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The Impact of Militarization and Industrialization as a Threat to Sustainable Environmental Development in NATO Countries

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ABSTRACT

There has been an increase in defense investment in recent years, which makes it necessary to investigate its impact on environmental degradation. This study examines the long-term relationships between militarization, industrialization, and environmental degradation as a risk factor and threat to sustainable environmental development in NATO countries over the long term, from 1995 to 2018, within the framework of the environmental Kuznets curve. Using the PMG-ARDL method, the study reveals that military spending, industrialization, and energy consumption have a significant and positive impact on environmental degradation, which hinders sustainable environmental development. The environmental Kuznets curve is valid in NATO countries. The analysis of the long-term relationship between the variables reveals a positive relationship between military spending and CO_2 emissions. Results from the PMG-ARDL test indicate that militarization, industrialization, and energy consumption have a positive and significant long-term impact on environmental degradation. In contrast, urbanization is found to have a negative and significant effect on environmental degradation. These results underscore the need for policymakers to adopt integrated strategies that align militarization and industrialization policies with environmental objectives and support sustainable environmental development.

1 | Introduction

In recent years, there has been an increase in defense investment, making it necessary to review its impact on environmental degradation. States tend to strengthen their military capacity by allocating a significant portion of their national income to military expenditures (Dunne and Perlo-Freeman 2003; Abbas et al. 2020) to protect their sovereignty against traditional security threats such as war, armed conflict, and terrorism (Art 1980). According to the Stockholm International Peace Research Institute (SIPRI), global military expenditures reached \$2.443 trillion in 2023, marking a 6.8% increase compared to

Abbreviations: ARDL, autoregressive distributed lag; CCEMG, common correlated effects mean group estimator; CCR, canonical cointegrating regression; CIPS, cross-sectionally augmented Im, Pesaran, and Shin; CS-ARDL, cross-sectional augmented autoregressive distributed lag; CSD, cross-sectional dependence; DH, Durbin Hausman; DOLS, dynamic ordinary least square; DOLSMG, the mean group dynamic least square; EKC, environmental Kuznets curve; FE, fixed effect; FMOLS, fully modified ordinary least square; GMM, generalized method of moments; ICT, ınformation and communication technology; NARDL, nonlinear autoregressive distributed lags; NATO, North Atlantic Treaty Organization; OLS, ordinary least square; PARDL, panel autoregressive distributed lag; QQ, quantile-on-quantile; QR, quantile regression; SIPRI, Stockholm International Peace Research Institute; STO, Science and Technology Organization.

the previous year. The world military burden—defined as military spending as a percentage of global gross domestic product (GDP)—rose to 2.3% in 2023 (SIPRI 2024). NATO, which mainly comprises highly industrialized and technologically advanced countries, holds a significant share in global military expenditures. The 31 NATO countries collectively allocated $1341 billion to military spending, representing 55% of global military expenditures in 2023. Moreover, all NATO member states increased their military expenditures except for Greece, Italy, and Romania. In 2014, NATO members committed to allocating 2% of their GDP to defense spending by 2024. Later, this target was revised to a minimum of 2% of GDP in 2023 (SIPRI 2024) and finally to 5% in 2025 (NATO 2025). This is expected to facilitate the allocation of additional funds to the defense industry, thereby providing an opportunity for the alliance to further strengthen and optimize its defense industrial infrastructure capacity.

While states pursue increasing military expenditures in response to military threats, there is a growing debate on whether these strategies contribute to new security challenges, such as environmental degradation. Many studies (e.g., Asongu and Ndour 2023; Uddin et al. 2024; Husnain and Ali 2023; Chang et al. 2023; Zhu et al. 2023; Qayyum et al. 2021; Pata et al. 2023) have demonstrated a positive relationship between military expenditures and environmental degradation. Additionally, Clark and Jorgenson (2012) emphasize that the organization, technologies, armaments, and operations of the military may lead to environmental problems. Military activities such as armed conflicts and wars cause environmental pollution through the use of chemicals, herbicides, and radiation (Qayyum et al. 2021). Metal residues resulting from military activities contaminate soil and water, posing threats to human, animal, and plant health (Skalny et al. 2021). Coyne et al. (2025) highlight that the fuels and explosives used in military operations contribute to air pollution. For instance, in the Russia–Ukraine war, the targeting of critical infrastructure has released toxic substances, causing severe environmental problems, while the increasing number of forest fires, habitat loss, and polluted natural resources have disrupted the ecological balance (Leal Filho et al. 2024; Zhu et al. 2024). Çolak et al. (2023) warn that NATO, as a strong military alliance composed of major industrial arms producers and high defense spending states, poses a risk of environmental harm. NATO's total military carbon footprint increased from 196 million metric tons of CO_2 equivalent in 2021 to 226 million metric tons in 2023. The alliance's annual average military carbon footprint—205 million metric tons—surpasses the total greenhouse gas emissions of many individual countries. If NATO's armed forces were considered a single country, they would rank as the 40th largest carbon emitter in the world (Lin et al. 2023).

At a time when environmental concerns are rising globally (Cutcu et al. 2025), NATO stands out as an international actor that has placed environmental security on its agenda. Key outcomes of this policy include the recognition of climate change as a security challenge for the first time in the 2010 Strategic Concept; the establishment of the NATO Science and Technology Organization (STO) in 2012 to promote and conduct scientific research in various fields, including environmental issues; and the declaration by NATO leaders at the 2014 Wales Summit that NATO would "continue to work to improve the energy efficiency of our military forces significantly." This commitment was followed by adopting the Green Defense Framework and implementing the Climate Change and Security Action Plan in 2021. NATO's Green Defense Framework aims to reduce the environmental impact of military operations and defense activities while promoting sustainability. It includes various strategies and practices to address environmental challenges—among them, the integration of circular economy principles to reduce waste, maximize resource efficiency, and extend the lifecycle of military assets. By applying circular economy practices, such as repair, reuse, and recycling within defense logistics and procurement processes, NATO contributes to minimizing its environmental footprint without compromising operational effectiveness. In their study, Molina-Moreno et al. (2019) emphasized the importance of adopting circular economy principles in the defense industry of NATO countries, which would mandate minimizing natural resource extraction and maximizing waste reduction. The Climate Change and Security Action Plan of 14 June 2021 (NATO 2021) outlines how NATO will respond to the potential threats posed by climate change to military operations, bases, and overall operational capacity, and it specifies NATO's steps. By recognizing climate change as a security issue, the action plan seeks to enhance NATO's existing strategies and implement collective measures to mitigate the security impacts of climate change. In line with this objective, the NATO Climate Change and Security Centre of Excellence (CCASCOE) was established in 2024 to advance the alliance's efforts in addressing climate-related security challenges.

