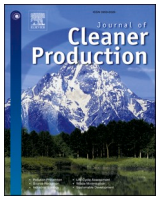
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Towards sustainable manufacturing: How does digitalization and development affect sustainability barriers?

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ABSTRACT

This study analyzes the relationship between digitalization and sustainability in the manufacturing industry, considering the effects on sustainability barriers and the existence of differences in the level of development between countries and regions. While digitalization can improve efficiency and support sustainable goals, mixed results from previous studies suggest that there is still a need to understand how this relationship works. Using a sample of 1334 manufacturing companies with more than 20 employees from the Flash Eurobarometer 486 database and by conducting multiple regression analysis, the results reveal that although digital technologies can directly enhance environmental sustainability, the level of development moderates the effect of digitalization on the various barriers to sustainability. This study contributes to the field by deepening the knowledge about the trade-offs between digitalization and sustainability in virtue of the existence of digital divide between different levels of development among countries.

1. Introduction

Sustainability and digitalization are transforming the economy and society. Digitalization, defined as the use of digital technologies to transform products, processes, and operations value chains (Lanzolla et al., 2020), has emerged as a key driver in the transition towards sustainability (Guandalini, 2022). However, the achievement of successful sustainable development occurs only when transformations towards digitalization and sustainability are synchronized (WBGU, 2019) (https://www.wbgu.de).

Day after day, companies face increasing pressure from a spectrum of stakeholders to prioritize sustainability initiatives (Bello-Pintado et al., 2023). In this context, digital technologies can enhance sustainable manufacturing practices by improving the efficiency of production processes (Ching et al., 2022) and promoting cleaner production processes (Amjad et al., 2021). Innovative solutions to sustainability increasingly rely on utilizing digital technologies (Yadav et al., 2020b). Nevertheless, prior research shows mixed results regarding the relationships between digitalization and sustainability (e.g. Chiarini, 2021; Hemmati et al., 2022; Ferreira et al., 2023). Hence, more investigation is needed into "how" digital technologies affect sustainability adoption.

While digitalization is often proposed as a universal tool to mitigate uncertainties and barriers inherent to sustainability (Despeisse et al., 2022), manufacturing firms still face challenges in leveraging digital technologies for sustainability (Yadav et al., 2020a). Digital technologies are being used worldwide (Luthra et al., 2020), yet sustainability barriers persist, especially in less developed countries (Sharma et al., 2021). Given the lack of a clear conclusion regarding the role of digital technologies in adoption (Del Río Castro et al., 2021), this study aims to address the following question: Does digitalization contribute to sustainability by overcoming sustainability barriers?

Addressing this question requires the consideration of intermediate and moderating factors (Brenner and Hartl, 2021), such as contextual factors (Bai et al., 2020; Dieste et al., 2023). For instance, the potential for digitalization to enhance sustainability may vary across sectors due to differences in labour, capital, and technology intensities (Hosan et al., 2022). Additionally, the inter- and intra-country differences in the level of development may play a significant role in the relationship between digital technologies and sustainability barriers (Ahmadova et al., 2022; Hemmati et al., 2022). While a high level of development might facilitate the adoption of advanced digital technologies (Yadav et al., 2020a), strengthen environmental regulations, or foster a national attitude that prioritizes sustainability (Wang et al., 2019), it can also lead to negative

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consequences. For instance, the increase in the use of digital technologies in less developed countries contributes to greater e-waste generation and the challenges regarding proper disposal and recycling, which can result in negative environmental and health impacts (Kalia et al., 2022). Moreover, disparities like the digital divide may exacerbate inequalities within populations or regions (Lythreatis et al., 2022); while vulnerabilities such as cyberattacks or technological failures could undermine sustainability and resilience efforts (Arroyabe et al., 2024). On this premise, another question emerges: What role does the country's level of development play on the link between digitalization, barriers to sustainability and sustainability adoption in manufacturing?

This approach seeks to provide a comprehensive understanding of the overall impact of digitalization on sustainability, while acknowledging sector-specific nuances and potential development disparities. To examine these relationships, this study uses data from a sample of 1334 manufacturing companies with more than 20 employees across 38 countries, drawn from the Flash Eurobarometer 486 database.

The paper is organized as follows. After the introduction, Section 2 provides a brief literature review and hypothesis development. Section 3 outlines the methodology, including sample description and measures. Section 4 presents the results, and finally, sections 5 and 6 cover the discussion of results, conclusions, and implications.

2. Theoretical framework

2.1. Digitalization and sustainability barriers

Digital technologies encompass a wide range of electronic tools, systems, and platforms that utilize digital information and processes. According to Lanzolla et al. (2020), these technologies can be grouped into four categories: efficiency technologies (i.e., cloud technology), connectivity technologies (i.e., the Internet of Things), trust disintermediation technologies (i.e., blockchains), and automation technologies (i.e., AI and big data). Evidence highlights their potential to enhance operational performance (Gillani et al., 2020; Lorenz et al., 2020), resource efficiency and cost-effectiveness (Ghobakhloo, 2020), as well as product/process innovation (Blichfeldt and Faullant, 2021).

Regarding sustainability, evidence is not conclusive. On the one hand, digital technologies can improve environmental, social and economic performance through efficient information gathering and processing, as well as real-time monitoring (Gregori et al., 2017; Li et al., 2020). They improve transparency in assessing sustainable development objectives (Bai et al., 2020) and circular economy practices (Findik et al., 2023). On the other hand, digitalization may foster imbalanced social relationships and have unintended negative impacts on firms' environmental and social sustainability performance (Ghobakhloo and Fathi, 2020; Dieste et al., 2023). Critics argue that while digitalization holds merits, its applications are insufficient to face sustainability challenges due to limited consideration of the balance and complexity within environmental, social and economic systems (Brenner and Hartl, 2021).

This preamble motivates an analysis of the relationship between digitalization and sustainability from the perspective of sustainability barriers. Malek and Desai (2021) classify sustainability barriers into six categories: *Strategic-Sustainability-related barriers* (e.g. planning and a balanced approach among social, environmental, and monetary benefits); *Knowledge and* support *barriers* (top management support, uncooperative staff, and insufficient training); *Technological barriers* (need of new technologies and technical expertise); *Behavioural barriers* (resistance to cultural change and negative attitudes toward sustainability); *Financial barriers* (need of investment for waste disposal and infrastructure changes; and *External barriers* (regulations; customers preferences). Generally, these barriers are universally present (Findik et al., 2023), though their significance may vary considerably depending on the sector of activity (e.g., Automotive vs. Construction) or the development context (Asif et al., 2024).

