

# Facts and Figures on Materials Science and Nanotechnology Progress and Investment

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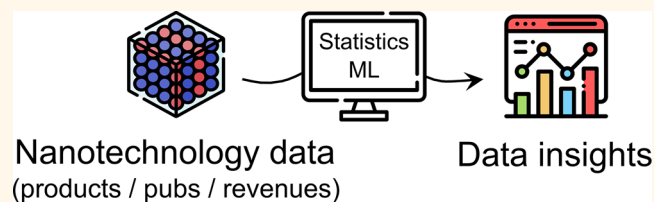
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**ABSTRACT:** As the twenty-first century unfolds, nanotechnology is no longer just a buzzword in the field of materials science, but rather a tangible reality. This is evident from the surging number of commercial nanoproducts and their corresponding revenue generated in different industry sectors. However, it is important to recognize that sustainable growth of nanotechnology is heavily dependent on government funding and relevant national incentive programs. Consequently, proper analyses on publicly available nanotechnology data sets comprising information on the past two decades can be illuminating, facilitate development, and amend previous strategies as we move forward. Along these lines, classical statistics and machine learning (ML) allow processing large data sets to scrutinize patterns in materials science and nanotechnology research. Herein, we provide an analysis on nanotechnology progress and investment from an unbiased, computational vantage point and using orthogonal approaches. Our data reveal both well-established and surprising correlations in the nanotechnology field and its actors, including the interplay between the number of research institutes–industry, publications–patents, collaborative research, and top contributors to nanoproducts. Overall, data suggest that, supported by incentive programs set out by stakeholders (researchers, funding agencies, policy makers, and industry), nanotechnology could experience an exponential growth and become a centerpiece for economical welfare. Indeed, the recent success of COVID-19 vaccines is also likely to boost public trust in nanotechnology and its global impact over the coming years.

**KEYWORDS:** nanotechnology, materials science, machine learning, artificial intelligence, nanoproducts, funding



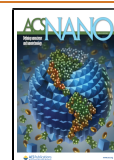
Tremendous advances have been made in the field of nanotechnology over the last two decades, translating early promises into reality and contributing to economic growth and public benefit. This is a direct consequence of the interest of policy makers and governments around the world in setting up different initiatives for the development of advanced nanotechnologies and their applications, particularly in healthcare. In fact, nanotechnology has already entered major industry sectors including materials and manufacturing, electronics and IT, healthcare and life sciences, and energy and environment.<sup>1–3</sup> Although progress in nanotechnology research has been particularly evident since the turn of the century, translating research into commercially available products and devices that benefit society is the ultimate goal. Nanomaterials offer avenues for societal advancement, and their presence in our daily lives is now ubiquitous. As a larger number of products become available, the exposure to nanomaterials increases and, thus, it is important to scrutinize a series of pertinent questions to gauge the (r)evolution of nanotechnology. In particular, one might question (i) how was the investment landscape in

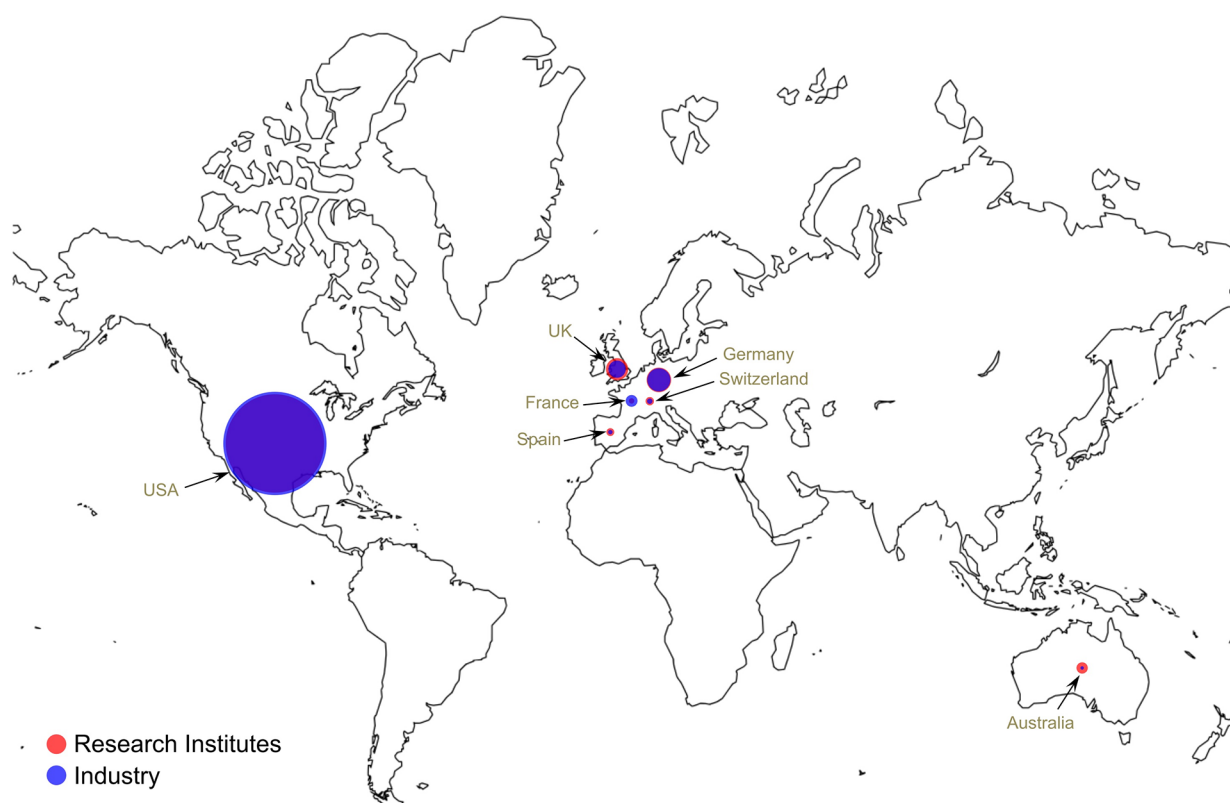
nanotechnology over the past two decades on a global scale?; (ii) are there any multilateral, tractable, and robust correlations between scientific output, privileged regional development hubs, and investment through research grants and seed capital?; (iii) have any particular nanomaterials been in the spotlight?; and (iv) for which applications have nanomaterials been developed in greatest extent and more successfully impacted society? Herein, we interconnect publicly available data and employ statistics—including machine learning (ML)—to provide a critical analysis and synthesize and aggregate information, thus generating knowledge and enlightening the future impact of nanotechnology in daily lives.

