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Innovation dynamics across institutional environments: regulatory exposure and geopolitical shocks in nanotechnology

David Svoboda^{a,b} , Michaela Matoušková^a  and Ondrej Havelka^{c,d} 

^aFaculty of Economics, Technical University of Liberec, Liberec, Czech Republic; ^bDepartment of Economics, Ambis University, Prague, Czech Republic; ^cDepartment of Chemistry, Faculty of Science, Humanities and Education, Technical University of Liberec, Liberec, Czech Republic; ^dInstitute for Molecular and Multimaterial Manufacturing, Hamburg University of Technology, Hamburg, Germany

ABSTRACT

Nanotechnology represents a general-purpose technology with significant transformative potential across industrial sectors. Its commercialization, however, unfolds within regulatory systems that differ across application domains and countries, making institutional exposure a strategic condition rather than a background factor. This study examines how geopolitical shocks and EU nano-specific regulatory provisions are associated with nanotechnology patenting in the United States, Germany, and Japan from 2004 to 2023. We contribute to innovation-management and institutional-theory debates by linking three elements that are usually analyzed separately: application-domain selection, regulatory exposure, and crisis-period innovation responses. A structured Scopus search, confirmed with Scite, is used to consolidate nanotechnology applications into eight market-relevant domains, which are then mapped to EU regulatory instruments. Patent counts are analyzed with PPML estimations and a Germany-focused difference-in-differences/event-study design. The results show strong positive shock-period patenting in the United States, weaker German responses, and a post-2020 relative decline in Germany's nano-specific regulated domains. The study offers managers a transparent and auditable framework for evaluating nanotechnology portfolios through technological potential, regulatory exposure, and institutional responsiveness.

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1. Introduction

In contemporary business environments characterized by regulatory complexity and geopolitical volatility, innovation management has become deeply embedded in institutional structures that shape strategic decision-making (Vasudeva et al., 2013). Firms no longer innovate in neutral market conditions; rather, they operate within multilayered governance systems that influence opportunity structures, risk allocation, and the expected returns on research and development investments (Aghion et al., 2023; Renda & Pelkmans, 2023). From the perspective of strategic management and institutional theory, regulation is not merely a constraint but a structuring force that actively shapes firm behavior, technological trajectories, and competitive positioning (Luo et al., 2022). Understanding how regulatory frameworks interact with uncertainty is therefore essential for explaining heterogeneous innovation outcomes across sectors and national contexts.

Regulatory exposure affects portfolio allocation decisions, the timing of commercialization, and the configuration of organizational capabilities required to navigate compliance-intensive sectors (Fahad et al., 2022; Sun et al., 2021). These challenges are particularly relevant in nanotechnology, where firms face a strategic paradox. Nanotechnology is regarded as a general-purpose technology with extraordinary transformative potential across industrial sectors (Mangematin & Walsh, 2012). As a technology with

CONTACT Ondrej Havelka  ondrej.havelka@tul.cz  Faculty of Science, Humanities and Education, Technical University of Liberec, Studentská 1402/2, 461 17 Liberec, Czech Republic.

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broad spillover effects, it enables the emergence of radical innovations capable of responding to crisis situations, such as the impacts of the war in Ukraine or the COVID-19 pandemic (Sitnicka & Serhiienko, 2025; Trčka et al., 2025).

However, the application potential of nanotechnologies is significantly shaped by an environment of regulatory fragmentation. Particularly within the EU, nanotechnologies are subject to strict safety requirements, and the burden of proof regarding safety is systematically shifted onto innovators (Miernicki et al., 2019; Rasmussen et al., 2025). As a result, technological potential alone does not guarantee market success. Strategic decision-making in technology management must therefore encompass not only an analysis of technological characteristics and current calls for relevant, rigorous and societally useful innovation research (Liguori et al., 2024a; 2024b), but also a systematic evaluation of regulatory conditions and the institutional context that shapes application potential (Aghion et al., 2023).

Empirical evidence suggests that the effects of regulation on innovation are not necessarily associated with a negative impact on innovation activity and depend on the specific design of the regulatory framework (Blind, 2012; Wu & Tham, 2023). At the same time, regulation often acts as a structural variable influencing the strategic return on R&D investments (Ma et al., 2024). This study therefore examines how geopolitical shocks and regulatory frameworks are associated with nanotechnology innovation across application domains that differ in regulatory exposure and institutional intensity.

The research in this study uses patent activity as a proxy indicator of the application potential of nanotechnologies within individual domains. Patent data therefore make it possible to capture the dynamics of technological trajectories and the relative attractiveness of individual sectors in terms of future market deployment.

A structured bibliometric search was used to identify recurring application labels in the nanotechnology literature, which were then consolidated into eight market-relevant application domains according to a documented coding key. These domains provide an analytically comparable taxonomy for patent and regulatory mapping rather than an exhaustive classification of all nanotechnology applications.

The COVID-19 pandemic in 2020 and the war in Ukraine in 2022 represented significant geopolitical shocks that fundamentally disrupted the global economic environment. Such shocks may induce more cautious innovation strategies but may also stimulate technological development in response to urgent new demands (Bettarelli et al., 2024; Bhattacharya et al., 2017; Chin, 2019; Moretti et al., 2025; Trčka et al., 2025).