Digital technologies have emerged as tools to overcome barriers (George et al., 2021; Despeisse et al., 2022), particularly to face technical and organizational challenges in manufacturing (Chen et al., 2015; Guandalini, 2022). Table 1 summarizes the main insights from the literature regarding the impact of different digital technologies on both sustainability barriers and on the adoption of sustainability practices.

For instance, AI technologies help tackle sustainability technical challenges (Agrawal et al., 2023). Big data analytics, blockchain and IoT sensors facilitate collaboration in supply chain through information sharing, joint planning and decision-making, helping companies to overcome barriers for implementing both global and local circular economy activities (Gebhardt et al., 2022).

Digitalization enables precise planning and data-driven decision-making to support business cases in overcoming strategic barriers. For example, advanced data analytics and simulations can assess the long-term profitability of sustainable practices (George et al., 2021) and implement and monitor comprehensive dashboards (Schiavone et al., 2022). Digital platforms facilitate integrated monitoring and communication to manage the social and environmental impact of manufacturing operations (Ching et al., 2022). Digital tools for training, team collaboration and learning of employees reduce the knowledge gaps (Marion and Fixson, 2021). Additionally, digitalization facilitates the use of innovative technologies to enhance waste management and energy efficiency. For instance, IoT tools such as sensors and AI technologies monitor and optimize circular strategies for resource usage and waste management in the manufacturing environment (Findik et al., 2023). Other digital tools such as mobile apps educate and motivate employees on sustainable practices, reducing behavioural barriers (Isensee et al., 2022). Digitized management systems reduce resource waste and optimize operational costs, improving economic and environmental performance (Khan et al., 2022). Digitalization also provides accurate data supporting requests for government support and regulatory compliance (Luoma et al., 2023). For example, detailed digital reports comply with regulatory standards and ease access to government incentives (Yu et al., 2023). Based on these arguments, we propose the following hypothesis.

H1. Digitalization contributes to sustainability through mitigating sustainability barriers.

2.2. Influence of a country's level of development

Despite the global advancement and widespread diffusion of digital technologies, significant disparities persist in their accessibility and utilization among countries, regions, and industries (World Bank, 2021). According to the Digital Divide Theory, disparities exist not only between highly and less developed countries but also within countries (i.e., differences between regions and urban-rural areas), in terms of access to and use of digital technologies (Lythreatis et al., 2022). The digital divide, encompassing inequalities in information and communication technology (ICT)-based opportunities, applications, adoption and outcomes (S. C. Liao et al., 2022), tends to be associated with unfavourable socio-economic situations, such as low income, unemployment or low educational attainment (Tewathia et al., 2020). Socio-economic disadvantages (i.e., lower level of a nation's economic development and education as well as digital skill) contribute to fewer opportunities to access and fully utilize digital technologies. Evidence confirms that different digitalization patterns are explained by different country-level variables. For instance, compared to less developed countries, highly developed countries are more involved with advanced technologies associated with e-commerce and broadband internet, greater levels of ICT diffusion, economic structures and governmental effectiveness (Billon et al., 2009). Additionally, highly developed countries are stronger in terms of digital readiness, including technology infrastructure, technology adoption, human capital, basic needs, ease of doing business, government investment and start-ups linking digitization

Table 1
Summary of literature review.

Digital tools	Sustainability Barriers						
	Strategic-Sustainability-related barriers	Knowledge and support barriers	Technological barriers	Behavioural Barriers	Financial barriers	External Barriers	Authors
Connectivity technologies (e.g., the High-Speed Infrastructure, the IoT, smart devices, smart sensors etc.)	✓	✓	✓	✓		✓	Ching et al. (2022); Gebhardt et al. (2022); Isensee et al. (2022); Findik et al. (2023)
Efficiency technologies (e.g., Cloud technology)	✓	✓			✓		Marion and Fixson (2021); Khan et al. (2022); Yu et al. (2023)
Trust disintermediation technologies (e.g., blockchains)			✓			✓	Gebhardt et al. (2022)
Automation technologies (e.g., artificial intelligence, big data, robotics etc)	✓		✓			✓	George et al. (2021); Gebhardt et al. (2022); Schiavone et al. (2022); Yu et al. (2023); Agrawal et al., (2023); Findik et al. (2023)

(Luthra et al., 2020). In this regard, recent studies provide practical and theoretical ideas to promote the adoption of technologies and foster sustainability in less developed countries (Yadav et al., 2020a; Sharma et al., 2021). However, evidence remains controversial, suggesting the need for caution when linking digitization, sustainability, and development levels.

On the one hand, technologies have a beneficial impact on the digital divide by enabling access to information, education, and services through digital inclusion (Mubarak et al., 2020). This dynamic empowers less developed communities to access resources, skills and opportunities that would otherwise be unattainable to them. However, highly developed countries are more likely to adopt and implement new technologies faster than less developed countries (Ghobakhloo and Fathi, 2020), potentially amplifying existing disparities subject to socio-economic determinants (Mubarak et al., 2020). On the other hand, there are also concerns about dependency or the lack of adequate adaptation of these technologies to local contexts, which could generate certain sustainability barriers that may not have existed before (Fromhold-Eisebith et al., 2021). Technologies play a crucial role in reducing negative environmental impacts, however, their adoption is insufficient without changes in behaviour and consumption patterns (Wang et al., 2019; Malek and Desai, 2021). Even in highly developed countries, there are structural, cultural, and financial challenges that hinder the effective implementation of sustainable practices (Caldera et al., 2019).

Evidence highlights that the issue lies not only in technology accessibility but also in how technology is utilized. This reliance is contingent upon social and institutional factors (Tewathia et al., 2020) and, above all, on knowledge and skills (Y. Liao et al., 2018). Both factors are related with a wider digital gap associated with the level of development.