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**Figure 1.** Global distribution of nanotechnology research and industry (source: Nanowerk, 2020). Depiction of the top 5 nanotechnology contributors per continent, both in number of research institutes (orange dots) and nanotechnology-exploiting industry (blue dots). The United States (US) industry is the largest contributor in either industry or research categories and was set to a dot size of 100%. All remaining dots are size proportional and highlight the US as the global leader in raw number of institutes (38% of total) and companies (45% of total), followed by Germany (9.4% and 10%, respectively) and the UK (8.6% and 7.5%, respectively). Regionally, North America and Europe host 41% each of all research institutes worldwide and 38.5% (Europe) and 49.7% (North America) of all companies. Note: Data are unavailable for more than five countries in the case of South America, Africa, and Oceania.

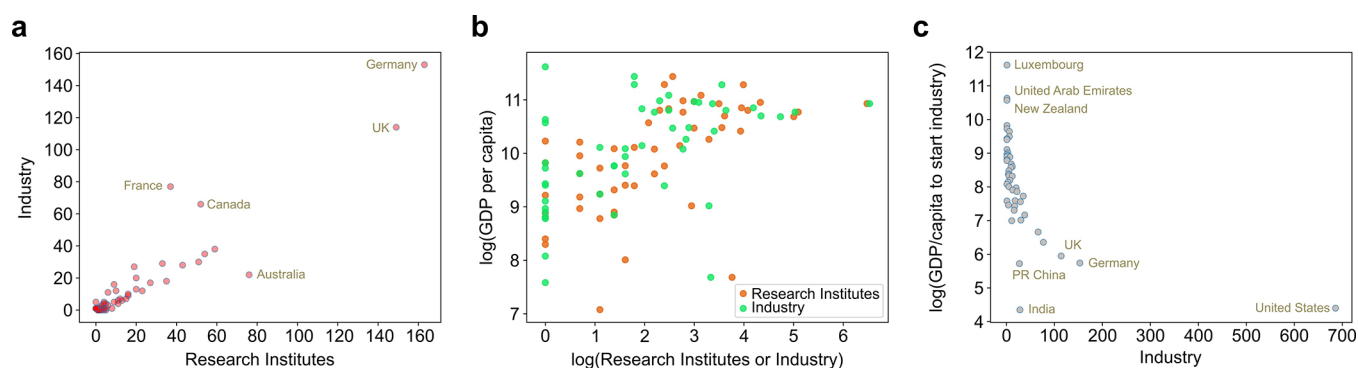
## RESULTS/DISCUSSION

**Nanotechnology as a National Priority.** Several countries around the world consider nanotechnology as a research priority due to its potential contribution to economic growth. National-level investments on basic and applied nanotechnology research and technology transfer have led to manifold breakthroughs. However, the majority of these investments come from “core” R&D programs, where the success rate of nanotechnology-related proposals cannot be anticipated.<sup>4</sup>

To scrutinize the facts behind global nanotechnology development and investments, we analyzed research indicators in the academic sector and ensuing companies—engaged in myriad activities such as publications, patents, products, applications, instruments, and technologies—from publicly available data (Figure 1).<sup>5</sup> Aggregating global data from the 2000–2020 period, we conclude that North America and Europe are the key drivers in academic research, with each one hosting 41% of all research institutes worldwide. Interestingly, the United States (US) is the leading contributor in North America (92% of all research), whereas in Europe, research efforts are widespread among its countries. For example, Germany is Europe’s largest contributor, but represents only 23% of all research in the region. Arguably, such differing global distribution and prominence of selected countries is supported by more sustainable funding policies, irrespective of fluctuations in recent years.<sup>6</sup> For example, the US NNI

investments over the last 20 years, together with current priority funding provided by several National Institutes of Health or European Commission programs, are designed to incentivize frontier science and entrepreneurial endeavors. The European Commission has explicitly included nanotechnology as a theme in its research funding programs over the past decade and supports many scientists and institutions through the European Research Council and Marie Curie Actions.<sup>7</sup> Furthermore, the Horizon 2020 program has reinforced the European Union (EU) nanotechnology sector by promoting opportunities in emerging nanotechnologies across a vast array of different areas. As such, expectations for the Horizon 2020 successor program—Horizon Europe—have been, up to recently, even higher when it comes to the translation of nanotechnology-enabled products.<sup>8</sup> However, the impacts of the recently announced 14.3% cut to the program budget—as related to the EU emergency response to the ongoing COVID-19 pandemic<sup>9</sup>—are now expected to cast a shadow over public investment in R&D in Europe.