The empirical part of the study further analyzes patent activity in the three largest G7 economies, the United States, Germany, and Japan, over the period 2004 to 2023, and examines how geopolitical shocks and regulatory interventions are reflected in the innovation performance of individual domains.

This article makes three contributions. First, it extends innovation-systems and institutional-theory debates by treating regulation as a domain-specific moderator of crisis-period innovation responses, rather than as a uniform country-level constraint. Second, it operationalizes regulatory exposure in nanotechnology through domain-classification that links literature-based application domains to patent-search queries and EU sectoral legal provisions. Third, it translates these institutional differences into a technology-management framework that helps firms assess where nanotechnology patents appear to grow fastest and where compliance-intensive market-entry pathways may reduce short-term innovation output.

Geopolitical shocks create demand and supply disruptions that can stimulate urgent technological search but can also delay formal innovation outputs. Regulatory exposure conditions the conversion of these shocks into patenting by increasing data-generation requirements, approval uncertainty, and compliance costs in selected domains. National institutional environments further shape absorptive capacity, financial depth, and the speed with which firms can respond.

Against this background, we formulate three research questions:

RQ1. Which market-relevant application domains can be identified and consolidated from the nanotechnology literature, and which of these domains exhibit the strongest application growth potential in patent data?

RQ2. How do geopolitical shocks (COVID-19 and the war in Ukraine) differentially influence innovation dynamics across major institutional environments?

RQ3. Has regulatory tightening after 2020 altered the relative innovation performance of regulated nanotechnology domains compared to unregulated ones in Germany?

We address these questions using a mixed-method research design that combines bibliometrics, regulatory mapping, and econometric analysis. First, a structured literature review consolidates more than thirty subfields into eight main application domains, which are then matched with EU regulatory instruments (horizontal versus sector-specific). Second, we use a twenty-year panel of patent counts (2004–2023) for the United States, Germany, and Japan as a tangible proxy indicator of the application potential within these domains. Finally, we combine panel PPML estimations to identify cross-country responses to shocks with a two-way fixed-effects DiD/event-study approach for Germany, in order to estimate the post-2020 association between nano-specific regulatory exposure and patenting relative to unregulated domains. This triangulation clarifies how governance choices and external shocks jointly translate into national innovation systems over time.

The analysis yields the following main findings. During the pandemic and the war in Ukraine, the rate of patent growth increased substantially in the United States, whereas in Germany the responses were much weaker. In Germany, regulated domains also show a persistent decline in patent counts after 2020 relative to unregulated ones, with flat pre-trend coefficients and negative, statistically significant post-2020 estimates. For policy practice, this suggests that the intensity and timing of regulation may matter: during periods of geopolitical uncertainty, regulatory design can be associated with materially different innovation trajectories across domains.

2. Materials and methods

The first objective of this study is to construct a transparent and analytically comparable classification of market-relevant nanotechnology application domains and to map the corresponding European Union regulatory frameworks governing market introduction within those domains. To achieve this, a multi-level methodological framework was adopted, combining bibliometric and patent analyses with a qualitative regulatory review. The bibliometric component relied on a structured database-based screening and thematic consolidation procedure. This approach aligns with a dual research focus: (1) identifying the primary technological domains where nanotechnologies are being actively applied, and (2) analysing the relevant EU regulatory mechanisms within those domains. The integration of multiple data sources and analytical methods allows for methodological triangulation, thereby enhancing the robustness and credibility of the findings.

The methodology was structured in four interlinked phases: (i) bibliometric analysis of scientific literature, (ii) classification of nanotechnology subdomains, (iii) patent data analysis for assessing technological trends and commercial relevance, and (iv) regulatory mapping. Each phase was designed to complement the others, enabling cross-validation of data across independent sources.

2.1. Bibliometric literature analysis

Bibliometric analysis was performed using the Scopus database of peer-reviewed scientific articles and cross-checked with Scite. Scopus was used as the primary retrieval source, while Scite served as a confirmatory citation-based source for checking whether the main application areas generated by the Scopus search were also visible in citation-supported outputs. No time-interval filter was applied. The Scopus and Scite searches were conducted on 4 November 2025; consequently, the retrieved corpus was treated as a dynamic database snapshot rather than as a permanently fixed set of publications.

Scopus Boolean string: (("nanomaterial" OR "nanomaterials" OR "nanoparticle" OR "nanoparticles" OR "nanocomposite" OR "nanocomposites" OR "nanofiber" OR "nanofibers" OR "nanostructure" OR "nanostructures") AND ("area" OR "application" OR "field" OR "sector" OR "branch")).

Scite prompt: In which areas are nanotechnologies used? The prompt was used only to confirm domain relevance and did not replace the Scopus search or introduce an automated frequency threshold.

Following the bibliometric results, the identified application subfields were consolidated through a documented thematic coding key. The coding key comprised four rules: (1) semantic equivalence, under which synonyms and closely adjacent subfields were merged under a broader market domain; (2) product

relevance, under which purely theoretical or material-property terms without a clear product or market-entry context were excluded; (3) patent-query feasibility, under which the domain had to be searchable with a stable keyword in PatentInspiration across the full period and all three countries; and (4) regulatory mappability, under which the domain had to be linkable to horizontal or sector-specific EU regulatory instruments.