According to Wang et al. (2019), the country's level of development affects the sustainable behaviours of manufacturing. Higher levels of economic development provide more resources and technologies for environmental initiatives (Reverte, 2022). While the adoption of advanced sustainable manufacturing practices has already incorporated industry 4.0 technologies in developed countries, the absence of infrastructure and advanced technological setups poses a significant challenge for less developed countries (Yadav et al., 2020a). This demonstrates the double-sided nature of this issue since certain sustainability obstacles in less developed countries are actually enablers in highly developed countries (Wang et al., 2019).

In this context, nations leading in sustainability, predominantly those within highly developed countries, imply a correlation between a country's developmental stage, its level of digitalization, and the attainment of sustainability objectives (Luthra et al., 2020). Digital technologies hold the potential in enhancing sustainability; however, their transformative impact isn't inherently assured but rather contingent upon addressing the factors contributing to the sustainability barriers (Yadav et al., 2020b). This underscores the significance of not only bridging the disparities in access to technology but also ensuring its effective utilization for sustainable practices, thereby fostering a convergence toward sustainability goals (Bello-Pintado et al., 2023). Building upon these reasoning, we posit the following hypothesis.

H2a. The country's level of development is positively associated with the adoption of sustainability practices.

H2b. The country's level of development moderates the effect of digitalization on sustainability barriers.

The structural model of this study is presented as follows (See Fig. 1).

3. Methodology

3.1. Sample

The data used in this study comprise a sample of manufacturing companies from the Flash Eurobarometer 486 published in 2020 (European Commission, 2020), carried out by the Gesis - Leibniz Institute for Social Sciences. This dataset was collected information through a survey of SMEs, Start-ups, Scale-ups, and Entrepreneurship from EU27

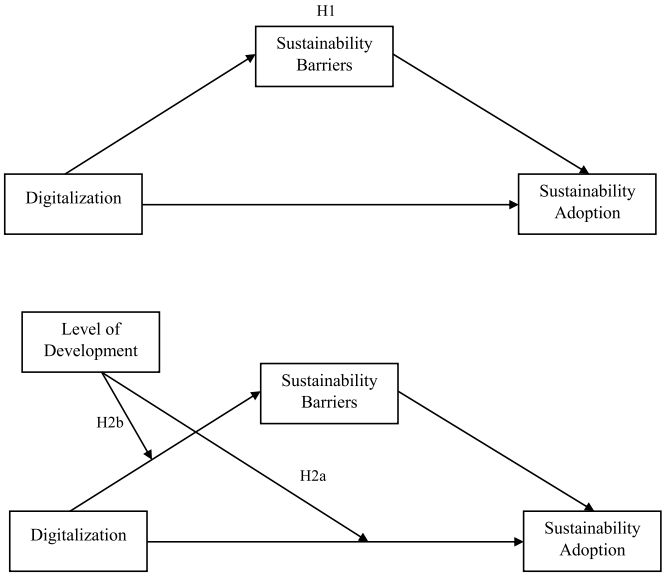


Fig. 1. Structural model.

and 12 non-EU countries and territories between 19th February and May 5, 2020. The survey involved more than 16000 telephone interviews in their respective national language, providing a final sample of 16,365 SMEs employing one to 250 employees. Given the focus of this study, only manufacturing companies with more than 20 employees were targeted, resulting in a sample of 1334 enterprises. Of this, 67,32% (n = 898) of the companies operate in highly developed countries while 32.68% (n = 496) are in less developed regions. The surveys have been utilized by several scholars (e.g. Ardito, 2023; Ferreira et al., 2023; Findik et al., 2023). Table 2 presents the distribution of the sample by country and macro country characteristics.

3.2. Measures

The Flash Eurobarometer 486 survey is structured into specific sections, with distinct categories for sustainability actions (including environmental and social initiatives), barriers to sustainability, and digitalization (https://data.europa.eu/data/datasets/).

For the purpose of this study, we used the questions regarding the adoption of environmental sustainability practices as the dependent variable. To configure this variable, the questionnaire asked respondents to indicate, "In terms of environmental sustainability, which of the following practices, if any, is your Enterprise actively taking?" by listing four environmental actions. Each of these actions was treated as a binary variable, assigned a value of 1 if the action was taken or 0 otherwise. These dummy variables are not mutually exclusive, as an enterprise may adopt multiple environmental actions. Subsequently, an additive index was created as an average of the four items and termed "ENS".

In the section addressing sustainability barriers, respondents were asked to indicate, "Which of the following, if any, are currently preventing your enterprise from becoming sustainable?" by listing various internal and external barriers. Each response represents a binary variable, taking the value 1 if the enterprise faces that barrier or 0 otherwise. Following Malek and Desai (2021), three additive indexes were created for internal barriers by averaging these variables: knowledge-skill barriers (KSB), behavioural barriers (BHB), and managerial barriers (MGB).

Regarding digitalization, the survey asked respondents to specify, "Which of the following digital technologies, if any, has your enterprise adopted to date?", listing different technologies. Each of these takes value of 1 if the technology is adopted and 0 otherwise. The enterprises can adopt multiple digitalization technologies. A similar approach was adopted to create the additive index, labelled "DIG", which is used as an independent variable. (Please see Table 2).

This study uses the level of development as another variable. To achieve this, the questionnaire categorizes enterprises into a sample of 27 EU countries and 12 other non-EU countries, according to the country in which they operate. The survey itself does not explicitly classify countries as high or less developed. Therefore, we employed the statistics from the World Bank, considering gross national income (GNI) per capita (www.data.worldbank.org), and the World Economic Forum's Global Competitiveness Report (GCR) (www.weforum.org) for our classification. GCR evaluates the competitiveness landscape of 140 economies based on various criteria encompassing aspects related to economic performance, government efficiency, business efficiency and infrastructure. These four competitiveness indicators, along with their comprising sub-factors, together provide information on how countries manage their competencies to provide high levels of prosperity to their citizens. In this study, the role of country's level of development is assessed using the standardized value for GCR, termed "DVL". Furthermore, in this study, Bosnia and Herzegovina, Bulgaria, Brazil, Croatia, Hungary, Kosovo-Metohija, North Macedonia, Romania, Serbia, Poland and Turkey are considered as less-developed nations.