Retrospectively, the current number of research institutes and laboratories might already reflect the success of those funding schemes that aim at a sustained pipeline of overarching and foundational nanoscience research. A similar pattern to the research institute distribution can be found for the nanotechnology industry, further suggesting the abundance of critical mass and more desirable economical policies in those continents (Figure 1). However, the gap between the US and



**Figure 2.** Key figures in nanotechnology investment. (a) The number of research institutes in a given country is a good linear predictor for the number of companies exploiting nanotechnologies (Pearson  $r = 0.9908$ ,  $p = 3.917 \times 10^{-52}$ ). For clarity, the US is excluded from the plot (research institutes = 651; industry = 686). France presents the highest industry-to-research institute ratio worldwide (77 vs 37, respectively). The ratio is abnormally high relative to the remaining countries: ratio (France) = 2.08 vs 95% confidence interval (ratio distribution) =  $[-0.36, 1.60]$ . Additional outliers include Russia (ratio = 1.83) and the Czech Republic (ratio = 1.78). Conversely, the US presents a ratio of 1.05, in line with the average distribution. (b) The number of research institutes and industry is nonlinearly correlated with the country's gross domestic product per capita (GDP/capita). Spearman  $\rho = 0.573$ ,  $p = 1.68 \times 10^{-6}$  (research institutes) and Spearman  $\rho = 0.602$ ,  $p = 3.59 \times 10^{-7}$  (industry). For clarity, data were transformed to  $\log_{10}$  values. (c) The generated wealth per capita required to start a company in a given country is correlated with the number of companies in said country (Spearman  $\rho = -0.803$ ,  $p = 3.72 \times 10^{-12}$ ). Countries with significant industrial expression, such as the US, require less GDP/capita. India and China deviate from the observed trend, requiring comparable wealth to global leaders (e.g., US, Germany, and UK), yet having lower than expected industrial representation.

Europe is more apparent regarding their contribution to the number of companies exploiting nanotechnology: 49.7% and 38.5%, respectively. This highlights that, collectively, Europe has significant room for improving its business ecosystem, through either increased seed capital for breakthrough technologies or indirect incentives to entrepreneurship.

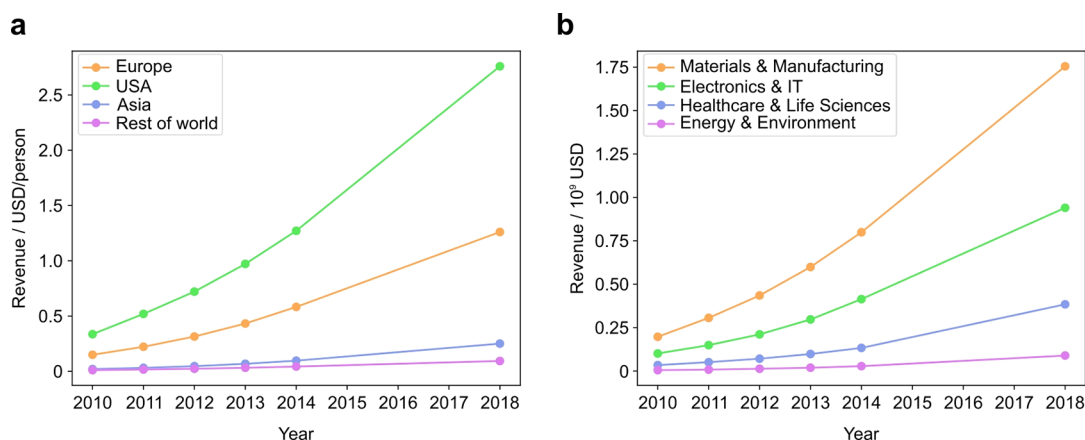
Our data analyses also show that the number of research institutes in any given country is a good predictor of their industrial sector size (Pearson  $r = 0.9908$ ,  $p = 3.917 \times 10^{-52}$ ); on average, one expects to find five research institutes per founded company in countries considered in our analysis (Figure 2a). In this regard, while the US presents an above average 1:1 industry-to-institute ratio, other countries, such as France, stand out even more, with the number of companies doubling that of research institutes, an observation that starkly deviates from the norm (ratio 95% confidence interval =  $[-0.36, 1.60]$ ). Moreover, we were surprised to observe that China—in spite of its significant academic output in nanotechnology—falls short in both basic science institutes and industry (19 and 27, respectively) as compared to their direct competitors. The lack of financial support from enterprise technology companies, as well as a comparatively lower volume of Chinese government funding, has been well documented for applied research<sup>10</sup> and could be the driving force behind poor translation of academic innovation. Following the field leadership, Russia and Iran, as well as several countries in Africa and South America, are now re-establishing/reorganizing national/regional research councils to prioritize nanotechnology research.<sup>11</sup> The practical results of such measures are already observed in some cases (*vide infra*) or expected to materialize in the near future.