Under this procedure, more than thirty narrower labels were consolidated into eight domains: Healthcare, Cosmetics, Agriculture, Food, Textiles, Electronics, Energy, and Environmental Remediation. The eight-domain structure was therefore not obtained from an arbitrary or invented numerical cutoff. It resulted from the Scopus-based application search, Scite confirmation, removal of non-market and overly narrow terms, and the need to maintain categories that could be compared consistently in patent and regulatory data. Ambiguous labels were retained only when they could be assigned to one of the eight domains without changing the meaning of the application context. The resulting eight domains should therefore be interpreted as stable analytical categories that were repeatedly visible in the literature-based search and suitable for subsequent patent and regulatory comparison, rather than as an exhaustive list of all emerging nanotechnology application areas.

2.2. Patent data analysis for quantitative trends

To complement the literature perspective on the application of nanotechnologies, we conducted a quantitative patent analysis for each of the eight identified areas. In this context, patent data serves as an indicator of the course of application potential in selected countries in the time interval from 2004 to 2023. To identify the shares of each area, we used the PatentInspiration online patent search with its global patent database.

PatentInspiration was selected because it allows worldwide patent searches using keyword logic comparable to the Scopus query. Each patent query used the same nanotechnology keyword block and added one final-domain keyword. The search template was: (("nanomaterial" OR "nanomaterials" OR "nanoparticle" OR "nanoparticles" OR "nanocomposite" OR "nanocomposites" OR "nanofiber" OR "nanofibers" OR "nanostructure" OR "nanostructures") AND [application domain]). For Healthcare, medicine and pharmacy terms were consolidated because both belong to the same healthcare market-entry pathway in the regulatory mapping. Annual patent counts were extracted for 2004–2023 for the United States, Germany, and Japan.

The United States, Germany, and Japan were selected because they are large G7 economies with substantial patenting activity and distinct institutional environments. Germany provides the EU case in which nano-specific sectoral provisions can be linked to country-level patent counts, while the United States and Japan provide non-EU comparator economies. This selection supports cross-country comparison while keeping the dataset balanced across domains and years.

2.3. Integration of methods and data triangulation

The integration of methods followed a sequential triangulation logic. The bibliometric step defined the application domains; the same domains then structured the PatentInspiration searches; and the regulatory review classified each domain according to the presence or absence of nano-specific EU provisions. The econometric models used this classification to estimate whether patenting trajectories differed by country, shock period, and regulatory exposure. This sequence reduces dependence on any single data source, although it cannot remove all omitted-variable concerns.

The key operational variables are therefore directly traceable to the preceding steps: Patents is the annual domain-country patent count; COVID equals 1 for 2020–2021; Ukraine equals 1 for 2022–2023; Regulated equals 1 for Healthcare, Cosmetics, Agriculture, and Food because these domains have nano-specific EU provisions beyond REACH; Post-2020 equals 1 from 2020 onward; and the German DiD variable is the interaction between Regulated and Post-2020.

2.4. Statistical analysis

To investigate RQ2, namely the heterogeneous effects of the COVID-19 pandemic and the war in Ukraine on patent activity in the three largest G7 economies, we employ a Poisson pseudo-maximum-likelihood

(PPML) model estimated within the generalized linear model (GLM) framework with country and sector fixed effects. Our panel dataset consists of annual observations for three innovation-oriented economies (the United States, Germany, and Japan), disaggregated into eight major industrial sectors over the period 2004 to 2023. Each observational unit corresponds to a unique combination of country and sector, yielding 24 cross sections observed across twenty years, for a total of 480 observations. This design allows the identification of both cross-country differences and sectoral heterogeneity. The United States serves as the reference category, while Germany and Japan enter the model via country dummies. Sectoral fixed effects are included by means of seven binary indicators, with one of the eight sectors omitted as the reference category.

The dependent variable is the annual number of patents. Given the count nature of the data, with non-negative integer values and the presence of zeros, the analysis employs the Poisson pseudo-maximum likelihood (PPML) estimator, implemented as a generalized linear model with Poisson family and log link. According to Mnasri and Nechi (2021), PPML provides consistent parameter estimates under general forms of heteroskedasticity, even in the presence of overdispersion and is well suited for handling zeros in the dependent variable. Robust Huber–White standard errors are employed to ensure valid inference without relying on the restrictive Poisson variance assumption (Motta, 2019).

The primary focus of the analysis is on the impact of two major global shocks, the COVID-19 pandemic and the war in Ukraine, on patenting activity. The effect of these shocks in the reference country (the United States) is captured by the coefficients on the COVID and Ukraine indicators, while cross-country heterogeneity is identified through interaction terms between the shock indicators and the country dummies for Germany and Japan. This specification disentangles the baseline effect of each shock in the United States from the additional deviations observed in Germany and Japan. Country and sector fixed effects are included to control for time-invariant national characteristics and persistent cross-sectoral differences in innovation intensity.