Following previous studies (Ardito, 2023; Findik et al., 2023), two sets of firm-specific factors-measuring firm size (the logarithm of the number of employees) and the logarithm of the annual turnover as a measure of total income from sales-are used in this study as control variables, labelled "Size" and "Turn". The variable "sector" controls for potential impacts arising from sectorial differences (Gillani et al., 2020), capturing the significance of sector-specific variation in digitalization and sustainability. However, our database does not differentiate among manufacturing sectors, which underscores the need for future research to explore and address these sector-specific nuances.

Table 3 reports descriptive statistics for our sample. Over half the sample (58%) adopts environmental sustainability practices, with specific action like recycling (67%), saving energy (62%), consumption reduction (58%) and sustainable product/service development (42%). Approximately 30% of those interviewed responded adopt and implement digital technologies, with cloud computing (54%) and smart devices (44%) being the most common. Regarding sustainability barriers, 28% cited consumer demand, 20% lack of awareness, 18% lack of skill, about 14% profitability concerns, 13% business model incompatibility, and 7% management's lack of willingness.

Table 4 presents the pairwise correlation between model variables. All correlation values are below the 0.70, suggesting multicollinearity is not a relevant issue. Environmental sustainability initiatives are positively and significantly correlated with digitalization and the level of development, as well as with both Knowledge and Behavioural barriers, which will be further analysed in the regression models.

Table 2
Distribution of sample by country and country characteristics.

No.	Country	GNI per Capita (current USD) year 2022[1]	HDI[2]	GCR[3]	Frequency
1	Austria	55,720	0.916	76.6	43
2	Belgium	53,890	0.937	76.4	36
3	Bosna and Herzegovina	7660	0.795	54.7	23
4	Bulgaria	13,350	0.754	64.9	64
5	Brazil	8140	0.936	60.9	31
6	Canada	52,960	0.896	79.6	28
7	Croatia	19,600	0.889	61.9	57
8	Cyprus	31,520	0.948	66.4	9
9	Czech Republic	26,100	0.89	70.9	29
10	Denmark	73,520	0.78	81.2	32
11	Estonia	27,120	0.94	70.9	57
12	Finland	54,930	0.903	80.2	46
13	France	45,290	0.942	78.8	55
14	Germany	54,030	0.887	81.8	37
15	Greece	21,810	0.858	62.6	39
16	Hungary	19,010	0.846	65.1	57
17	Iceland	68,660	0.945	74.7	20
18	Ireland	79,730	0.959	75.1	10
19	Italy	38,200	0.895	71.5	56
20	Japan	42,440	0.925	82.3	16
21	Kosovo-Metohija	5660	NA	71.67	7
22	Latvia	21,850	0.875	67	32
23	Lithuania	23,870	0.93	68.4	30
24	Luxembourg	89,200	0.863	77	8
25	Netherlands	60,230	0.77	82.4	24
26	North Macedonia	6660	0.941	57.3	21
27	Norway	95,520	0.961	78.1	13
28	Poland	18,900	0.876	68.9	64
29	Portugal	25,950	0.866	70.4	44
30	Romania	15,570	0.821	64.4	51
31	Serbia	9290	0.802	60.9	25
32	Slovakia	22,070	0.918	66.8	45
33	Slovenia	29,590	0.848	70.2	52
34	Spain	32,090	0.905	75.3	48
35	Sweden	63,500	0.947	81.2	45
36	Turkey	10,640	0.838	62.1	36
37	United Kingdom	49,240	0.929	81.2	11
38	United States of America	76,770	0.921	83.7	33
				Total	1334

Source: [1] World Bank; [2] Human Development report; [3] World Economic Forum

Table 3
Descriptive analysis.

Variable	Description	No. of Obs.	Mean	Sd.	Min	Max
Environmental Sustainability (ENS)		**1334**	**0.576**	**0.350**	**0**	**1**
Env01	Recycling or reusing materials	1334	0.674	0.469	0	1
Env02	Reducing consumption of or impact on natural resources	1334	0.582	0.493	0	1
Env03	Saving energy or switching to sustainable energy sources	1334	0.624	0.485	0	1
Env04	Developing sustainable products or services	1334	0.424	0.494	0	1
Digital Technologies (DIG)		**1334**	**0.296**	**0.232**	**0**	**1**
DIG01	Artificial intelligence, e.g., machine learning or technologies identifying objects or persons, etc.	1334	0.120	0.325	0	1
DIG02	Cloud computing, i.e., storing and processing files/data on remote servers hosted on the internet.	1334	0.541	0.498	0	1
DIG03	Robotics, i.e., robots used to automate processes	1334	0.308	0.462	0	1
DIG04	Smart devices, e.g., smart sensors, smart thermostats, etc.	1334	0.442	0.497	0	1
DIG05	Big data analytics, e.g., data mining and predictive analysis	1334	0.211	0.408	0	1
DIG06	High speed infrastructure	1334	0.397	0.489	0	1
DIG07	Blockchain	1334	0.052	0.223	0	1
Knowledge-Skill Barriers (KSB)		**1334**	**0.195**	**0.320**	**0**	**1**
STB01	Lack of awareness about how to integrate sustainability into the enterprise's business model.	1334	0.203	0.402	0	1
STB02	Lack of skills, including managerial skills	1334	0.187	0.390	0	1
Behavioural Barriers (BHB)		**1334**	**0.208**	**0.312**	**0**	**1**
STB03	Lack of consumer or customer demand	1334	0.280	0.449	0	1
STB04	It would not be profitable	1334	0.136	0.343	0	1
Managerial Behavioural (MGB)		**1334**	**0.102**	**0.226**	**0**	**1**
STB05	Lack of willingness among the management	1334	0.074	0.262	0	1
STB06	It is not compatible with your current business model	1334	0.129	0.335	0	1
Control Variables:						
DVL		1334	71.617	7.331	55	84
Size		1334	4.565	1.020	3.045	9.405
Turn		1334	15.627	2.119	1.386	18.369

4. Estimations and results

This study used the PROCESS macro proposed by Hayes (2017) for version 27.0 of IBM SPSS to validate the hypotheses. Due to the potential shortcomings of multiple regression analysis, particularly regarding the type I error about the mediation, Preacher and Hayes (2004) suggested a more powerful tool for estimating the size and significance of the effect and developed an SPSS macro program (i.e., PROCESS) (Li et al., 2020). Relying on a nonparametric bootstrapping procedure, PROCESS can assess a complex model including both mediator and moderator variables and has been widely used in prior studies (Li et al., 2020; Blichfeldt and Faullant, 2021). Since a multiple regression analysis should be conducted based on the PROCESS program, the variance inflation factor (VIF) was calculated for each model. The results show that the VIF values are lower than the threshold value of 5, confirming that multi-collinearity is not a serious issue for this study. Accordingly, the PROCESS types 4 and 7 were applied to examine the mediating effect of sustainability barriers (H1) and moderated-mediation effect of the level of development (H2b) on the relationship between digitalization, sustainability barriers and environmental sustainability adoption.