While our data suggest that the US remains the go-to hub in nanotechnology research, the introduction of an economy size variable, such as the gross domestic product per capita (GDP/capita), provides an alternative perspective to these figures. Such normalization is particularly relevant in order to unveil country-specific commitment to nanotechnology. As expected, there is a positive, yet nonlinear correlation between the

number of research institutes (Spearman  $\rho = 0.573$ ,  $p = 1.68 \times 10^{-6}$ ) and industry (Spearman  $\rho = 0.602$ ,  $p = 3.59 \times 10^{-7}$ ) with increasing economy size (Figure 2b). More importantly, the population-normalized funds required to start a company greatly vary with country and continent. While in Oceania each company is on average started for every 20 800 USD/capita, in Europe 9600 USD/capita are required. This sharply contrasts with North America (1430 USD/capita) and in particular the US, which requires a meagre 81 USD/capita. Significantly, this is an exponential trend we found in all major nanotechnology players (Spearman  $\rho = -0.803$ ,  $p = 3.72 \times 10^{-12}$ ), namely, Germany (311 USD/capita) and the UK (383 USD/capita). Conversely, values of 576, 1111, and 2269 USD/capita were found for France, Spain, and Switzerland, respectively, which might justify their lower contribution to the nanotechnology sector, despite their world class research track record (Figure 2c).

Overall, our analyses on global nanotechnology development and investment data revealed an expectable correlation between the number of research institutes in any given country and their industrial sector size. Particularly, the economy size (as indicated by GDP/capita) is a key factor in determining the number of research institutions and industries active in nanotechnology across the globe. Along similar lines, population-normalized funds required to start a company could be another variable in determining the success of a given country in establishing larger nanotechnology industries/companies. Given enough of this type of data, these analyses could be instrumental for governments to assess the shortcomings of their national initiatives and make the necessary adjustments to fulfill continuous growth of nanotechnology.

**Nanotechnology Revenues.** For some countries, nanotechnology has the potential to evolve into a “national treasure”. The field not only provides specific business opportunities but also contributes to cross-sectional societal benefit. However, to fully capture gains and revenue, products and processes need to be translated into instruments that



**Figure 3.** Overview of revenues generated by nanotechnology. (a) Evolution of population-adjusted revenues from nanotechnology products, as grouped by regions and in the 2010–2018 period. The US and Europe are experiencing an exponential revenue in the past decade, in opposition to the rest of the world. (b) Gross revenue generated from nanotechnology products, as grouped by industry sector and in the 2010–2018 period. Data show only negligible contribution by the energy and environment sector as opposed to materials and manufacturing, which account for a 55% share of all produced wealth in 2018.<sup>13</sup>

address real-world needs. As mentioned before, this requires a package of actions entailing adequate funding for R&D, which will ultimately lead nanotechnology-based products to the market and yield sales.<sup>12</sup> While data on nanotechnology investment are generally sparse and incomplete, the world-leading status of the US is clear and is backed by continuous investment over the last 20 years.<sup>13</sup> More importantly, such economical effort is leading to exponential growth of revenues (Figure 3a) that ultimately contribute to market expansion in its most varied applications. As of 2018, the nanotechnology industry in Europe and the US were able to generate identical gross revenue (\$941 million and \$903 million, respectively), yet the latter was twice as productive when adjusted to population size (\$1.26/person vs \$2.76/person). Again, this observation contrasts with the economical reality in Asia; despite the global influence and potential of its industry (estimated at a \$1.14 billion revenue), its productivity falls far behind when normalized to its inhabitants (\$0.25/person), again supporting that another level of incentives could further propel the economy. Noticeably, higher population growth rates observed in Asia (annual growth rate of 1.04% in 2010–2018) as compared to Europe and the US (0.18% and 0.81%, respectively), although considerable,<sup>14</sup> cannot fully account for the observed trends (Figure 3a).

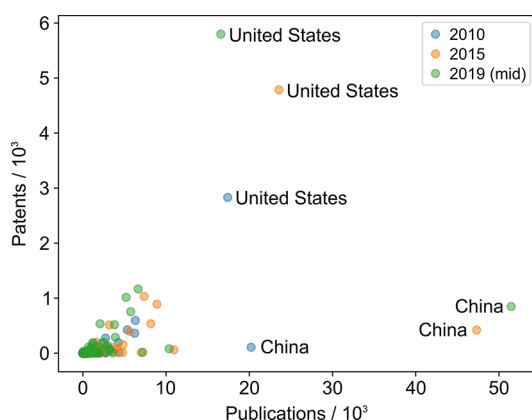
Mining nanotechnology revenues by sector also revealed an interesting and exponential growth across most applications (Figure 3b). While we had already mentioned that nanotechnology has become ubiquitous in daily life through commodity products, one can realize that revenue has been maximized for the materials and manufacturing sector, while it is only now starting to impact healthcare and life sciences, through either drug delivery systems, diagnostics tools, or medical devices.<sup>15</sup> Unfortunately, the potential of nanotechnology for energy production and soil and water remediation among others is still far from fulfilled, as most of these solutions are yet to mature into effective and marketable products, despite their promise to support a sustainable future. This can be attested by the negligible expression of the energy and environment sector relative to the gross global revenue in 2018, a mere 2.8% (Figure 3b).

In summary, analyses on global nanotechnology revenues showed that incentives can propel economic gains from

nanotechnology. Conversely, factors such as the public's concerns regarding nanotechnology safety and stringent government requirements in the frameworks of environmental regulation could negatively impact the global nanotechnology/nanomaterial market.<sup>16</sup> Regulatory bodies in the US and EU have effectively managed to address such issues early on by publishing guidelines that boosted public trust on these matters. This might have contributed to exponential growth of the nanotechnology market and revenue in such regions as compared to others. Also, nanotechnology revenues by sector revealed that materials and manufacturing contributed the most to total nanotechnology revenue. Such a trend is expected considering that the first stage of development in creating any general purpose technology includes foundational interdisciplinary research, which in case of nanotechnology translates into the discovery of material properties and semiempirical synthesis of nanoscale components. Hence, it is expected that in the upcoming decades this trend would shift more toward application sectors as nanodevices are amalgamated with existing technologies.<sup>17</sup>