NATO's prominent role in global military spending, combined with its stated commitment to environmental protection, may appear contradictory. At this juncture, it is essential to examine whether military and industrial activities within NATO member states contribute to environmental degradation. Considering the emission-reducing effects of green defense (see Bellingeri et al. 2024; Ahmad 2024), examining NATO's initiatives in this area becomes even more significant. Such an assessment is critical to understanding whether NATO can effectively balance environmental sustainability with its military security objectives.

This study examines the long-term relationships between militarization, industrialization, and environmental degradation as a risk factor and threat to sustainable environmental development in NATO countries over the long term, from 1995 to 2018, within the framework of the environmental Kuznets curve (EKC). Due to data limitations, the analysis includes only 15 of NATO's 32 members: Germany, the United States, Belgium, the United Kingdom, Türkiye, Denmark, France, the Netherlands, Italy, Spain, Canada, Hungary, Norway, Poland, and Portugal. These relationships were examined using the PMG-ARDL panel method. The PMG-ARDL approach rests on the assumption that, while the units forming the panel may exhibit different economic behaviors in the short term, they display similar long-term patterns. This method was selected because it is suitable for small samples and is flexible regarding variables with different levels of stationarity (Loayza and Rancière 2006). Economic growth, urban population, energy consumption, and the added value of industry constitute the variables of the research.

NATO countries are generally among the advanced economies of industrialization worldwide and have a significant share in global industrial production. NATO's founding members and the countries that joined later varied in terms of their level of industrialization, but they are generally among the highly industrialized and technologically advanced countries. When the existing literature is examined, *there is a gap in researching the combined effects of militarization and industrialization on environmental degradation in NATO countries* since there is only one study (Çolak et al. 2023) investigating this issue, but it only includes 15 NATO countries with the data between 1965 and 2018. Thus, this study has the potential to fill this gap.

Following the introduction, the study provides a literature review on military expenditures, industrialization, and the EKC. It then outlines the model, data, and methodology used in the research. The next section presents the findings, followed by a discussion, conclusion, and policy recommendations in the final section.

2 | Literature Review

This chapter revises the current literature on (1) military expenditures and environmental degradation, (2) industrialization and environmental degradation, and (3) economic growth, energy consumption, urbanization, and environmental degradation in sequence. In addition, before the sub-sections, a literature table consisting of the recent publications on military expenditures and environmental degradation between 2018 and 2024, as shown in Table 1, is prepared.

As Table 1 presents, although some studies investigate the relationship between militarization and environmental degradation, the literature neglects the relationship between the three variables of militarization, industrialization, and environmental degradation, especially in NATO countries. That is why there seems to be a significant need to conduct such research and fill this gap to provide evidence for policymakers to ensure environmental sustainability.

2.1 | Military Expenditures and Environmental Degradation

In recent years, more research has focused on how militarization impacts the environment. Lawrence et al. (2015) noted that militarization could cause significant and unpredictable changes to ecosystems. Gould (2007) described militarization as one of the most destructive actions humans take against nature. Hooks and Smith (2005) argued that people often overlook the environmental harm caused by military activities and wars. They pointed out that military operations drastically consume natural resources, especially when feeding, clothing, and transporting troops. Research indicates that military weapons often involve toxic chemicals, which harm the environment. Even in less severe cases, military actions leave long-term environmental damage. In more extreme situations, the land where battles occur might remain uninhabitable for many years.

One of the earliest studies examining the impact of militarization on environmental degradation is the research conducted by Hooks and Smith (2004), which is based on the "theory of destruction." They demonstrate that the military development of the United States has negative effects on the environment, and the energy demands of military institutions are significantly high, not only during wartime but also in peacetime. Even in the absence of armed conflict, energy demands remain substantial due to infrastructure research and development, with a large portion of this demand being met by non-renewable energy sources (Jorgenson et al. 2010; Ullah et al. 2021).

Clark et al. (2010) emphasize that military expenditures typically have harmful environmental consequences, which negatively affect environmental sustainability. Furthermore, vehicles used during military exercises, training, and experiments—such as tanks, rockets, missiles, ships, aircraft, and helicopters—consume excessive amounts of fuel, resulting in significant emissions of CO_2 and other toxic greenhouse gases (Solarin et al. 2018; Jorgenson et al. 2010).

The most empirical research examining the relationship between military expenditures and the environment has concluded that military expenditures contribute to environmental pollution. Zandi et al. (2019) investigated the effects of corruption, democracy, and military spending on environmental degradation in six ASEAN countries from 1995 to 2017, utilizing FMOLS and DOLS methods, and concluded that military expenditures exacerbate environmental degradation. Türedi and Yildiz (2022) explored whether militarization caused environmental pollution in MENA countries between 1995 and 2018 using the two-stage GMM method. They found a significant positive relationship between CO_2 emissions and militarization, natural resource abundance, per capita GDP, and trade openness, and a significant negative relationship between CO_2 emissions and economic globalization and total capital formation. Cutcu et al. (2023) also found that the transportation sector strongly affects the amount of CO_2 emissions and significantly determines climate change since it is heavily dependent on fossil fuels. This finding can also be transferred to the impacts of militarization because it also increases the amount of transportation. Similarly, Ahmed et al. (2022) employed the CS-ARDL method to examine the relationship between militarization, fossil fuel consumption, renewable energy, and economic growth in 22 OECD countries from 1971 to 2020. They concluded that militarization increases CO_2 emissions, confirming the validity of the treadmill of destruction theory.