The choice of the Poisson pseudo-maximum likelihood (PPML) estimator is motivated by both the nature of the data and the theoretical advantages of the method. First, the dependent variable is the number of patents, a non-negative integer with naturally occurring zeros. Traditional log-linear models that apply OLS to the logarithm of the dependent variable encounter the fundamental problem that $\log(0)$ is undefined and often produce biased estimates (Krisztin & Fischer, 2015). PPML circumvents this issue by modeling the logarithm of the conditional expectation rather than the logarithm of the observed outcome, thereby allowing for a consistent treatment of zeros.

PPML is also robust to heteroskedasticity and overdispersion, which are common features of patent data, since the variance of patent counts typically exceeds their mean. As demonstrated by Silva and Tenreyro (2006), PPML yields consistent parameter estimates as long as the conditional mean is correctly specified, even if the variance is not. PPML results are directly interpretable in terms of incidence rate ratios (IRR), which can be straightforwardly converted into percentage changes. This property makes the coefficients easily interpretable as relative changes in patenting activity associated with the shocks under study, directly aligning with the research question focused on heterogeneous effects of the COVID-19 pandemic and the war in Ukraine across countries. Alternative count-data models, such as the negative binomial GLM, can be used as robustness checks, but are not required in the main specification. While the negative binomial explicitly models overdispersion, PPML, implemented through the Poisson GLM, is generally preferred in empirical work (Weidner & Zylkin, 2021) because it does not rely on assumptions about the exact variance structure and provides consistent estimates under general forms of heteroskedasticity.

Consistent with the Poisson pseudo-maximum likelihood (PPML) approach, the conditional expectation of patent counts y_{cst} in country c , sector s , and year t is specified as

$$E[y_{cst} | X_{cst}] = \exp(\alpha + \beta_1 \text{COVID}_t + \beta_2 \text{UKR}_t + \gamma_c + \delta_s + \theta_c^{\text{cov}} (\text{COVID}_t \cdot D_c) + \theta_c^{\text{ukr}} (\text{UKR}_t \cdot D_c)) \quad (1)$$

where γ_c denotes country fixed effects, δ_s denotes sector fixed effects, and D_c is the country indicator. The coefficients β_1 and β_2 capture the baseline effects of the COVID-19 pandemic and the war in Ukraine in the US, while the θ_c parameters measure the additional deviations in Germany and Japan relative to the US.

The interpretation of results follows from the log link specification. Coefficients are transformed into incidence rate ratios (IRR) by exponentiation, and percentage changes are reported as $100(\exp(\beta)-1)$. Accordingly, the baseline effects of the shocks in the US correspond to the coefficients on the COVID-19 and Ukraine indicators, while the total effect in Germany and Japan is obtained by adding the baseline coefficient and the relevant interaction. Wald tests are conducted to examine heterogeneity hypotheses, both jointly, testing whether Germany and Japan differ from the US, and pairwise, testing whether Germany and Japan differ from each other.

To estimate the relationship between regulatory exposure and innovation outcomes, the empirical analysis is confined to the German subsample of the dataset. This within-country design avoids many confounding effects arising from cross-national differences in legal frameworks, innovation systems, or macroeconomic environments. At the same time, the estimates should be read as a comparison of relative patenting trajectories around post-2020 regulatory exposure, not as a complete causal experiment.

The identification strategy relies on the assumption that, in the absence of nano-specific regulatory tightening, the trajectories of patent activity in regulated and unregulated sectors would have evolved similarly. This parallel-trends assumption cannot be tested directly. Its plausibility is assessed using pre-2020 event-study coefficients, but the post-2020 period also overlaps with COVID-19, supply-chain disruptions, and other sector-specific shocks. The revised interpretation therefore treats the German estimates as evidence consistent with a regulatory-exposure mechanism rather than as definitive proof of a regulatory cause.

To account for unobservable time-invariant sectoral characteristics, such as differences in baseline R&D intensity, market maturity, or technological capabilities, the model includes sector fixed effects (Ke et al., 2024). Year fixed effects are also incorporated to control for macroeconomic shocks or structural changes affecting all sectors simultaneously, such as the COVID-19 pandemic or the war in Ukraine. These specifications are designed to estimate the conditional post-2020 association between nano-specific regulatory exposure and patenting by leveraging cross-sectional variation across sectors and temporal variation before and after the relevant regulatory period. They do not, by themselves, eliminate all sector-specific post-2020 confounders.

The estimated coefficient on the interaction term between the regulation indicator and the post-2020 period captures the conditional post-2020 difference in patenting between regulated and unregulated domains, net of persistent sectoral characteristics and year-specific shocks included in the model.

The following panel regression model is estimated using least squares with fixed effects (Goodman-Bacon, 2018):

$$\text{Patents}_{it} = \alpha + \beta_1 \cdot \text{Treated}_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (2)$$

where

- Patents_{it} is the number of patents in sector i at time t ,
- Treated_{it} is DiD interaction term equal to 1 for regulated sectors after 2020, and 0 otherwise,
- γ_i are sector fixed effects, controlling for time-invariant heterogeneity,
- δ_t are year fixed effects, accounting for time-specific shocks,
- ε_{it} is the error term.

