of 0.564 (56.4%) indicates the extent to FOD, FDI, ECP, POG, ING, TIN explain POV. The speed at which the variable adjusts from the short term to the long term is 51.9%. The implication revealed that for Visegrad region to meet the poverty reduction rate, the region must have adjusted speed at 51.9% to the on a stable and normal level.

4.5 Robustness test of full modified ordinary least square (FMOLS)

To ensure the robustness of the econometric model of CS-ARDL, the PMG-ARDL technique was employed to validate it. In reference to Shashwat et al. (2025) PMG help to deal with heterogenous in cointegration. The results illustrated in Table 9 affirms the empirical results of CS-ARDL techniques. However, economic progress had a positive favourable affiliation with poverty reduction in Visegrad region.

4.6 Panel granger causality

This step of the research presented the causal affiliation between each regressor (FOD, FDI, ECP, POG, ING, TIN) with POV (see Table 10, and Fig. 3). The findings from the D-H investigation highlighted that FOD, FDI, POG, and TIN had a unidirectional influence on POV. The implication is that FOD, FDI, POG, and TIN can be employed as a catalyst to depreciation the level of poverty in the Visegrad communities. The inspection has material significance for government and other stakeholders in the development of strategic polices in the alleviation poverty within the region. Likewise, the causal affiliation served as a guide in the allocation of resources and investment needs to achieve the SDG1 by 2030. However, ECP and ECP displayed a bidirectional nexus with POV. Though, economic progress has been seen to be tired to improve in the living standards, this was not so in the investigation. Again, inflation growth in the Visegrad region have

Table 9 Pool Mean Group (*PMG-ARDL– Poverty)*

	Model 1		Model 1 (Moderating -TIN)	
	Coeff	Stand.Error	Coeff	Stand. Error
Long-term				
FOD	0.210	0.061	0.198	0.141
FDI	0.501	0.219	0.645	0.033
ECP	0.259	0.138	0.328	0.053
POG	0.080	0.697	0.069	0.045
ING	−0.170	0.137	−0.214	0.151
TIN	0.501	0.104	0.643	0.079
FOD*TIN-> POV	–	–	0.728	0.021
Short-term				
FOD	0.12	0.086	0.188	0.068
FDI	0.169	0.112	0.356	0.020
ECP	0.046	0.488	0.107	0.172
POG	0.018	0.071	0.027	0.009
ING	−0.026	0.082	−0.113	0.047
TIN	0.534	0.042	0.563	0.034
FOD*TIN- > POV	–	–	0.541	0.011
ECT (− 1)	−0.519	0.000		

Note: *, **, *** illustrates at 10%, 5%, 1% respectively

Table 10 Dumitrescu-Hurlin (D-H) causality outcome

Hypothesis	W-Statis	Z-Statis	Prob Value	Outcome
$FOD \neq POV$	5.489 ***	2.453	0.0151	Unidirectional
$POV \neq FOD$	2.648*	0.274	0.784	
$FDI \neq POV$	5.071***	2.111	0.004	Unidirectional
$POV \neq FDI$	2.253*	0.024	0.980	
$ECP \neq POV$	6.280***	3.761	0.000	Bidirectional
$POV \neq ECP$	9.160***	5.095	0.000	
$POG \neq POV$	21.292***	14.403	0.000	Unidirectional
$POV \neq POG$	4.188*	1.441	0.149	
$ING \neq POV$	5.874***	2.719	0.006	Bidirectional
$POV \neq ING$	7.090***	3.641	0.000	
$TIN \neq POV$	5.019**	2.075	0.038	Unidirectional
$POV \neq TIN$	2.320*	0.026	0.978	