Table 5 shows the estimation results regarding the effect of digitalization on environmental sustainability practices through the effect on internal barriers for whole sample (mediation effect). By differentiating between high-developed and less-developed countries, the estimations also consider the effect of country context. In all three cases, Model 1 and its subsequent models (model 2 and model 3) provide estimation for the direct effects of sustainability barriers and digitalization, as well as the potential effect of sustainability barriers as mediators.

By conducting OLS regression for the whole sample, the results reveal that while digitalization significantly impact sustainability ($\beta = 0.573$, $p < 0.01$), managerial barriers are the main hindering factor for environmental sustainability adoption ($\beta = -0.107$, $p < 0.05$). However, the mediation effect of sustainability barriers in the link between digitalization and sustainability adoption illustrates insignificant effects, close to zero, for all three barriers (KSB: −0.001, $P > 0.1$; BHB: 0.000, $p > 0.1$; MGB: −0.003, $p > 0.1$). Furthermore, the country's level of development, as a controlling factor, reports a statistically significant and positive impact, justifying the division of the sample into two subsamples of high and less-developed countries.

Model 1 in both subsamples shows that among the three types of sustainability barriers, only managerial barriers hinder sustainability adoption in high-developed countries, while knowledge-skill barriers as well as behavioural barriers do not exhibit any statistically significant impacts (KSB: $\beta = 0.041$, $p > 0.1$; BHV: $\beta = -0.003$, $p > 0.1$; MGB: $\beta = -0.174$, $p < 0.05$). Regarding less-developed countries, while knowledge-skill barriers and managerial barriers do not affect the adoption, behavioural barriers prompt it (KSB: $\beta = 0.112$, $p > 0.1$; BHV: $\beta = 0.161$, $p < 0.1$; MGB: $\beta = 0.050$, $p > 0.1$).

Model 2 demonstrates a highly significant relationship between digitization and sustainability in both sub-samples (high-developed: $\beta = 0.599$, $p < 0.000$ and less-developed: $\beta = 0.591$, $p < 0.000$), indicating homogenous convergence between digitalization and sustainability adoption in manufacturing companies.

Model 3 in both sub samples provides statistically insignificant reports for the mediation effect of barriers, with value close to zero, indicating that the convergence between digitalization and sustainability is independent from sustainability barriers in both high-developed countries (mediation effect for KSB: −0.001, $P > 0.1$; BHB: −0.000, $p > 0.1$; MGB: 0.000, $p > 0.1$) and less-developed countries (mediation effect for KSB: 0.011, $P > 0.1$; BHB: 0.006, $p > 0.1$; MGB: −0.001, $p > 0.1$). In other words, digitalization has a significant influence on sustainability adoption but does not have a significant impact on explaining or reducing the effect of its barriers. This result could not provide sufficient evidence to support our initial hypothesis, therefore, H1 is rejected.

The results regarding the potential effect of the level of development are presented in Table 6. As evident, the direct effect of level of development on sustainability is statistically significant ($\beta = 0.102$, $p < 0.000$), thereby supporting hypothesis H2a.

Table 4
Correlation Matrix.

Variables	ENS	DIG	MGB	KSB	BHB	DVL	Size	Turn
ENS	1.0000							
DIG	0.4968*	1.0000						
MGB	−0.0015	0.0224	1.0000					
KSB	0.0560*	0.0241	0.2471*	1.0000				
BHB	0.0821*	0.0600*	0.1952*	0.2262*	1.0000			
DVL	0.3186*	0.2530*	0.0711*	0.0857*	0.1426*	1.0000		
Size	0.1365*	0.2215*	−0.1058*	−0.1031*	−0.0592*	0.0016	1.0000	
Turn	0.1852*	0.1440*	−0.0279	−0.0018	0.0343	0.2373*	0.2637*	1.0000

Table 5
Regression results for the mediation effect of sustainability barriers (Source: Authors' Estimation using PROCESS Model 4).

Variables:	Whole Sample			Developed Countries			Developing Countries		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Control variables									
Size	**0.043 (p=0.000)**	0.018 (p = 0.090)	0.016 (p = 0.124)	**0.041 (p=0.002)**	0.014 (p = 0.279)	0.012 (p = 0.299)	**0.060 (p=0.010)**	0.023 (p = 0.274)	0.030 (p = 0.192)
Turn	**0.013 (p=0.029)**	**0.011 (p=0.026)**	**0.011 (p=0.032)**	**0.023 (p=0.000)**	**0.015 (p=0.024)**	**0.015 (p=0.008)**	−0.008 (p = 0.460)	0.003 (p = 0.753)	0.002 (p = 0.842)
DVL	**0.096 (p=0.000)**	**0.067 (p=0.000)**	**0.065 (p=0.000)**						
Direct Effect:									
DIG– > KSB			−0.014 (p = 0.801)			−0.014 (p = 0.820)			0.108 (p = 0.323)
DIG– > BHB			0.020 (p = 0.695)			0.031 (p = 0.606)			0.037 (p = 0.656)
DIG– > MGB			0.027 (p = 0.471)			−0.001 (p = 0.991)			**0.174 (p=0.050)**
DIG– > ENS		**0.573 (p=0.000)**	**0.577 (p=0.000)**		**0.599 (p=0.000)**	**0.600 (p=0.000)**		**0.591 (p=0.000)**	**0.575 (p=0.000)**
KSB– > ENS	0.040 (p = 0.228)		0.047 (p = 0.130)	0.041 (p = 0.284)		0.047 (p = 0.174)	0.112 (p = 0.132)		0.101 (p = 0.149)
BHB– > ENS	0.019 (p = 0.585)		0.014 (p = 0.662)	−0.003 (p = 0.944)		−0.013 (p = 0.719)	0.161 (p = 0.060)		**0.166 (p=0.039)**
MGB– > ENS	**−0.107 (p=0.027)**		**−0.121 (p=0.005)**	**−0.174 (p=0.002)**		**−0.174 (p=0.005)**	0.050 (p = 0.589)		−0.006 (p = 0.944)
Mediation Effect:									
DIG– > KSB– > ENS			−0.0006, BootSE 0.0029, 95% IC (−0.0075, 0.0048)			−0.0006, BootSE 0.0035, 95% IC (−0.0089, 0.0060)			0.0109, BootSE 0.0166, 95% IC (−0.0163, 0.0505)
DIG– > BSB– > ENS			0.0003, BootSE 0.0019, 95% IC (−0.0031, 0.0049)			−0.0004, BootSE 0.0023, 95% IC (−0.0058, 0.0039)			0.0061, BootSE 0.0219, 95% IC (−0.0336, 0.0554)
DIG– > MSB– > ENS			−0.0033, BootSE 0.0053, 95% IC (−0.0150, 0.0064)			0.0001, BootSE 0.0073, 95% IC (−0.0149, 0.0143)			−0.0011, BootSE 0.0193, 95% IC (−0.0411, 0.0417)
F	22.57	92.38	45.50	8.37	69.11	32.56	2.79	16.29	7.55
Prob	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0188	0.0000	0.0000
R-Squared	0.1362	0.2668	0.2745	0.0616	0.2193	0.2350	0.0624	0.1470	0.1781
ΔR2		0.1306	0.008		0.1577	0.016		0.0846	0.031