Asongu and Ndour (2023), in their study utilizing the GMM method, concluded that military expenditures increase carbon emissions in 40 African countries. Uddin et al. (2024) analyzed the effects of military expenditures, energy consumption, information, and ICT variables on emissions in G20 countries from 1980 to 2019 using panel ARDL and GMM methods, finding that military expenditures and energy consumption have an emission-increasing effect. Husnain and Ali et al. (2023), employing the ARDL approach, found that military spending and economic growth contribute to environmental degradation in the most militarized countries of Asia—Pakistan, India, and China—while the use of renewable energy reduces emissions during the period from 1993 to 2017. Chang et al. (2023) emphasized the increase in military

TABLE 1 | Related studies in the literature between 2018 and 2024.

Authors	Variables	Methods and countries	Findings
Solarin et al. (2018)	Variables: The gross domestic product (GDP) per capita, population, energy consumption per capita, non-renewable energy consumption per capita, renewable energy consumption per capita, urbanization, trade openness, and financial development serve as additional determinants of air pollution. Ecological indicators were used as an alternative measure of pollution.	Role of military expenditure on emissions in the USA during the period 1960–2015. Time series methods are utilized.	All the variables are cointegrated.
Ahmed et al. (2022)	CO_2 emissions, economic growth, consumption of fossil fuels, consumption of renewable energy, and militarization.	Impact of militarization on the environment in 22 OECD countries. Econometric approaches are robust against endogeneity, heterogeneity, and cross-sectional dependence.	A positive contribution of militarization to CO_2 emissions implies that militarization contributes to environmental degradation in OECD nations.
Khan et al. (2023)	Geopolitical risk (GPRI), economic uncertainty (EUI), and marginalization (GMI) affect environmental quality through production-based CO_2 emissions, primary energy consumption, and GHG emissions.	Data from Brazil, China, India, Russia, and South Africa (BRICS) between 2000 and 2021. Using the updated econometric algorithms.	GPRI and GMI are degrading the environmental quality.
Asongu and Ndour (2023)	Military expenditure per capita and CO_2 emissions per capita are used as indicators of environmental degradation.	How good governance counteracts the effects of military expenditure on carbon emissions in 40 African countries. The generalized method of moments (GMM) is used (2010–2020).	With interactive regressions, improved governance harms CO_2 emissions per capita.
Zhu et al. (2023)	Economic growth, militarization, renewable energy, and environment in the Next Eleven nations from 1990 to 2022.	Military spending and environmental sustainability within the N-11 countries. The cross-section autoregressive distributed lag (CS-ARDL) model is employed.	GDP and militarization positively influence a country's environment.
Appiah-Otoo and Chen (2023)	Russia-Ukraine war, policy uncertainty, and carbon footprint to represent environmental degradation.	Impact of the Russia-Ukraine conflict on Ukraine's and Russia's carbon footprint. Using quantile regression and wavelet coherence analysis.	Conflict exacerbates environmental degradation by causing an increase in carbon footprint in both countries over time.
Çolak et al. (2023)	The annual balanced panel data for carbon dioxide emissions (CO_2), the defense burden in the percentage of military expenditure to GDP ratio (ME), and primary energy use (EN).	The 15 oldest members of NATO were analyzed using panel ARDL and NARDL methodologies from 1965 to 2018.	The findings of the panel ARDL analysis do not indicate a significant long-term effect of the defense burden (ME) on carbon dioxide emissions (CO_2).

(Continues)

TABLE 1 | (Continued)

Authors	Variables	Methods and countries	Findings
Khurshid et al. (2024)	Consumption-based CO_2 emissions (CCO_2), militarism (MITEX), and gross fixed capital accumulation (GFC).	Nonlinear consequences of consumption-based CO_2 emissions (CCO_2) and militarism (MITEX) on environmental sustainability in Pakistan. The nonlinear autoregressive distributive lag model (NARDL) was used.	MITEX, and GFC all have a negative influence on environmental sustainability.
Muhammad et al. (2024)	Economic Growth, Military expenditure, Finance, Industrial growth, Environmental degradation, and Political regime.	A bound cointegration approach that can account for structural breaks (Gregory and Hansen), the autoregressive distributed lags (ARDL) model, and the spectral Granger causality approach of Breitung and Candelon.	The chosen variables are cointegrated for the long run in the existence of structural breaks.

spending in the Asia-Pacific region over the past decade, examining the effects of military expenditures on the environmental footprint of 15 countries included in the Regional Comprehensive Economic Partnership (RCEP) agreement from 1990 to 2018 using the CS-ARDL approach. Their findings revealed a positive relationship between increasing military expenditures and ecological footprint. Zhu et al. (2023) used the CS-ARDL method to investigate the relationship between military expenditures and ecological footprint in N-11 countries from 1990 to 2022, concluding that military spending harms the environment.

Studies also examine militarization's impact on environmental degradation through the lens of the EKC. For example, Qayyum et al. (2021) investigated the effects of armed conflicts and militarization on environmental damage in South Asian countries from 1984 to 2019. Their study, which employed ARDL and Granger causality tests, found that military expenditures and internal and external conflicts positively affect the ecological footprint and that there is a causal relationship between armed conflict and militarization to the ecological footprint. Pata et al. (2023) examined the impact of military expenditures on environmental degradation in 15 OECD countries from 1991 to 2018 using the CS-ARDL method, concluding that the EKC is valid and that military expenditures and energy consumption contribute to environmental degradation.

While most of the literature suggests that military expenditures increase emissions, some studies have concluded that military spending may reduce emissions. Ullah et al. (2021) examined the effects of demilitarization and militarization on CO_2 emissions in Pakistan and India from 1985 to 2018 using the NARDL method. Their research found that both variables have an adverse long-run impact on emissions in Pakistan. In contrast, militarization was found to have a negative long-run effect on emissions in India. Konuk et al. (2024), in their study of G7 countries utilizing DOLSMG, FMOLS, and CCR methods from 1921 to 2019, concluded that energy consumption positively affects emissions, while military expenditures negatively impact emissions.