Note: Note: *, **, *** illustrates at 10%, 5%, 1% respectively

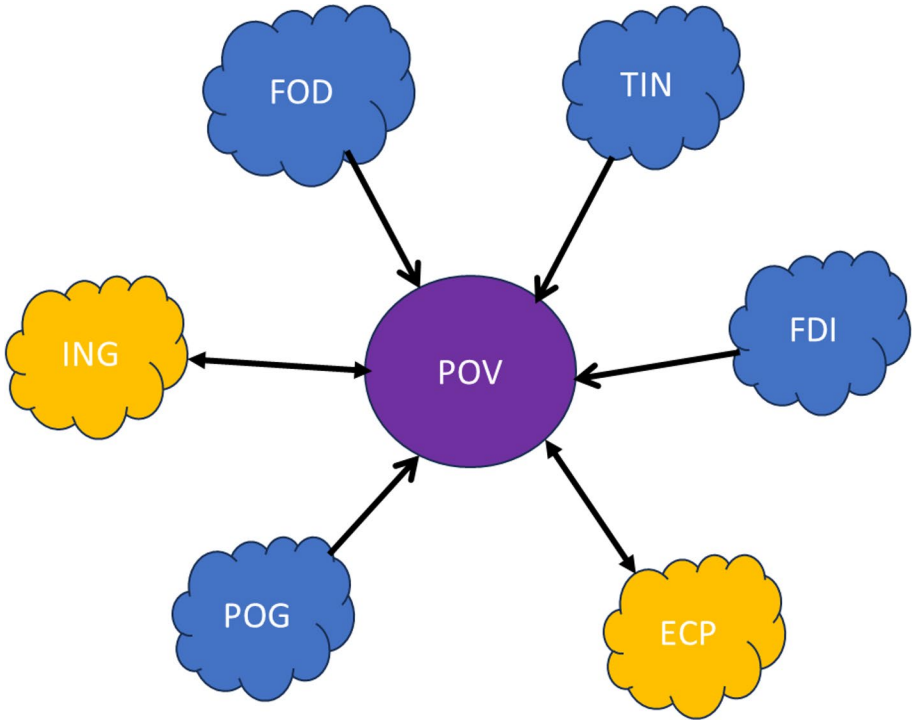

Fig. 3 Causality outcome

been appreciation after the Covid-19 pandemic which the findings of this research provide governments the strategic resources to developed policies for the region.

5 Conclusion

The research evaluated the affiliation between food security, foreign direct investment inflow, economic progress, population growth, inflation growth, and technological innovation on poverty reduction. Employing panel data from 2000–2022 on Visegrad region, with the econometric model of CS-ARDL technique and the Dumitrescu-Hurlin causality test. To ensure the reliability and validity of the evaluation, the preliminary assessment of cross-sectional dependence, unit root, and cointegration test. (a) The findings from the econometric model of CS-ARDL technique indicate that FOD, FDI, POG, and TIN had a material

significance in the mitigation of poverty in the Visegrad communities. (b) However, ECP and ING were found not to improve in the depreciation of the level of poverty. (c) Additionally, a serial moderating effect was identified on the influence of TIN on the affiliation between FOD and POV reduction (FOD*TIN->POV). (d) Finally, FOD, FDI, POG, and TIN had a unidirectional flow to POV. Also, a bidirectional flow was identified in ECP and ING to POV.