However, the level of development demonstrates positive impacts on all three sustainability barriers (KSB: $\beta = 0.065$, $p < 0.01$; BHB: $\beta = 0.069$, $p < 0.01$; MGB: $\beta = 0.031$, $p < 0.05$), while the moderation effect of the level of development on the association between digitalization and sustainability barriers exhibits negative coefficients for all three barriers (KSB: $\beta = -0.108$, $p < 0.05$; BHB: $\beta = -0.074$, $p > 0.1$; MGB: $\beta = -0.080$, $p < 0.05$). This suggests that the convergence between digital technologies and the level of development can reduce the hindering effect of sustainability barriers, particularly knowledge-skill barriers and managerial barriers. This result indicates that mitigating the digital divide could lead to a reduction in barriers related to sustainability's knowledge and skills, as well as managerial perception of sustainability. However, the moderated mediation effect of the level of development on sustainability adoption through digitalization in the presence of sustainability barriers is statistically insignificant for all three sustainability barriers (the indirect effect for KSB: −0.006, $P > 0.1$; BHB: −0.003, $P > 0.1$and MGB: 0.010, $P > 0.1$), suggesting that the convergence between the level of development and digitalization is not able to promote the adoption of sustainability by overcoming sustainability barriers. Thus, H2b was not supported.

Finally, regarding the effect of control variables, a significant and positive impact from firm's annual turnover was observed for the adoption and usage of digitalization for the purpose of environmental sustainability practices, which suggests that larger firms tend to have more financial capacities to invest in digitalization initiatives aimed at promoting sustainability within their operations.

Table 6
Regression results for the moderated mediation effect of the level of development (Source: Authors' Estimation using PROCESS model 7).

Variables:	Environmental Sustainability	Environmental Sustainability
Control variables		
Size	**0.045 (p=0.000)**	0.009 (p = 0.384)
Turn	**0.013 (p=0.021)**	**0.018 (p=0.000)**
Direct Effect:		
DVL– > ENS	**0.102 (p=0.000)**	
DIG– > KSB		0.012 (p = 0.823)
DIG– > BHB		0.032 (p = 0.531)
DIG– > MGB		0.042 (p = 0.287)
DVL– > KSB		**0.065 (p=0.001)**
DVL– > BHB		**0.069 (p=0.000)**
DVL– > MGB		**0.031 (p=0.033)**
DIG*DVL– > KSB		**−0.108 (p=0.044)**
DIG*DVL– > BHB		−0.074 (p = 0.145)
DIG*DVL– > MGB		**−0.080 (p=0.037)**
DIG– > ENS		**0.645 (p=0.000)**
KSB– > ENS		0.058 (p = 0.065)
BHB– > ENS		0.033 (p = 0.306)
MGB– > ENS		**−0.129 (p=0.003)**
Indirect Effect:		
Index of DVL on DIG-KSB-ENS		−0.0063, BootSE 0.0048, 95%IC (−0.0176, 0.0010)
Index of DVL on DIG-BHB- ENS		−0.0025, BootSE 0.0034, 95% IC (−0.0109, 0.0027)
Index of DVL on DIG-MGB-ENS		0.0103, BootSE 0.0069, 95% IC (−0.0007, 0.0260)
F	43.22	44.80
Prob	0.0000	0.0000
R-Squared	0.1320	0.2398

4.1. Robustness test

As a robust test, the models were re-estimated with Structural Equation Modelling (through multivariate software EQS-6.4), yielding similar results for the mediation effect of sustainability barriers as well as the moderated mediation effect of the level of development. Model 1, testing the hypothesis 1, reports fit indexes: Chi Square: 486.30 (145 df), $p = 0.000$; CFI = 0.806, SRMR = 0.062 and RMSEA = 0.051 for high-developed countries, and Chi Square: 284.75 (145 df), $p = 0.000$; CFI = 0.791, SRMR = 0.063 and RMSEA = 0.047 for less-developed countries. Model 2, testing the hypothesis 2b, reports the following fit indexes: Chi Square: 796.86 (176 df), $p = 0.000$; CFI = 0.854, SRMR = 0.061 and RMSEA = 0.052, presenting reasonable fit for all three models for our sample (Bagozzi and Yi, 1988).