The parameter of interest is β_1 , which captures the average conditional post-2020 difference in patent activity in regulated sectors relative to unregulated ones. Because all treated domains are exposed after 2020 and the sectoral setup is small, β_1 is interpreted together with the event-study coefficients, robustness diagnostics, and the limitations discussed below.

We employ the White period (cross-section cluster) covariance estimator (MacKinnon et al., 2023) to compute standard errors that are robust to arbitrary forms of heteroskedasticity and contemporaneous correlation within time periods. This adjustment is important because policy shocks and macroeconomic disruptions may affect multiple sectors simultaneously. The small number of sectors nevertheless limits the precision of inference, and the revised discussion explicitly treats the German DiD results as indicative rather than conclusive.

To examine the dynamic association between sector-specific EU regulatory interventions and patent activity in Germany, an event-study extension of the standard difference-in-differences (DiD) approach was employed. The analysis is restricted to German sectors only, thereby isolating within-country variation in regulatory exposure while controlling for macroeconomic shocks affecting all sectors through year fixed effects. A set of binary treatment variables was constructed to capture the interaction between the treated sectors (Healthcare, Cosmetics, Agriculture, and Food) and individual years between 2016–2023. These interactions allow both visual and statistical assessment of pre-2020 trends and the persistence of post-2020 differences.

As an additional robustness diagnostic addressing potential concerns regarding spurious regression and trend behavior in patent-count data, a Levin-Lin-Chu (LLC) panel unit-root test was conducted for the four regulated German patent-domain series that constitute the treated group in the DiD specification (Levin et al., 2002). The LLC test was used because each series contains only twenty annual observations, while the panel procedure pools information across domains and provides a joint test of the unit-root null. The diagnostic focused on the regulated German domains because these domains represent the regulatory-exposure group whose post-2020 patenting trajectory is central to the DiD and event-study interpretation. The LLC procedure was estimated with individual intercepts and automatic lag selection for the period 2004–2023. Given its assumption of a common autoregressive coefficient across domains, the test is interpreted only as a supplementary panel-level diagnostic.

3. Results

3.1. Main areas of nanotechnology application and their regulatory framework in EU

The bibliometric analysis, combining Scopus with Scite confirmation under the coding protocol described above, identified more than thirty discrete application labels and consolidated them into eight overarching domains: Agriculture, Energy, Environmental Remediation, Electronics, Healthcare, Cosmetics, Food, and Textiles. These domains capture the main market-oriented trajectories of applied nanoscience and provide the taxonomy used in both the patent searches and the regulatory classification. In this sense, Table 1 is not only descriptive; it operationalizes the regulatory-exposure variable used in the German DiD and event-study analysis.

Mapping the eight domains onto European Union regulatory instruments reveals a clear distinction between domains with nano-specific sectoral provisions and domains governed mainly through horizontal or general rules. The horizontal framework for nanomaterial governance is provided by REACH (Regulation (EC) No 1907/2006), which operationalizes the precautionary principle by assigning to manufacturers the burden of demonstrating safety under scientific uncertainty. Sectoral instruments extend this framework in four application areas: the Medical Devices Regulation (Regulation (EU) 2017/745), the Cosmetics Regulation (Regulation (EC) 1223/2009), the Biocidal Products Regulation (Regulation (EU) No 528/2012), and the Novel Foods Regulation (Regulation (EU) 2015/2283).

Based on the presence of these nano-specific provisions, Healthcare, Cosmetics, Agriculture, and Food were classified as regulated domains, while Energy, Electronics, Environmental Remediation, and Textiles were categorized as unregulated for the purposes of the DiD model. This binary coding does not mean that the latter domains are free from regulation. It means that, within the scope of this study, they do

Table 1. Overview of sector-specific regulatory frameworks and application of the precautionary principle in EU (Germany).

Application area	EU regulatory framework in addition to REACH	Valid From	Amendment regulating nanomaterials	Valid from
Healthcare	Medical Devices Regulation (EU 2017/745)	May 2021	Delegated Regulation (EU) 2023/502	March 2023
Cosmetics	Cosmetics Regulation (EC 1223/2009)	July 2013	Regulation (EU) 2021/850 concerning the extension of Annex II	October 2021
Agriculture	Biocidal Products Regulation (EU No 528/2012)	September 2013	Delegated Regulation (EU) 2021/525	April 2022
Food	Novel Foods Regulation (EU 2015/2283)	January 2018	Commission Regulation (EU) 2022/63	February 2022

not face comparable nano-specific EU sectoral provisions beyond the horizontal REACH framework. Heterogeneity within the regulated group is therefore acknowledged as a limitation of the empirical design.

3.2. Geopolitical shocks: COVID 19 and the war in Ukraine (PPML analysis)

The effects of major geopolitical shocks, the COVID-19 pandemic and the war in Ukraine, on nanotechnology patenting were examined using a Poisson pseudo-maximum likelihood (PPML) estimator on a balanced panel comprising three countries and eight sectors over the period 2004–2023 ($N=480$). Country and sector fixed effects were included to absorb unobserved heterogeneity. The raw patent counts are reported in [Supplementary Materials, Tables S1–S8](#), while the Wald tests and model diagnostics are reported in [Tables S9 and S10](#).