2.2 | Industrialization and Environmental Degradation

The rise in industrialization and economic growth in many countries has often supported economic sustainability, but they have been accompanied by the neglect of environmental pollution caused by fossil fuel use, which hurts environmental sustainability. Previous studies examining the effects of industrialization on the environment generally indicate an increase in environmental pollution (Azam et al. 2022).

Zhongping et al. (2011) argue that the rapid growth of China's heavy industry sector in recent years has significantly intensified the country's industrial structure, leading to a substantial increase in both energy consumption and carbon emissions. To investigate the serious impact of the heavy industrial structure (HIS) on China's carbon emissions, the study employs an error correction model. The results indicate that the formation and expansion of HISs have a positive effect on carbon emissions, and that this effect is more pronounced in the long term than in the short term.

Xu and Lin (2015) examine the effects of industrialization and urbanization on CO_2 emissions in China using nonparametric additive regression models and provincial-level panel data for the period 1990–2011. The empirical results reveal a nonlinear, inverted U-shaped relationship between industrialization and CO_2 emissions across China's three regions. In the case of urbanization, an inverted U-shaped relationship with CO_2 emissions is observed in the eastern region, while a U-shaped pattern emerges in the central region. In contrast, the nonlinear impact of urbanization on CO_2 emissions in the western region is found to be statistically insignificant.

Li and Lin (2015) analyze the effects of urbanization and industrialization on energy consumption and CO_2 emissions across 73 countries, categorized by income level. According to the results, in low-income countries, urbanization reduces energy consumption but increases emissions. In lower-middle and high-income countries, industrialization decreases energy consumption while increasing emissions, whereas urbanization leads to increases in both. In upper-middle-income countries, urbanization helps curb emission growth and has no significant impact on energy consumption. Population growth generally contributes to increased energy use and emissions. The study emphasizes the need to adopt differentiated urbanization and industrialization strategies based on income levels.

Raheem and Ogebe (2017) examined the effects of industrialization and urbanization on CO_2 emissions in 20 African countries over the period 1980–2013. The results show that both industrialization and urbanization directly increase environmental degradation. Interestingly, the study also finds that industrialization and urbanization reduce environmental degradation indirectly through their effects on per capita income. Overall, the authors argue that the indirect effect of industrialization outweighs its direct effect, resulting in a net reduction in carbon emissions. In contrast, the positive (increasing) direct effect of urbanization is stronger than its negative (reducing) indirect effect, indicating that in the long term, urbanization will have a net positive effect on carbon emissions and pose a threat to the environment.

Zafar et al. (2020) concluded that industrialization increased CO_2 emissions in 46 Asian countries between 1971 and 2018. Mahmood et al. (2020) analyzed the impact of industrialization on CO_2 emissions in Saudi Arabia from 1968 to 2014 using the ARDL model, finding that industrialization significantly increased CO_2 emissions. Jebli et al. (2020) found that industrialization negatively affected environmental conditions in upper-middle-income countries.

Opoku and Aluko (2021) analyzed the relationship between industrialization and ecological footprint in 37 African countries from 2000 to 2016, finding that industrialization's impact on ecological footprint varied across different conditional distributions. Aslam et al. (2021) used the error correction model to examine the EKC for China from 1962 to 2018, showing that industrialization leads to environmental degradation.

Azam et al. (2022) found evidence that industrialization, urbanization, and energy consumption increased environmental pollution in OPEC countries from 1975 to 2018, applying the robust least squares method. Sikder et al. (2022) discovered that industrialization, energy consumption, and economic growth increased CO_2 emissions in 23 developing countries between 1995 and 2018. Elfaki et al. (2022) reported a statistically negative relationship between industrialization and economic growth with CO_2 emissions while finding a positive relationship between energy consumption and CO_2 emissions in selected 8 ASEAN+3 countries for 1994–2018, indicating that industrialization increased environmental degradation.

Mentel et al. (2022) analyzed the relationship between industrialization and CO_2 emissions in 44 Sub-Saharan African countries from 2000 to 2015 using a two-step GMM estimation method, finding that the share of industrialization in GDP increased CO_2 emissions. Voumik et al. (2023) investigated the enhancing effects of industrialization and urbanization on CO_2 emissions in five South Asian countries from 1972 to 2021 within the STIRPAT model framework using CS-ARDL, AMG, MG, and CCEMG approaches. Prempeh (2024) examined the impacts of globalization, financial development, industrialization, and renewable energy on environmental degradation in 10 ECOWAS countries for the period 1991–2019, supporting the validity of the N-shaped EKC hypothesis and concluding that industrialization hurts environmental quality.

Muhammad et al. (2024) examined the impact of military expenditures, industrial growth, and financial development on economic growth and environmental degradation under two political regimes—democracy and autocracy—in Pakistan during the period 1971–2014. In the short term, they found that military expenditures increased both environmental emissions and economic growth, while financial development had a positive effect on environmental emissions. In the long term, their findings showed that during periods of democratic governance, military spending and industrial growth negatively affected environmental quality, whereas during autocratic regimes, these factors had a positive impact on the environment.

Conversely, some studies suggest that industrialization can reduce environmental pollution (Elfaki et al. 2022). Kwakwa (2022) found that, in the long run, industrialization, military expenditures, and population increase CO_2 emissions, while government spending has a reducing effect, supporting the validity of the EKC. Ali et al. (2023) found that urbanization and energy usage increased carbon intensity in the Kingdom of Saudi Arabia between 1991 and 2020 using QQ and QR approaches, while industrialization was found to reduce carbon emissions.

Studies show that industrialization increases environmental degradation, but they also suggest that industrialization neither reduces nor positively affects it. Appiah et al. (2021) found no significant relationship between industrialization and CO_2 emissions in 25 Sub-Saharan African countries from 1990 to 2016; however, they did establish a bidirectional causality relationship between the two variables.