Next, the individual effects of each technology on sustainability barriers were examined. The results reveal different contributions across two contexts (high and less-developed countries). Specifically, in high-developed countries, only two technologies exhibit statistically significant relationships: AI impacts knowledge-skill barriers ($\beta = -0.144$, $p < 0.01$) and smart devices affect behavioural barrier ($\beta = 0.055$, $p < 0.05$). In contrast, in less-developed countries, additional technologies also demonstrate influence: Cloud Computing affects knowledge-skill barriers ($\beta = 0.114$, $p < 0.05$). This variation underscores the importance of tailored solutions that account for differences in infrastructure, available resources and technologies, and institutional capacity across nations. Notably, none of the digital technologies show an effect on overcoming managerial barriers. This highlights the need for further investigation into how digital technologies are currently utilized or integrated within companies. It could indicate that while digital tools may assist in knowledge transfer and behaviour modification, they might not directly address deeper organizational or managerial issues related to sustainability decision-making, resource allocation, or leadership strategies. Understanding these nuances is crucial for organizations aiming to leverage digital technologies for sustainability.

Additionally, the entire sample was grouped into three new subsamples based on the countries' size to address inter-regional development disparities: Large (USA, Canada and Brazil); Medium (e.g., Finland, France, Germany, and Spain); Small (e.g., Denmark, Estonia, and Greece). By running the models for H1, we observed that the positive link between digitalization and sustainability is maintained. It confirms the reliability of the initial estimation indicating that digitalization can enhance sustainability across regional contexts, despite developmental differences. Managerial barriers continue to play a dominant hindering role in medium and small subsamples, but not in large subsample. Specifically, digitalization significantly mitigates managerial sustainability barriers only in large countries, potentially due to stronger organizational capabilities and advanced regulatory frameworks. In contrast, medium and small countries, though developed, do not benefit as much from digitalization in overcoming these barriers, likely due to specific organizational and regulatory challenges unique to these regions.

Finally, the models were re-run using the GINI index (representing income inequality) as a proxy for the level of development. The estimation for H1 indicates that the GINI index, as a control variable in the model, shows an insignificant relationship, suggesting that the impact of digitalization on sustainability, as well as the interaction between digitalization and sustainability barriers to explain sustainability, are independent of the country's level of development. The estimation for H2a/b demonstrates that GINI index, as a moderator, has a positive direct impact only on managerial barriers. However, its interaction with digitalization shows insignificant relationships for all three barriers but negative direction. These findings suggest that in countries with higher income inequality (as indicated by a higher GINI index), there may be greater challenges related to managerial barriers in adopting sustainability practices, however the effect of digitalization in overcoming these barriers does not vary significantly with the level of development. These findings support the initial conclusion that the digital divide does not significantly affect the contribution of digitalization to sustainability.

5. Discussion of findings

The empirical evidence of this study supports the notion that digital technologies are crucial for advancing sustainability. However, this study delves deeper into the relationship between these two major industrial trends, particularly from the point of view of barriers to sustainability.

The estimates demonstrate that various internal barriers play different roles towards sustainability, and their significance varies depending on the environment in which companies operate. For example, while knowledge-skill barriers do not impact environmental sustainability adoption in both high-developed and less-developed countries, managerial barriers serve as obstacles only in high-developed countries. Furthermore, certain barriers are perceived as challenges that motivate sustainability adoption (Arroyabe et al., 2024). As observed, behavioural barriers serve as a driver of sustainability in less-developed countries.

Interestingly, while behavioural barriers show a negative coefficient

in high-developed countries, indicating a potential inhibitory effect, it is statistically insignificant. This suggests that resistance to change, stemming from a lack of customer demand or the perception of sustainability as non-profitable, may not significantly impede sustainability practices in high-developed countries but may motivate companies in less-developed countries to embrace practice aimed at saving energy or recycling/reusing materials. This discrepancy could be due to the complex interplay of factors such as environmental regulations, stakeholder pressures and organizational priorities in high-developed countries, leading managers to view sustainability as a deterrent to short-term objectives like profit-making and growth. As a result, sustainability barriers are perceived differentially across countries with varying socio-economic levels, highlighting the importance of addressing managerial barriers to foster sustainability adoption as "best practices" globally.

Our findings underscore that while digital technologies are key enablers of environmental sustainability, they still fall short in overcoming sustainability barriers. In other words, although digital technologies boost sustainability through mechanisms such as operational transparency, resource management and human capital development, they cannot be universally relied upon to overcome the challenges to sustainability adoption. This result contrasts with the conclusion made by other researchers (e.g., Chen et al., 2015; Guandalini, 2022). One explanation could be related to the high investment cost of implementing digital technologies that may hamper companies from adopting environmental practices demanding additional investment (Yadav et al., 2020a). Furthermore, efforts and resources are needed to simultaneously be allocated to the challenges related to the adoption and implementation of digitalization. Additionally, high energy consumption and e-waste generation of digital tools, and a lack of policy frameworks may hinder the promised advantages of digitalization for sustainability (Verma et al., 2022).

This study provides evidence that the country's level of development influences the adoption of sustainability as well as digitalization. This finding delineates an inherent duality: On one hand, higher levels of development amplify sustainability barriers, potentially due to a stronger national institutional environment (Ahmadova et al., 2022), which may lead to barriers being perceived more intensely in high developed countries. However, the negative interactions between the country's level of development and digitalization on the three sustainability barriers suggests that while the level of development of a country increases, the effectiveness of digital technologies in mitigating sustainability barriers also increases. The digital divide may explain this phenomenon, as manufacturing companies in less-developed countries, despite possessing high levels of IT expertise, may encounter greater challenges related to supportive national regulations, infrastructure limitations, or the application of digital technologies in sustainability-focused industrial activities at the corporate level. Thus, the effectiveness of digital technologies in addressing sustainability barriers is contingent upon the developmental context of the country in which they are implemented.

On the other hand, an insignificant moderated mediation index was observed for the level of development on the association between digitalization, sustainability and all three barriers. While acknowledging the existence of a digital divide across different economic contexts, suggesting that this divide does not substantially impact the interplay between digitalization and sustainability barriers in explaining sustainability adoption. In sum, in high developed countries, despite enhanced awareness of sustainability and strong technological infrastructure, know-how and financial resources to invest on digital technologies and sustainability initiatives, the convergence of the level of development with digitalization does not necessarily facilitate sustainability through mitigating its barriers in these nations. This could be due to various factors that need further investigation in future research. For instance, regulatory frameworks and national institutional environments may influence the perception of sustainability barriers differently, leading manufacturing companies in high-developed countries to rely on other organizational resources and practices better suited to their context. Digital technologies are not enough to substantially reduce sustainability barriers; complementary resources, strategies, or organizational practices are needed to address the challenges to sustainability and achieve sustainability goals.