The results indicate substantial cross-country heterogeneity in shock-period patenting responses ([Table 2](#)). In the United States, both shocks coincide with statistically significant increases in patenting intensity ([Figure 1](#)). During the COVID-19 shock, patent counts increased by approximately 74% (incidence rate ratio (IRR) = 1.74, $p < 0.001$), while during the war in Ukraine, patenting rose by 65% (IRR = 1.65, $p = 0.002$). These values serve as the baseline reference for comparative interpretation.

In Germany, the estimated interaction terms for both shocks suggest a markedly attenuated innovation response. During the pandemic, German patenting rose by around 31% (IRR = 1.31, $p = 0.019$), and during the war in Ukraine, by 13% (IRR = 1.13, $p = 0.008$). Wald tests confirm significant cross-country heterogeneity relative to the U.S. baseline (COVID-19: $\chi^2 = 7.87$, $p = 0.005$; Ukraine war: $\chi^2 = 15.55$, $p < 0.001$; see [Supplementary Materials, Table S9](#)).

Table 2. PPML estimation results for patenting activity, 2004–2023.

Variable	Coefficient	Std. Error	z-Statistic	p-value
GER	−1.869	0.065	−28.54	0.000
JAP	−1.148	0.079	−14.56	0.000
Healthcare	1.629	0.116	14.07	0.000
Cosmetics	0.341	0.090	3.81	0.000
Food	1.281	0.104	12.28	0.000
Electronics	2.513	0.088	28.56	0.000
Energy	2.301	0.086	26.72	0.000
Environment	−1.273	0.125	−10.21	0.000
Textile	−0.176	0.094	−1.86	0.063
COVID_dummy	0.551	0.083	6.67	0.000
Ukraine_dummy	0.503	0.083	6.05	0.000
COVID×GER	−0.282	0.100	−2.81	0.005
COVID×JAP	−0.206	0.155	−1.33	0.184
Ukraine×GER	−0.383	0.097	−3.94	0.000
Ukraine×JAP	−0.191	0.163	−1.17	0.243
Constant	6.831	0.078	87.58	0.000

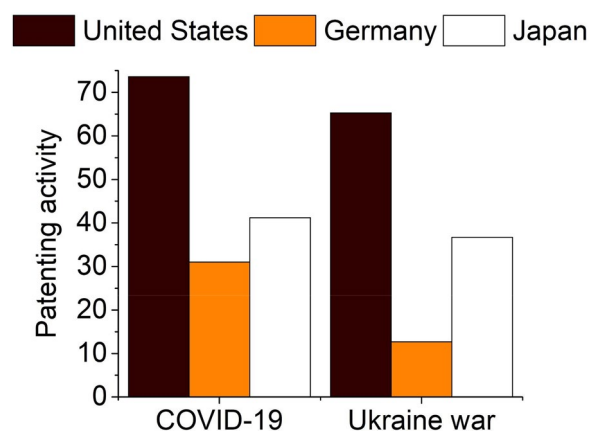


Figure 1. Estimated effects of COVID-19 (2020–2021) and the war in Ukraine (2022–2023) on patenting activity (PPML model).

For Japan, the interaction coefficients are negative in magnitude but statistically indistinguishable from zero ($p > 0.10$). Pairwise Wald tests show no significant difference between Germany and Japan (pandemic: $\chi^2 = 0.28$, $p = 0.60$; war: $\chi^2 = 1.23$, $p = 0.27$), implying similar patterns of muted response across the two economies.

Model diagnostics indicate satisfactory fit and stability, with a log likelihood of -91671.60 and an LR statistic of 1648061.03 ($p < 0.001$). The AIC and BIC values reported in [Supplementary Materials, Table S10](#), provide additional model-fit information. Huber-White robust standard errors were applied to address heteroskedasticity.

In sum, geopolitical shocks are associated with asymmetric patenting responses across the three economies. The United States exhibited strong positive shock-period patenting, whereas Germany's increases were more modest. This pattern is consistent with the interpretation that institutional and regulatory conditions may shape the conversion of external demand shocks into measurable patenting outcomes, but it should not be read as direct evidence that regulatory design alone caused the cross-country differences.

[Figure 1](#) provides a visual summary of the PPML estimates reported in [Table 2](#). It separates the U.S. baseline shock-period effects from the additional country-specific deviations for Germany and Japan, which makes the weaker German and Japanese responses easier to interpret. The figure should therefore be read as a graphical representation of the PPML model, not as a separate estimation or additional causal test.

3.3. Association between EU nanotechnology regulation and application potential (German DiD and event study)

The association between EU nano-specific regulation and patenting was assessed through a within-country analysis focusing on Germany. A two-way fixed-effects difference-in-differences (DiD) model compared patenting trends between regulated and unregulated domains before and after 2020, the period when several nano-specific provisions began to take effect or were amended. Robustness was evaluated using an event-study design covering 2016–2023, capturing both pre-2020 differences and post-2020 persistence.

The DiD results reveal a statistically significant negative post-2020 association. The Treated $\times$ Post-2020 interaction term is negative ($\beta = -1260.528$) and statistically significant ($p = 0.0153$), indicating that patenting in regulated sectors declined relative to unregulated sectors after 2020 (see [Supplementary Materials, Table S11](#)). The model exhibits high explanatory power ($R^2 = 0.8786$), and the joint F-test confirms overall model significance (see [Supplementary Materials, Table S12](#)).