**Scientific Outputs and IP Protection in Nanotechnology.** Scientific publications and patents significantly contribute to nanotechnology development and intellectual property (IP) protection and are essential platforms for knowledge dissemination and transfer from foundational research to industrial application.<sup>18</sup> More than an analysis on impact metrics—such as the *h*-index—that can be skewed in unpredictable fashion,<sup>19</sup> here we deemed it more appropriate to scrutinize the evolution of nanotechnology literature in select countries, as an indirect indicator of national commitment and/or funding to the field. To that end, we aggregated USPTO and EPO patent data per country and identified a yearly, nonlinear correlation between the number of publications and patents in the last 10 years, where information is more abundant and complete (Spearman rho = 0.814,  $p = 5.43 \times 10^{-26}$ ; Figure 4). These results refer to USPTO/EPO, which focus on the two main regions (US and Europe) previously analyzed (see Figure 1) with more prevalence in research institutes and industry and representing around 25% of all patents.

Interestingly, our analyses revealed the growing effort in translating research—in particular in the US—as there is an



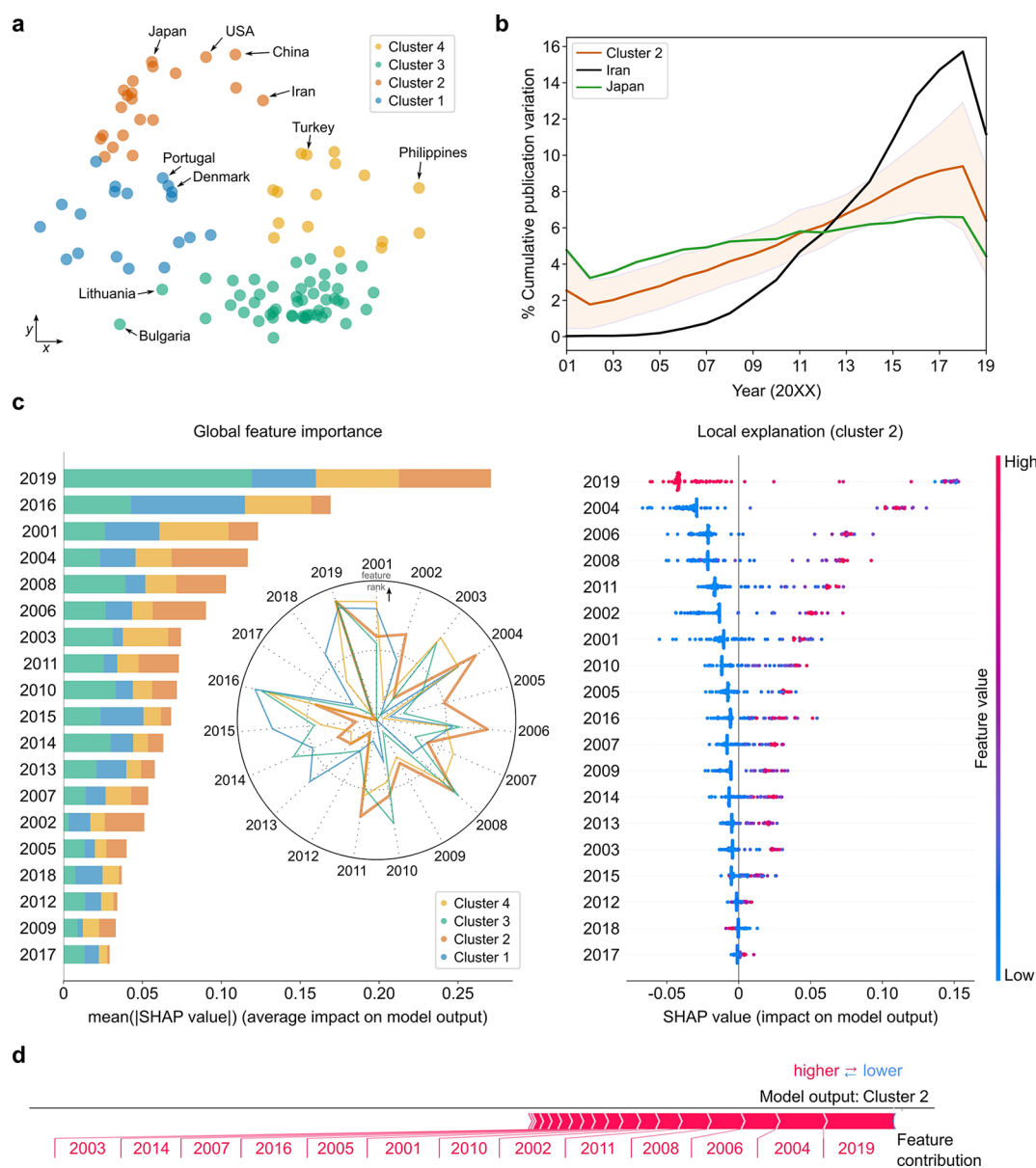
**Figure 4.** Evolution of scientific output measured in USPTO/EPO patents and publications for select years. Aggregated USPTO and EPO patent and publication data (2000–mid 2019) show there is a nonlinear correlation between both scientific outputs. For clarity, only data from 2010 (Spearman  $\rho = 0.756$ ,  $p = 8.57 \times 10^{-21}$ ), 2015 (Spearman  $\rho = 0.823$ ,  $p = 4.46 \times 10^{-27}$ ), and 2020 (Spearman  $\rho = 0.813$ ,  $p = 5.43 \times 10^{-26}$ ) are shown. The data highlight the diverging national priorities among the two nanotechnology-leading countries—US and China—with the former placing more emphasis on the patent-to-publication ratio.