2.3 | Economic Growth, Energy Consumption, Population, and Environmental Degradation

Studies on the EKC aim to understand the relationship between a country's economic growth and environmental degradation and develop sustainability-oriented policies based on the findings. The EKC hypothesis strongly connects per capita GDP and CO_2 emissions. It posits that environmental degradation initially increases with real income growth but decreases over time as

TABLE 2 | Recent studies on the environmental Kuznets curve.

Author	Method	Variables	Environmental Kuznets curve
Mohammed et al. (2024)	FMOLS DOLS AMG	Economic growth Energy consumption Population structure	EU-27 Verified Kuznets curve
Golpîra et al. (2023)	Panel quantile regressions	Economic growth Energy consumption Population Structure	OECD countries Verified Kuznets curve
Hasan et al. (2023)	FMOLS DOLS	Economic growth Fossil fuel energy consumption Financial Development Trade Openness	BRICS countries Verified Kuznets curve
Thio et al. (2022)	ARDL bounds test approach VECM granger. Causality	Economic growth Energy consumption Urbanization	The top 10 countries Verified Kuznets curve
Verbič et al. (2021)	FMOLS PMG	Economic Growth Energy Consumption Urbanization	Southeast Europe Verified Kuznets curve in the long run

personal income rises. The EKC predicts an inverted U-shaped relationship between income and environmental degradation processes (such as CO_2 emissions). Recent studies on the EKC, which emerged in the 1990s and focused on energy consumption and urbanization, are included in Table 2.

3 | Methods and Materials

This study analyzes the relationship between militarization, industrialization, and environmental degradation in NATO member countries between 1995 and 2018. NATO is a regional organization with 32 members today. However, in this study, only 15 NATO member countries (Germany, USA, Belgium, United Kingdom, Türkiye, Denmark, France, Netherlands, Italy, Spain, Canada, Hungary, Norway, Poland, and Portugal) are included in the analysis due to the limited access to data, which is one of the most critical limitations of panel data analysis. The impact of militarization and industrialization on environmental degradation in these 15 countries is examined using panel data analysis. Economic growth, urban population, energy consumption, and industrial value are included variables in the model. The equation, established by taking the natural logarithms of all variables, is presented below:

$$\begin{aligned}\text{lnCO}_{it} = \beta_0 + \beta_1 \text{lngdp}_{it} + \beta_2 \text{lngdps} + \beta_3 \text{lnmilitary}_{it} + \beta_4 \text{lnpop}_{it} \\ + \beta_5 \text{lnen}_{it} + \beta_6 \text{lnindust}_{it} + \beta_7 (\text{lnind}) * (\text{lnmilitary})_{it} + u_{it}\end{aligned} \quad (1)$$

where lnCO_2 is the per capita carbon dioxide emissions, lngdp is defined per capita real GDP, and lngdps is the square of per capita real GDP, lnpop denotes the population density, meaning people per sq. km of land area. The increase in population density in urban areas leads to excessive resource consumption, air, and water pollution. Moreover, environmental damage increases in spatially dense regions due to reasons such as waste management and land use. Increasing population density, together with rapid urbanization, accelerates environmental degradation due to insufficient environmental management capacity (Angel et al. 2011; Bai et al. 2012; Seto et al. 2012). For this reason, the population density variable is employed as a proxy for urbanization in this study; lnmilitary represents the total expenditures on defense in US$m at constant 2020, lnindust defines the net contribution of a country's industrial sector to the economy and calculates constant 2015 US$, and the last variable is lnenergy, which refers to the primary energy consumption (TWh). The variable lnind*lnmilitary was added as a new series created by the interaction of military expenditures and industrial value added. This variable allows us to examine how the impact of military expenditures on emissions varies according to industrial value added.

Table 3 below presents the variables used in the model, including their form, type, and the official data source from which they were obtained.

In the study, the CSD test developed by Pesaran (2004) is applied to test whether horizontal cross-section dependence exists among the units. Following the CSD test, the Delta test developed by Pesaran et al. (2008) is used to test for homogeneity. The cross-sectionally Augmented Dickey-Fuller ADF unit root test developed by Pesaran (2007) is then applied to test the stationarity of the variables based on the results of the horizontal cross-section dependence test. The presence of a unit root in the overall panel is tested using the CIPS (Cross-sectionally Im-Pesaran-Shin) unit root test developed by Pesaran (2007). Since the variables are found to be stationary at first order difference due to the unit root test, the Durbin–Hausman cointegration test developed by Westerlund (2008) is applied next. PMG-ARDL long run estimation test is then used to estimate the long-run relationship between the variables. Finally, the Dumitrescu–Hurlin causality test developed by Dumitrescu and Hurlin (2012) is applied to determine the causal relationship between the variables. After providing a brief overview of the

TABLE 3 | Definitions of variables.

Variables	Abbreviations	Unit of measurement	Sources
CO_2 emissions	lnCO	Metric tons per capita	Statistical review of World Energy, Energy Institute (2023)
Gross domestic product	lngdp	Per capita in constant 2015$	World Bank (2023)
Military expenditures	lnmil	Military expenditures at constant 2020, US $m	SIPRI (2022)
Population	lnpop	Population density people per sq. km of land area	World Bank (2023)
Industrial value added	lnindust	Value added of GDP constant 2015 US$	World Bank (2023)
Primary energy consumption	lnenergy	Primary energy consumption (TWh)	Our World in data

methods used, the analysis results are presented and interpreted according to previous studies.