The event-study results corroborate this pattern (see [Supplementary Materials, Table S13](#)). Pre-treatment coefficients (2016–2019) are small and statistically indistinguishable from zero ($p > 0.10$), which is consistent with the parallel-trends assumption. Beginning in 2020, treatment coefficients become consistently negative and statistically significant: $\beta = -1357.69$ ($p = 0.032$) in 2020, $\beta = -1305.74$ ($p = 0.027$) in 2021, $\beta = -1439.55$ ($p = 0.021$) in 2022, and $\beta = -1483.54$ ($p = 0.039$) in 2023. These coefficients indicate a persistent relative decline in patenting output for regulated sectors after 2020, rather than proving a stand-alone regulatory cause.

Diagnostic statistics (see [Supplementary Materials, Table S12](#)) show a low Durbin-Watson statistic (0.06), suggesting possible serial correlation. Period-clustered standard errors were used to account for heteroskedasticity and contemporaneous correlation across domains, while the event-study analysis provided an additional assessment of pre-treatment dynamics. Nevertheless, residual serial correlation cannot be fully excluded. As an additional robustness diagnostic, an LLC panel unit-root test was applied to the four regulated German domain series constituting the treated group in the DiD specification (see [Supplementary Materials, Table S14](#)). The test rejects the null hypothesis of a common unit root at the 5% significance level (statistic $= -1.7799$, $p = 0.0376$). This result reduces concern that the post-2020 trajectory of the treated group is driven solely by stochastic trend behavior, but it does not establish stationarity of each individual domain or independently validate the causal interpretation of the DiD estimates. The German DiD specification relies on only eight sectoral units, which limits statistical power and makes inference sensitive to domain-specific shocks and serial correlation. The estimates should

therefore be interpreted as indicative evidence consistent with a regulatory-exposure mechanism rather than as definitive causal proof.

Taken together, the DiD and event-study evidence suggests a sustained negative post-2020 association between nano-specific regulatory exposure and patenting activity in Germany's regulated nanotechnology domains. Because the intervention period overlaps with COVID-19 and other contemporaneous disturbances, the result is framed as consistent with a regulatory constraint mechanism, not as definitive proof that regulation alone caused the decline.

3.4. *Synthesis and interpretation*

The results provide coherent answers to the study's research questions while also indicating where caution is required. First, bibliometric and regulatory mapping identify that the eight consolidated domains capture the main nanotechnology applications, with Healthcare, Food, Agriculture, and Cosmetics representing the domains subject to the most explicit nano-specific regulatory provisions.

Second, the cross-country PPML analysis shows that geopolitical shocks have asymmetric innovation effects across leading economies. The United States experienced large positive patenting responses to both COVID-19 and the war in Ukraine, while Germany's responses were substantially weaker and Japan's statistically indistinct from the U.S. baseline. These results are consistent with institutional and regulatory factors acting as plausible moderators of crisis-induced innovation, while the models do not separately measure all mechanisms behind these differences.

Third, the within-Germany DiD and event-study analyses identify a clear negative post-2020 association between regulatory exposure and innovation performance. During the period in which EU nano-specific provisions were introduced or amended, patenting activity declined significantly and persistently in regulated sectors compared to unregulated ones, with no evidence of differential pre-2020 trends in the event-study coefficients.

Collectively, the evidence supports the conceptual proposition that regulatory exposure can moderate the conversion of external shocks into patenting output. Economies or sectors operating under more flexible or adaptive institutional conditions may be better positioned to translate demand shocks into accelerated technological activity. In the German case, however, the timing and stringency of nano-specific regulation after 2020 appear to coincide with weaker patenting in regulated domains, and this interpretation remains subject to the alternative explanations discussed below.

4. Discussion

The findings of this study have implications for firms operating in nanotechnology domains, but these implications should be read as inferences from sector-country patenting patterns rather than as direct estimates of firm-level performance. The evidence indicates that application potential is shaped not only by technological progress or market demand but also by the regulatory exposure and institutional environment in which innovation takes place.

First, the choice of application domain should systematically account for regulatory intensity. The German analysis shows that regulated domains exhibit a statistically significant relative decline in patenting activity after 2020 compared to unregulated sectors. This does not imply that regulation is inherently harmful; rather, it suggests that compliance requirements, approval uncertainty, and data-generation obligations may affect the timing and volume of formal patenting in selected domains.

Second, the geographical location of innovation activities represents a strategic variable. The pronounced differences between the United States and Germany in their responses to geopolitical shocks are consistent with the view that institutional flexibility and financial depth shape how quickly innovation systems respond to external impulses. However, these mechanisms are not measured directly in the present models and should therefore be treated as interpretation rather than as separately identified causal channels.

Third, regulatory interventions introduced during periods of global uncertainty may coincide with a temporary dampening of patenting in affected domains. For technology management, this underscores

the importance of assessing not only the substance of regulation but also its timing relative to broader macroeconomic and geopolitical conditions.