increasing tendency to patent research findings. Specifically, the total number of nanotechnology articles published per year had an impressive increase of around 780% by mid 2019 relative to the year 2000. This is mostly due to the massive contribution of China (51 468), the US (16 577), India (10 363), Iran (7202), and South Korea (6636), who share over 30% of all scientific output worldwide. China's performance on publication output is, in fact, rather intriguing and starkly contrasts their decreased number of companies, filed patents, and general progress as compared to the US. While data for China show a stronger focus on foundational research and original research manuscripts, our analysis highlights an opposite trend for the US. This is aligned with their previously discussed industry productivity. Taken together, one can argue that harnessing nanotechnology is a priority in both countries, yet diverging approaches have been taken.

Assuming that the number of publications is a relevant metric for the scientific output and associated economic outcomes of each country,<sup>20,21</sup> we next wondered how 105 different countries have been progressing, on a yearly basis, with respect to their commitment to advancing nanotechnology, and if relevant patterns in publishing outputs could be identified. To that end, we calculated pairwise publication number differences in consecutive years between 2000 and mid 2019. With the engineered features in hand, we resorted to unsupervised ML to cluster data with the aim of capturing different publication patterns in the analyzed period. Specifically, we reduced data dimensionality with manifold learning before investigating an appropriate and statistically motivated number of clusters representing the structure of the data in hand (Figure 5a). An inertia analysis revealed that assigning each country to one of four clusters in a  $k$ -means computation<sup>22</sup> was appropriate and captured different tiers of publication practices. The devised organization included one highly, one lowly, and two intermediately committed groups according to the employed feature set, which suggests different policies and priorities for nanotechnology in the pooled countries. This is in line with the analysis in previous sections.

To gain further insight into the publications' profile of tier 1 countries (including the US, China, and Europe; Cluster 2) and assess if there is intraclass heterogeneity, we heuristically searched for outliers, in hopes of identifying countries that are either growing above average or, conversely, decelerating in comparison to their cluster peers. We thus implemented an isolation forest to extract countries whose percent cumulative publication growth, in consecutive years, deviated from the norm. In essence, isolation forests use recursive partitioning over a number of decision trees and calculate an outlier score that is a function of the average decision path for each training entry. In this process, inliers are harder to isolate and require a larger number of recursions relative to outliers that surface over shallower leaves. Using this principle, the decision function identified Iran and Japan as outliers (Figure 5b). Both countries present publication growth rates over the analyzed time series that are different from what is expected to find in the analyzed cluster, and their profiles are largely opposing. While Japan had a growth rate above average in the early 2000s, it is now notorious for an asymptotic growth that falls short of its nearest competitors. Conversely, Iran had a negligible expression in nanotechnology until 2010, but has since experienced an exponential growth in publication contributions. This may be at least partly related to policy changes—implemented by the Iran Nanotechnology Innovation Council—to improve infrastructure, promote international collaborations, attract experts, and develop tools for measuring progress and impact.<sup>23</sup> Such a seemingly successful measure can be reproduced by other countries.

To more thoroughly interpret the generated clusters, attest their meaningfulness, and scrutinize which are the deciding years for label assignment, we also built a random forest classifier using cluster labels as target variables. Our model accurately captured patterns in data that motivated the assignment of different labels/clusters (average model accuracy =  $90.8 \pm 0.01\%$  in repeated stratified 10-fold cross-validation studies). Importantly, label randomization strongly affected pattern recognition by the implemented tool (average accuracy =  $40.0 \pm 0.02\%$ ), which supports the utility of the originally devised heuristics, the relevance of the engineered features (yearly publication differences), and that real patterns were learned rather than memorized. We thus considered it plausible to harness our bespoke ML model to analyze data and extract knowledge in a statistically motivated fashion. Applying Shapley values from coalitional game theory,<sup>24,25</sup> we simulated the presence and/or absence of some features to collect many local explanations for the training data that, together, faithfully represent their global structure (Figure 5c,d). Shapley values thus provide a feature importance according to an additive, surrogate linear model that boosts interpretability relative to the native predictive model. Our analyses revealed that feature importance ranks change dynamically with the predicted cluster (*cf.* radar plot in Figure 5c). According to our source data, 2019, 2016, 2001, 2004, and 2008 emerged as the most important years on a global model scale. This observation apparently links with the surge of publication numbers a decade ago by some of the current world-leading countries in nanotechnology research and development. In finer detail, the picture is somewhat shifted when explaining the most important contributing factors for Cluster 2. In general, high feature values are desirable, but not decisive (*e.g.*, 2019), which shows that label assignment, in this particular case, is likely deeply rooted in a long-standing