3.1 | Cross-Sectional Dependence (CSD) Test

In econometric analyses, testing the cross-section dependency before performing unit root and cointegration tests is essential for the validity of the results. The tests applied to investigate CSD vary depending on the time and cross-sectional dimensions of the data. Specifically, when the time dimension is larger than the cross-sectional dimension ($T > N$), the CD LM1 test developed by Breusch and Pagan (1980) is used. If the time and cross-sectional dimensions are equal ($T = N$), Pesaran's (2004) test is applied. Finally, when the time dimension is smaller than the cross-sectional dimension ($T < N$), the CD LM2 test developed by Pesaran (2004) is used. In this study, the CD LM1 test was applied because $T = 35$ and $N = 15$.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{ij}\right) \quad (2)$$

The CD LM test is given by Equation (2) above. The test statistics obtained in Equation (2) follow an asymptotic normal distribution (Pesaran 2004). The hypotheses for the CD LM test are as follows:

H0. *There is no cross-sectional dependence.*

HA. *There is cross-sectional dependence.*

The null hypothesis is rejected if the test statistic obtained from the analysis is significant ($p < 0.10$). Second-generation unit root tests should be conducted for CSD between the series (Baltagi 2008).

3.1.1 | Slope Homogeneity Test (Delta Test)

A homogeneity test should be applied before testing the existence of a long-run relationship between variables. The homogeneity test developed by Pesaran et al. (2008), also known as the delta (Δ) test, examines the homogeneity of the slope parameter. The delta test is used for large sample groups, while the delta adj test is used for small sample groups (Pesaran et al. 2008).

$$\tilde{\Delta} = \sqrt{N}\,\frac{N^{-1}S - E(Zit)}{2k} \quad (3)$$

$$\tilde{\Delta}_{adj} = \sqrt{N}\,\frac{N^{-1}S - K}{\mathrm{Var}\,(Zit)} \quad (4)$$

The following hypotheses are tested in the delta test.

H0. *$\beta i = \beta$, the slope coefficients are homogeneous.*

H1. *$\beta \neq \beta j$, the slope coefficients are not homogeneous (heterogeneous).*

Table 4 presents the results of the CSD test and slope heterogeneity test. According to the table, all test statistics in the CSD test were significant, leading to the rejection of the null hypothesis (H0), which states that there is no CSD. Therefore, CSD exists between the variables, meaning that any shock occurring in one of the units in the panel affects other countries. These findings necessitate the use of tests that account for CSD. Additionally, the test results are also provided in Table 4 above. Given the significance of the Delta test results ($p < 0.10$), homogeneity was concluded. Accordingly, it was determined that the slope coefficients of the variables are homogeneous. The second-generation unit root tests will be conducted based on the results of the CSD and slope heterogeneity tests.

3.1.2 | CIPS Unit Root Test

Cross-sectional dependency tests developed by Breusch and Pagan (1980) and Pesaran et al. (2008) are widely used. By taking the lagged and first-degree difference of the cross-sectional means of the units in the panel, these tests are combined with Extended Dickey-Fuller (ADF) tests, and cross-sectional augmented Dickey-Fuller (CADF) statistics are obtained. In this process, the error term is separated from the unobservable common factors and included in the estimation (Pesaran 2007).

TABLE 4 | CD and slope homogeneity test results.

	CD test *p* value	Prob.
*ln*co	23.880	0.000
*ln*gdp	42.526	0.000
*ln*gdps	42.463	0.000
*ln*primary	4.755	0.000
*ln*indust	33.905	0.000
*ln*pop	16.698	0.000
*ln*military	8.213	0.000
*ln*indmilitary	31.258	0.000
$\tilde{\Delta}$	7.967	0.000
$\tilde{\Delta}_{adj}$	10.078	0.000

TABLE 5 | CIPS unit root test results.

	I(1)		I(1)	
Variable(s)	**Level**	**Cons**	**Level**	**Cons**
*ln*co	−1.984	−1.123	−4.973	−4.706
*ln*gdp	−1.730	−0.541	−3.103	−2.838
*ln*gdps	−1.776	−0.634	−3.075	−2.187
*ln*primary	−2.105	−1.884	−5.433	−5.155
*ln*indust	−1.908	−1.436	−4.027	−3.879
*ln*pop	−2.180**	−1.106	−2.396	−2.201
*ln*military	−1.714	−1.152	−4.691	−4.244
*ln*indmilitary	−2.039	−1.609**	−4.097	−3.453

**Denote significance at 5% level.

TABLE 6 | Durbin–Hausman cointegration test results.

	Statistics	*p*
DH panel	−2.890	0.001
DH group	−3.001	0.002

CADF statistics were calculated for all cross-sections by Pesaran (2007). Additionally, the IPS unit root test developed by Im et al. (2003) is applied and calculated cross-sectionally following specific procedures. The statistics obtained from the CADF and CIPS unit root tests are compared with the critical values in Pesaran (2007), and a decision is made. If the CADF test statistic is smaller than the table value, the null hypothesis (H0) is rejected, and the series is considered stationary.

$$\mathrm{CIPS} = N^{-1} \sum_{i=1}^{N} \mathrm{CADF}_i \tag{5}$$

Table 5 presents the CIPS unit root test results. The CIPS test statistics were compared with the critical values in Pesaran (2007), and it was concluded that the variables are stationary at the first difference. In the third stage, we apply the Durbin–Hausman cointegration test to investigate the long-run relationship between variables in NATO countries.

3.1.3 | Durbin–Hausman Cointegration Test

Since the variables were stationary in the first difference in the unit root test results, the Durbin–Hausman cointegration test developed by Westerlund (2008) was applied to examine the cointegration relationship between the variables. The Durbin–Hausman cointegration test, used to assess the long-run relationship between the variables, requires the dependent variable to be stationary in the first difference (Westerlund 2008).

Table 6 presents the results of the Durbin–Hausman test, which accounts for cross-sectional dependency and slope heterogeneity, to test the existence of a long-run relationship between variables. The result indicates a cointegration relationship between variables, as evidenced by the table's significant ($p<0.05$) group and panel statistics. This suggests that the series moves together in the long run. The Durbin–Hausman cointegration test confirmed a long-run relationship between the variables. Coefficient estimation was performed using the mean group (MG) and pooled mean group (PMG) estimators developed for the ARDL model. The PMG-ARDL long-run coefficient estimation results are presented in Table 7 below.