Overall, regulatory exposure and institutional context should be treated as integral components of strategic evaluation when assessing nanotechnology portfolios. Decisions regarding entry into specific segments require the integration of technological analysis with a systematic assessment of the regulatory environment, expected approval timelines, compliance costs, and the possibility of sector-specific shocks.

From a theoretical perspective, this study advances research on innovation systems, technology management, and institutional theory in three ways. It shows how general-purpose technologies can follow different innovation trajectories depending on domain-level regulatory exposure. It connects macro-level geopolitical shocks with meso-level sectoral regulation in one empirical design. It also demonstrates how institutional conditions can act as moderators of crisis-induced innovation rather than merely as background features of national innovation systems.

Several limitations warrant acknowledgment. First, patent counts measure codified innovation output but not commercialization, adoption, product quality, or tacit knowledge diffusion. Second, the study focuses on Germany, the United States, and Japan; extending the analysis to other EU member states could provide a more comprehensive picture of intra-European heterogeneity. Third, the binary classification into regulated and unregulated domains simplifies a continuum of regulatory intensity and implementation timing. Fourth, the German sectoral setup is small, which limits the scope for additional robustness tests and makes all inference sensitive to domain-specific shocks.

Beyond nanotechnology, these contributions add nuance to theories of how general-purpose technologies are governed under overlapping crises. They suggest that regulatory exposure can have different implications for innovation resilience depending on where technologies sit within sectoral regulatory regimes and on countries' institutional and financial capacities to absorb shocks. Future comparative work on other general-purpose technologies could use similar mixed-method designs to test whether the interaction between regulation, uncertainty, and crisis timing generalizes beyond nanotechnologies.

5. Conclusion

This study examined how regulatory frameworks and exogenous geopolitical shocks, specifically the COVID-19 pandemic and the war in Ukraine, are associated with the application potential of nanotechnologies and with strategic decision-making in innovation management. Using a triangulated approach that combined bibliometrics and regulatory mapping with quantitative econometric analysis, we find evidence that regulatory design, institutional context, and crisis timing matter for patenting trajectories. The contribution lies in connecting domain classification, regulatory exposure, and shock-period patenting in a single framework that is relevant for both innovation theory and managerial portfolio decisions.

First, RQ1 is addressed through bibliometric and regulatory mapping. More than thirty identified application labels were consolidated into eight principal domains: Agriculture, Energy, Environmental Remediation, Electronics, Healthcare, Cosmetics, Food, and Textiles. REACH forms the horizontal backbone of EU nanomaterial regulation, whereas Healthcare, Cosmetics, Food, and Agriculture are subject to targeted sectoral rules based on nano-specific provisions. Energy, Electronics, Environmental Remediation, and Textiles lack comparable nano-specific instruments within the scope of this study. This institutional heterogeneity is significant because it alters firm incentives, data-generation requirements, and pathways to market.

Second, in addressing RQ2, the PPML estimates show that geopolitical shocks are associated with stronger patenting increases in the United States (+74 percent during the pandemic; +65 percent during the war) than in Germany (+31 percent and +13 percent). Although point estimates for Japan suggest increases during both shocks, the interaction terms are not statistically significant. These patterns indicate that observed differences in patenting are consistent with differences in national absorptive capacity and institutional responsiveness, but the models do not directly measure all mechanisms behind those differences.

Third, in answering RQ3, the DiD and event-study analyses for Germany identify a negative, statistically significant, and persistent post-2020 decline in patenting activity in regulated domains relative to unregulated ones. Pre-intervention coefficients (2016–2019) are not statistically significant, supporting

the plausibility of the parallel-trends assumption. However, because post-2020 regulation overlaps with COVID-19 and other disturbances, the results are interpreted as consistent with mechanisms of higher compliance costs, authorization uncertainty, and delayed translation of research into formal intellectual property protection, rather than as definitive proof of a single causal channel.

From the perspective of innovation management within firms, these findings suggest the need to integrate regulatory analysis into strategic portfolio management. Domain selection should combine technological competence and market potential with assessments of regulatory intensity, approval time-lines, compliance costs, and institutional responsiveness. Firms may therefore benefit from diversifying across regulated and less regulated segments, allocating R&D activities across institutional environments, and strengthening internal capabilities for regulatory monitoring and scenario planning during periods of geopolitical uncertainty.

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Author contributions

CRedit: **David Svoboda**: Conceptualization, Formal analysis, Data curation, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing; **Michaela Matoušková**: Formal analysis, Funding acquisition, Resources, Validation, Writing – review & editing; **Ondrej Havelka**: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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ORCID

David Svoboda  <http://orcid.org/0000-0003-2365-7040>
 Michaela Matoušková  <http://orcid.org/0009-0008-3451-5260>
 Ondrej Havelka  <http://orcid.org/0000-0003-2177-9589>

Data availability statement

The data supporting the findings of this study were derived from the PatentInspiration database using the structured keyword-based search strategy reported in the Materials and Methods section and covering the period 2004–2023. The resulting dataset, including annual patent counts by country and application domain, is provided in the [Supplementary Material](#). The replication code used for the PPML estimations, the German DiD and event-study analyses, and the Levin-Lin-Chu panel unit-root diagnostic is available from the corresponding author upon reasonable request and can be provided as an additional supplementary file.

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