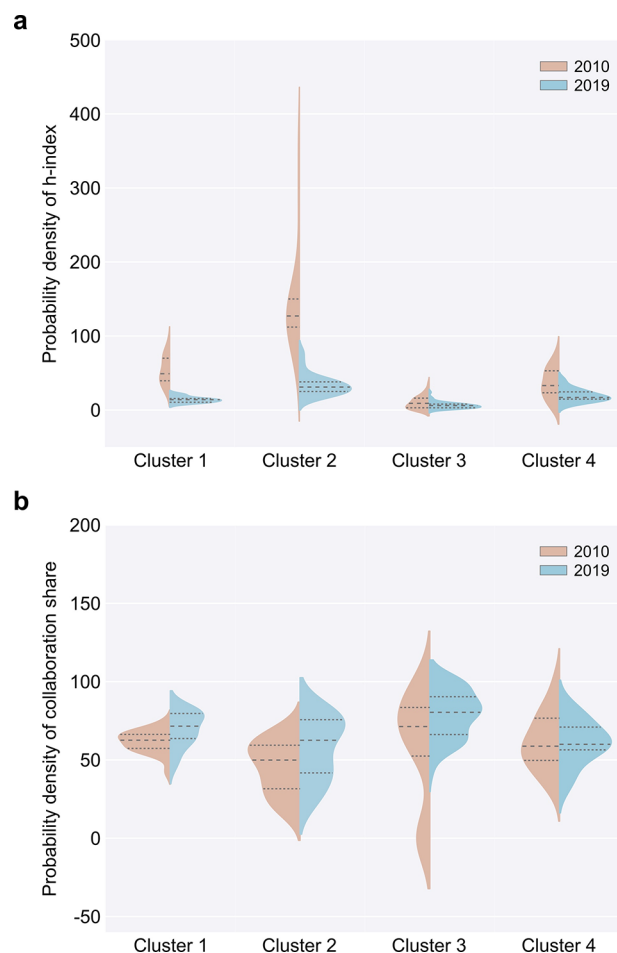


**Figure 5.** Unsupervised and interpretable, supervised machine intelligence reveals hidden patterns in the nanotechnology publishing evolution on a global scale. (a) 105 countries display one of four distinct publishing patterns in the 2000–mid 2019 period. The tiered classification was achieved by calculating pairwise publication number differences between consecutive years and reducing dimensionality with manifold learning (*t*-distributed stochastic neighborhood embedding). These data were subjected to *k*-means clustering using the elbow method to determine a plausible number of clusters describing the structure of the training data set. Cluster 1: Argentina, Austria, Belarus, Belgium, Colombia, Czech Republic, Denmark, Finland, Greece, Hungary, Ireland, New Zealand, Norway, Portugal, Romania, Serbia, Slovakia, Slovenia, and Ukraine. Cluster 2: Australia, Brazil, Canada, China, France, Germany, India, Iran, Italy, Japan, Netherlands, Poland, Russia, Singapore, South Korea, Spain, Sweden, Switzerland, Taiwan, UK, and US. Cluster 3: Afghanistan, Albania, Armenia, Azerbaijan, Bahrain, Bangladesh, Bolivia, Bosnia, Bulgaria, Cameroon, Costa Rica, Croatia, Cuba, Cyprus, Ecuador, Estonia, Georgia, Iceland, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Latvia, Lebanon, Liechtenstein, Lithuania, Luxembourg, Moldova, Morocco, Nepal, Nigeria, North Korea, Oman, Panama, Paraguay, Peru, Senegal, Sri Lanka, Syria, Tajikistan, Turkmenistan, United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Yemen, and Zimbabwe. Cluster 4: Algeria, Chile, Egypt, Indonesia, Iraq, Malaysia, Mexico, Philippines, Qatar, Saudi Arabia, South Africa, Thailand, Tunisia, Turkey, and Vietnam. (b) Anomaly analysis of Cluster 2 with a bespoke isolation forest revealed two outliers (Iran and Japan) whose nanotechnology publication records deviate from the norm. Orange line: average of publications by Cluster 2 members (excluding Iran and Japan). Shaded region denotes the 95% confidence interval. (c) A random forest classifier built with *k*-means labels as target value provides orthogonal validation of the clustering method (accuracy = 92.3% in 10-fold cross-validation) and an opportunity to interpret the model both globally and locally. Feature importance values were extracted for each of the clusters, suggesting that publication value differences between 2019–2018, 2016–2015, 2001–2000, 2004–2003, and 2008–2007 are the top 5 features for dissecting the progression of a given country. Of note, feature importance values/ranks vary for each label; for example, the 2016–2015 difference ranks higher than the 2019–2018 difference in the case of Cluster 1, showing the nonlinear nature of the classification model (radar plot). More specifically, for Cluster 2, high values for each engineered feature are generally favorable, yet low values can be more frequently encountered among Cluster 2 members. (d) The prediction of Cluster 2 for Iran is positively correlated with high values in 2019, 2004, 2006, 2008, and 2011.

priority and sustainable funding for nanotechnology (Figure 5c). As such, it is probable that countries from other clusters cannot overturn their slower progress within the next years alone, but would require a long-term commitment (estimated for 10–15 years) to reach comparable contribution to nanotechnology relative to countries in Cluster 2, which includes world-leading nanotechnology research institutes. Indeed, this was the observed trend for Iran (Figure 5d). Although ML can be effectively applied in pattern analysis, the utility of learning approaches is dependent on the quality of the data sets.<sup>26</sup> The data sets employed here comprised information for 105 countries, but the inclusion of yet inaccessible data can lead to nuanced clustering by the utilized unsupervised methods and alternative interpretations. These should be confronted with timelines and identifiable research policies for proper rationalization.

We also queried the evolution of citations over the past 10 years within each of the identified clusters, as a general proxy of impact and quality of research. As expected, Cluster 2 presented the highest number of cited manuscripts, as gauged by the *h*-index. Moreover, the *h*-index tended to be more polarized in 2010, possibly due to the relative novelty of the field and a lower abundance of key players and citable items (Figure 6a) that may have led to a concentration of citations on select studies. More importantly, we found that the nanotechnology community is now significantly more interconnected than in 2010, with most research projects involving countries from multiple clusters. While Cluster 1 countries have traditionally presented an average share of collaborative projects over 60% (likely to mitigate national structural weaknesses in research policies), there is a growing trend to follow such a strategy (Figure 6b). For example, Cluster 3 countries—which include some of the most fragile economies worldwide—were originally highly polydispersed in share of collaborative projects (0–100% range; average = 59% share), but are now among the most collaborative countries (average 79% share). Ultimately, such a stance and commitment to collaborations might benefit the local development of nanotechnology by transferring knowledge and/or cutting-edge technologies.