Table 7 presents the long-run panel period estimation results. When evaluating the long-run analysis results, it can be stated that primary energy consumption increases emission levels and contributes to environmental degradation in the relationship between the variables and CO_2 emissions. The coefficients for military expenditures and industrialization are both significant and positive, indicating that they contribute to higher carbon dioxide emissions. Specifically, military expenditures positively and statistically significantly affect environmental degradation. These findings are consistent with those of Zandi et al. (2019) and Ahmed et al. (2022). Additionally, the model supports the validity of the EKC, which suggests that while environmental pollution increases with income up to a certain point, it decreases after reaching an optimal level. The results regarding the validity of the EKC align with those of Qayyum et al. (2021) and Pata et al. (2023). In the study of selected NATO countries, the effect of urbanization on CO_2 emissions was found to be statistically significant and negative.

The interaction between industrialization and military expenditures has a statistically significant negative impact on CO_2 emissions. A 1% increase in the moderated variable results in a 19% reduction in environmental degradation.

3.1.3.1 | Dumitrescu–Hurlin Causality Test.

After estimating the long-run coefficient, the causality relationship between the variables is analyzed using the Dumitrescu–Hurlin Causality test. According to the test developed by Dumitrescu and Hurlin (2012), the causality relationship that holds for any country in the panel is also valid for other countries. Additionally, the results obtained for the cases where ($T>N$) and ($T<N$) are significant.

TABLE 7 | PMG-ARDL long run estimation results.

Long run	Coefficient	Standard error	*p*
*ln*gdp	1.892540	0.651843	0.0046
*ln*gdps	−0.150093	0.078230	0.0579
*ln*energy	0.196846	0.037104	0.0000
*ln*indust	0.525817	0.179321	0.0042
*ln*pop	−1.279706	0.141739	0.0000
*ln*mil	0.679523	0.214436	0.0020
*ln*indmilitary	−0.193490	0.048510	0.0001

The causality test results in Table 8 confirmed a two-way causality between energy consumption and CO_2 emissions. On the other hand, there is a one-way causality from economic growth to CO_2 emissions. The directions (two-way or one-way) of the causalities are given in Figure 1.

TABLE 8 | Dumitrescu–Hurlin causality test results.

	W-stat	*Z*-stat	*p*
*ln*gdp > *ln*co*	4.2551	8.9146	0.0000
*ln*primary > *ln*co*	5.1510	11.3681	0.0000
*ln*indust > *ln*co*	4.5762	9.7938	0.0000
*ln*pop > *ln*co*	6.1629	14.1392	0.0000
*ln*military > *ln*co*	2.1265	3.0852	0.0020
*ln*indmilitary > *ln*co*	3.1299	5.8331	0.0000
*ln*co > *ln*gdp	1.2658	0.7279	0.4667
*ln*co > *ln*primary*	4.6378	9.9624	0.0000
*ln*co > *ln*indust*	2.1047	3.0252	0.0025
*ln*co > *ln*pop*	21.5668	56.3244	0.0000
*ln*co > *ln*military*	2.4294	3.9147	0.0001
*ln*co > *ln*indmilitary*	2.1395	3.1207	0.0018

4 | Results and Discussion

This section compares the literature results (Table 1) with the findings from the current study (Tables 3–8), highlighting similarities, differences, and novel contributions.

4.1 | Military Expenditure and Environmental Degradation

The findings from the literature emphasize the mixed or detrimental effects of military expenditure on environmental quality. Solarin et al. (2018) and Ahmed et al. (2022) found that military spending contributes to CO_2 emissions, aligning with the present study's results that military spending increases environmental degradation. Similarly, Zhu et al. (2023) reported that militarization exacerbates environmental damage. However, the current study adds nuance by demonstrating a statistically significant negative interaction between industrialization and military expenditures on CO_2 emissions, indicating that industrial-military synergy may mitigate environmental degradation. This interaction, leading to a 19% reduction in emissions, is an innovative finding absent in prior studies, which may be useful in developing new policies to assure environmental sustainability in a balance with economic sustainability.

4.2 | Urbanization and Environmental Impact

A considerable number of studies present urbanization as a driver of environmental degradation (e.g., Solarin et al. 2018; Voumik et al. 2023). Conversely, our results indicate a statistically significant negative impact of urbanization on CO_2 emissions, suggesting that urbanization in NATO countries may lead to improved environmental outcomes, potentially due to urban planning or energy-efficient infrastructure. This divergence underscores the contextual specificity of urbanization's ecological effects. Supporting this result, Martínez-Zarzoso and Maruotti (2011), in their study examining the impact of urbanization on CO_2 emissions in developing countries during the period 1975–2003, found that in some countries, once urbanization reaches a certain level, it may lead to a reduction in emissions. Similarly, Lv and Xu (2019), in their study analyzing the effects of urbanization and trade openness on CO_2 emissions in 55 middle-income countries over the period 1992–2012 using the PMG estimator, concluded that urbanization reduced emissions in both sub-periods, thereby contributing to improved environmental quality. Furthermore, Degirmenci et al. (2024), in their study examining the effects of financial development, human development, urbanization, and industrial employment on environmental quality in E-7 countries using regularized common correlated effects and Augmented Mean Group estimators, revealed that urbanization worsens environmental quality in China but enhances it in Brazil.

4.3 | Energy Consumption and Industrialization

The positive relationship between primary energy consumption and CO_2 emissions observed in our study corroborates findings by Ahmed et al. (2022) and Khan et al. (2023), who highlighted the role of energy usage in environmental degradation. Furthermore, our analysis confirms industrialization's positive impact on emissions, which is consistent with prior research. However, the present study's support for the EKC offers a broader framework, suggesting that environmental degradation may decline after economic development reaches a threshold, echoing Qayyum et al. (2021) and Pata et al. (2023).

4.4 | Governance and Policy Implications

While Asongu and Ndour (2023) emphasized governance's role in mitigating military expenditure's environmental impacts, our study did not explicitly test this dimension. However, the findings regarding military–industrial interactions offer indirect insights into policy avenues for optimizing resource allocation and mitigating emissions.