6. Conclusions, implications and limitations

6.1. Conclusion

Understanding how digital technologies can contribute to sustainability is essential for integrating sustainability practices into their use. This study sought to advance the knowledge on the interplay between digitalization and the adoption of sustainability practices in manufacturing by considering influential contextual factors, including sustainability barriers and a country's level of development. The literature review highlights the challenge of comprehending the relationships between these elements, which may seem intuitive at first glance but are subject to the influence of various external and internal factors. The empirical analysis of this study shows that despite the existence of a digital divide in different socio-economic contexts, the convergence of digital technologies and sustainability is homogenous across high-developed and less-developed countries. Nevertheless, digital technologies still fall short in playing a pivotal role in overcoming sustainability barriers. Additionally, it is observed that the level of development influences the effectiveness of a company's digitalization efforts for addressing sustainability barriers. However, the convergence between the level of development and digitalization could not help manufacturing promote sustainability by mitigating its barriers. This study offers evidence underscoring that both digitalization and sustainability emerge as distinct strategic goals that may intersect, but their trade-off to overcome sustainability barriers require complementary strategies as well as managerial/organizational resources and practices at corporate level.

6.2. Implications

While challenges to sustainability limit the adoption of sustainable practices, companies often fail to realize the inherent benefits of sustainability (Ahmadi-Gh and Bello-Pintado, 2022). Digitalization and sustainability are often viewed as separate organizational goals that may conflict (Guandalini, 2022). Many companies adopt digitalized manufacturing practices primarily to increase competitiveness rather than to boost sustainability (Satyro et al., 2022). By establishing a path between digitalization, sustainability barriers and sustainability, our study aimed to contribute to the academic discourse on using digitalization for sustainability purposes. Understanding these nuances is crucial for organizations seeking to leverage digital technologies for sustainability. As observed, integrating digitalization and sustainability involves navigating complex relationships influenced by contextual factors such as sustainability barriers and a country's level of development. Managers and policy makers should be prepared to address these complexities through comprehensive strategies.

Regardless of socio-economic development, we encourage managers to implement digital technologies to promote environmental sustainability. However, they should align digital tools with their broader organizational strategies to address various sustainability challenges.

Additionally, specific sustainability barriers may serve as obstacles in one nation, but as driving factors in another. Actions to identify and address these barriers may vary from country to country, especially due to differences in infrastructure, available resources and institutional capacity (Ahmadova et al., 2022). Digital technologies alone are insufficient to tackle sustainability barriers directly, particularly managerial barriers. Therefore, addressing sustainability barriers requires considering national regulations, infrastructures, and a company's capability to use digital technologies in sustainability-focused activities.

A one-size-fits-all approach to sustainability through digitalization may not effectively address the diverse challenges faced by manufacturing companies in different countries. Understanding the unique socio-economic, environmental, and cultural factors influencing each context is essential, even in countries with high levels of IT expertise. Hence, managers should adopt complementary approaches such as organizational culture shifts, leadership commitment, or structural changes, particularly in less developed nations. Integrating sustainability practices supported by digitalization requires fostering a corporate culture that values sustainability as a central goal seeking not only economic growth, but also social and environmental development. Moreover, an ethical approach should be adopted in the implementation of digital technologies, addressing issues related to data privacy, cybersecurity, and equity in access to technologies.

The convergence of digitalization and sustainability unifies across different socio-economic contexts. While highly developed countries, due to their regulatory framework and strong industrial base, facilitate the effective integration of digital technologies into sustainability initiatives, emerging markets and countries with inter-regional disparities may face greater challenges related to digital infrastructure and regulatory support. Considering the digital divide, governments should promote digital transformation with a triple bottom line perspective, creating incentives for companies to adopt digital tools targeting sustainability barriers. Policymakers in emerging economies should prioritize building digital infrastructure and providing training programs to enhance digital literacy of the workforce. In this vein, the implementation of Industry 4.0 standards in advanced countries offers valuable case studies for other nations to benchmark (Luthra et al., 2020). However, it is crucial to recognize the importance of contextual factors, such as regulatory frameworks, institutional environments, and infrastructure differences, in shaping the effectiveness of digitalization and sustainability initiatives. Hence, policy makers should tailor their approaches to account for these contextual factors when reconciling digitalization and sustainability.

This paper contributes to academia in several ways. Firstly, it responds to the call for further investigation on the use of digitalization for sustainability (Guandalini, 2022; Matt et al., 2023). By undertaking a multidisciplinary approach, this article links digitization, sustainability, its barriers and the level of development to visualize the trade-offs between digitization and sustainability within the context of countries' developmental levels in manufacturing. The integration of these dimensions is innovative and provides a comprehensive understanding of how digital technologies can be strategically leveraged to overcome sustainability challenges and how the country's level of development interacts in this relationship. This new knowledge can help provide better academic responses to practical issues around sustainability (Guandalini, 2022). Secondly, the research provides empirical evidence from 1334 manufacturing companies employing more than 20 employees across 38 diverse countries, encompassing both highly developed and less-developed settings. The database allows distinguishing between different sustainability barriers (Knowledge-skills; Behavioural; Managerial) for the adoption of environmental sustainability. In sum, this study sheds light on how digitalization works in different context for sustainability and opens new doors for researching in the field.

6.3. Limitations

This study has some limitations that future research could address. One primary limitation is the nature of our database, which shows a positive correlation between sustainability barriers and sustainability adoption. This suggests that certain sustainability barriers are perceived not as obstacles but as challenges that motivate sustainability adoption, indicating a potential bias in barriers perception. Further analysis is needed to provide a more nuanced understanding of these barriers.

Additionally, our findings indicate that digital technologies cannot effectively tackle managerial barriers to sustainability. Future research should investigate how digital technologies can address these managerial barriers, considering technical, economic, cultural, and ethical perspectives. Understanding how companies can overcome contextual barriers using digitalization will offer valuable insights to promote sustainable practices in various contexts.

CRediT authorship contribution statement

Zahra Ahmadi-Gh: ahmadi@unavarra.es, Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alejandro Bello-Pintado:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Data availability

The data that has been used is confidential.

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