The evaluation has discovered the significance of the SLF theory in the mitigation of poverty within the Visegrad region by 2030 to meet the SDG1 target. The theory emphasis the role of human resources, financial capital, and social concerning in addressing food security taken into the environmental sustainability. The SLF theory suggests the integration of innovative methodologies in the depreciation of poverty through digital agriculture, AI in food production and storage. The outcome discovered that food security had material significance in the poverty alleviation journey within the Visegrad communities. To attain the sustainability development gaol 1, Visegrad region (Czech, Hungary, Poland, and Slovakia) should give prior polices importance in the production of food. Government and other institutions should support rural populace with the necessary tools and equipment to increase in the productivity output. Also, governments should provide subsides and incentives for rural communities where poverty rate is below the six dollars a day. As agriculture is considered a significance role in the creation of jobs and income generation for rural communities. On the relationship between FDI inflow and poverty reduction, the findings from the CS-ARDL model established a favourable positive affiliation and a unidirectional causality. The findings highlight that Visegrad region can reduce the levels of poverty with the inflow of FDI received to the region. These inflows can be directed to development of innovative technologies such as renewable energies, digital agricultural tools, and improve the infrastructure in the rural communities. The outcome from the investigation has significant suggestions for Visegrad region on the mitigation of poverty. First, the findings shows that food security is a material component to achieving zero poverty and meeting the sustainable development goals by 2030. Therefore, Visegrad region should invest in food security production within the rural communities where poverty is high. Also, there should be education on food security and food supply chain, to reduce waste during food abundance. Government and institutions should invest in food processing which create sustainable job. Secondly, the findings indicated that FDI inflow had a favourable affiliation in the depreciation of poverty levels. The recommendations are that government should provide tax holiday and subsides for foreign enterprises that wants to operate within the Visegrad region. Again, government should make polices that will shift these enterprises to the rural and disadvantage communities where the impact will be visible. Third, the empirical results illustrate that technological innovation had a favourable moderating effect on the nexus between food security and poverty reduction. The inspection recommends that policymakers in Visegrad region should emphasize investments in technological advances that economically empower women and enhance agricultural productivity. Governments can enhance regional knowledge inputs, crucial for fostering technological progress, by establishing a conducive environment for research and innovation. Integrating technological solutions with governance enhancements, government can realise a more efficacious framework for addressing poverty and other manifestations of poverty. Moreover, given that innovation predominantly pertains to spatial dynamics, it is evident that tailored solutions reflecting the unique characteristics of each Visegrad nation are necessary. Policymakers must collaborate to leverage each nation's assets to address deficiencies in innovation capacity. This collaborative approach can support

the realization of enhanced methods for poverty alleviation through knowledge exchange and the promotion of best practices.

We recommended the following suggestion from the findings of the research and according to the Visegrad report in 2021 for each nation on their poverty and food security. While the Visegrad region shares common goals in poverty alleviation and food security, their diverse institutional approaches reflect tailored responses to national contexts. These differences highlight the necessity of considering institutional variations in designing and implementing effective poverty reduction strategies. For poverty reduction policies (a) The Czech government should implement measures to combat rapacious lending practices, including legal reforms to reduce personal debt to alleviate public debts. These efforts will help contributed to low unemployment and poverty rates, positioning the Czech Republic as one of the least indebted European nations. (b) For Poland the government should improve the financial support programs (Dobry Start) offering a lump sum for each child at the start of the school year. These initiatives will boost birth rates, improve quality of life, and reduce poverty. (c) With the high inflation in Hungary, we recommend that government should continue to improve on the cap on profit margins on essential food items, aiming to protect consumers from escalating costs. Lastly, the study's findings suggest that Slovakia should implement various family policies, including birth prizes, parent subsidies, and child allowances, to combat population decline and support working families. On food security within the Visegrad region, the regions exiting policies on joint agriculture projects to collectively address food security concerns by engaging in joint declarations and negotiations within the framework of the European Union's Common Agricultural Policy (CAP). These collaborations will help to secure favourable financing and reforms to enhance food security across the region.

5.1 Limitations and further studies

As encapsulated in the research, the outcome has some limitations that need to be addressed in future studies. First, the investigation and data were limited to the Visegrad region, which makes its applicability in different regions judgmental. Future studies could do comparative research with the Visegrad region and MENA regions. Again, the evaluation didn't consider individual country poverty mitigation separately, which may have shown the difference in the poverty mitigation outcome in each county. Future investigation can be done on individual nation datasets to determine their poverty levels. Furthermore, future research could explore ways to mitigate poverty in the Visegrad region, focusing on variables such as human capital, financial development, and climate change. Also, the research employed CS-ARDL and the second generational unite root estimates. These method has bias as the research data set and country was limited making the outcome and implementation challenging. Nevertheless, the findings of the research have significant policy and theoretical contributions to the sustainable development goals set for 2030.

Author contributions

Takyi and Mikeska: Conceptualization, Writing—original draft, Writing—review & editing, Data curation, Methodology, Resources, Formal analysis. Gavurova - review & editing, and Supervision.

Data availability

Data is provided within the manuscript. All data use for this research are publicly opening available at www.worldbank.org.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors reviewed and approved the manuscript for publication.

Competing interests
The authors declare no competing interests.

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