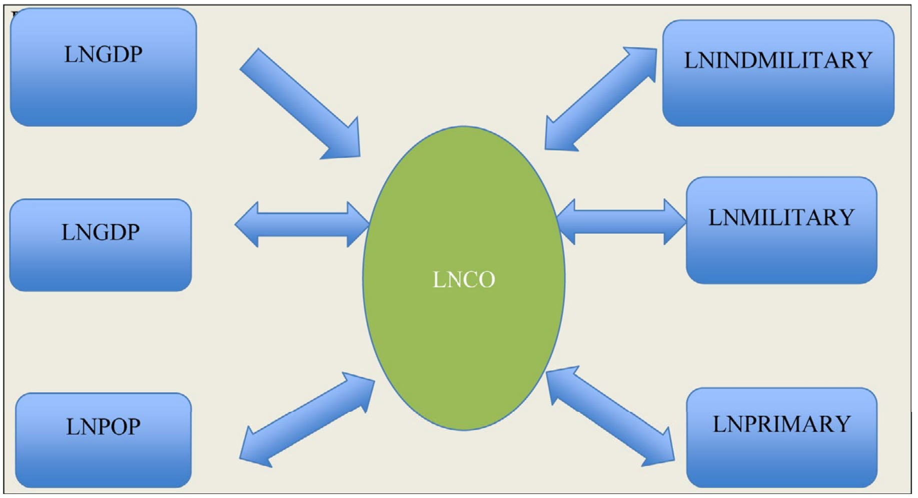

FIGURE 1 | The direction of causality.

4.5 | Causality Relationships

The Dumitrescu–Hurlin causality test confirmed bidirectional causality between energy consumption and CO_2 emissions, consistent with the findings of Appiah-Otoo and Chen (2023). Additionally, one-way causality from economic growth to CO_2 emissions aligns with Ahmed et al. (2022), reaffirming the precedence of economic activities in driving emissions.

4.6 | Contribution to the Literature

The current study uniquely combines advanced econometric methodologies, such as the PMG-ARDL model and the Dumitrescu–Hurlin causality test, to provide robust insights. It advances understanding of the interplay between industrialization and military expenditures, suggesting potential pathways for mitigating environmental harm through strategic policy measures. Furthermore, the study underscores the importance of contextual factors, such as urbanization dynamics and governance structures, in shaping environmental outcomes for sustainable development.

5 | Conclusion

The findings reinforce and extend the literature on the environmental implications of military spending, economic activities, and urbanization for sustainable development. By addressing gaps in the contextual specificity of variables like urbanization and providing novel insights into military-industrial interactions, this study offers a foundation for further research and policy formulation.

Both militarization and industrialization are among the sectors with the highest energy demands. This study examines the effects of military expenditures and their moderating impact on industrialization on CO_2 emissions in NATO countries. The analysis of the long-run relationship among the variables reveals a positive relationship between military expenditures and CO_2 emissions. Consistent with the existing literature, one of the primary recommendations to reduce environmental pressures in NATO countries is to decrease military expenditures or to meet energy needs associated with militarization through renewable energy sources to prevent their possible damage on environmental sustainability. In this context, countries must increase investments in research and development for renewable energy production. Moreover, as asserted by Keser et al. (2024), "policymakers should enhance the contribution of the community to decision-making to stimulate, refrain from augmenting political tension, provide a sustainable, safe and secure environment" and try to protect the balance between all three dimensions of sustainability hitherto: economic, socio-cultural, and environmental. The analysis also finds a statistically significant and positive relationship between primary energy consumption and CO_2 emissions in the long run. Based on these findings, we recommend producing alternative clean energy sources and increasing their output to mitigate the environmental impact of primary energy consumption.

The transition of the defense industry toward more sustainable production models, the adoption of the 3R approach (reduce, reuse, recycle) within the framework of the circular economy, and the increased use of renewable energy sources will enhance energy efficiency and contribute to environmental sustainability (Molina-Moreno et al. 2019). In particular, the industry could shift toward alternative materials for critical resources such as rare earth elements, and the use of biofuels could be expanded.

Allocating a certain proportion of NATO member states' defense budgets to mitigating the impacts of climate change (e.g., the establishment of early warning systems for drought and water scarcity) would contribute to the reduction of environmental damage on a global scale. Conflict prevention initiatives should be prioritized in NATO members' risk management plans, particularly in border regions where water and energy resources are located. By mandating environmental and social governance (ESG) criteria for investments, restrictions could be imposed on high-carbon military investment projects. Moreover, the adoption of the "polluter pays" principle—already implemented by European Union member states—by NATO could incentivize the transformation of member states' industries toward green industries. In addition, promoting investments in nanotechnologies that remediate soil and water pollution in military projects may contribute to the ecological integration of military bases and facilities. A "Green Base Fund" could be created through contributions from member states' defense budgets and directed toward ecosystem restoration. Innovative financing tools, such as "military carbon credit trading" or "green military bonds," could also be developed to support the establishment of eco-designed military bases. To reduce the environmental degradation caused by waste generated by the defense industry, waste management strategies should be developed within the framework of the circular economy, thereby supporting environmental sustainability. Real-time calculation of the environmental footprint of NATO military operations, opening NATO's satellite network to climate data collection, and setting net-zero emission targets for member states' armed forces could strengthen NATO's global image and pave the way for climate leadership.

This study focuses on selected NATO countries due to data limitations. Due to the large number of NATO member states, the varying levels of development among these countries, and the lack of consistency in the dataset in terms of time and content to assess each member individually, separate analyses for each NATO country could not be conducted. In this regard, future studies may consider analyzing each NATO country individually or forming country groups based on the specific objectives of the research. Such approaches could contribute to a clearer understanding of causal relationships and enhance the validity of econometric models. Moreover, incorporating variables aimed at preventing environmental damage—such as green investment and green financing—into model development could offer new opportunities for green military investment planning.

NATO members are generally advanced in terms of industrialization and technology. Future research could provide valuable comparative insights by examining the impact of military expenditures and industrialization on environmental degradation in less developed countries. Additionally, incorporating a geopolitical risk index into future studies could help analyze the effect of defense spending on environmental degradation more comprehensively.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

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