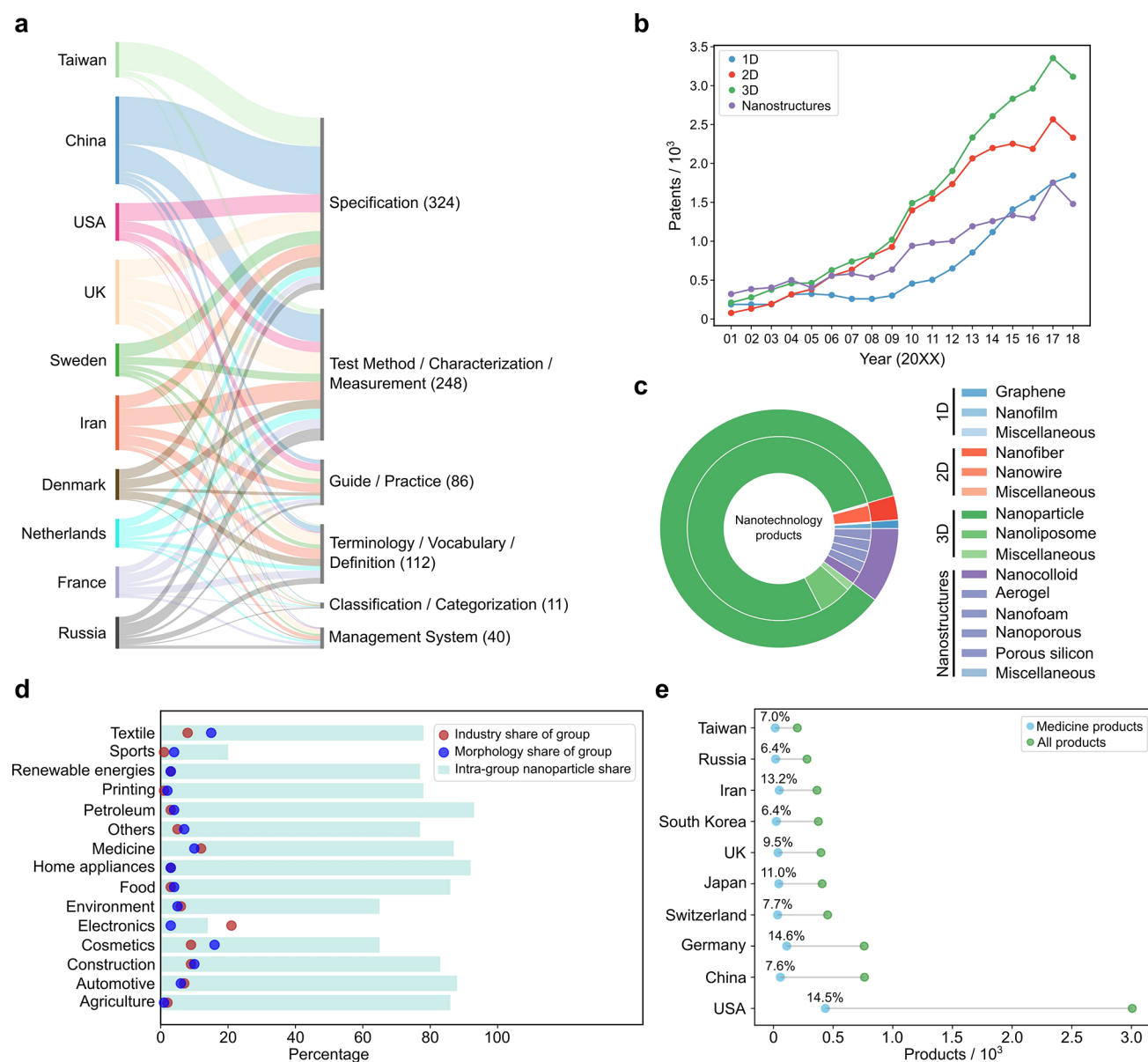
While analyzing publication and patent data, a difference was observed in the way countries like the US and China approach their dissemination of nanotechnology science. While the US puts more emphasis on patenting and commercialization, China is more oriented toward publishing original research in scientific journals. These contradicting approaches could be a consequence of multiple factors such as the economic model in China imposing the lack of connection between the public and private sector, as well as weak IP protection in China.<sup>28</sup> Furthermore, our ML might be a viable approach to analyze related data sets. In doing so, we dissected countries into different clusters and rationalized the decision function through interpretation confronted with actual policy measures, e.g., in Iran and Japan. In both cases, government policies and economical circumstances were the driving forces behind such change. This could be justified by devotion of more resources to nanotechnology research by Iranian authorities and deduction in R&D research investment in nanotechnology by the Japanese government.<sup>29,30</sup> It was also shown that global collaboration had a major impact on the regional distribution of high-impact research, emphasizing the importance of cross-border international linkages in scientific success of less advanced countries. This type of analysis could be useful for



**Figure 6.** Impact of nanotechnology on collaborative research. (a) Probability density of *h*-index values in 2010 and mid 2019 for countries in each of the computed clusters. Data show that in 2010 citations were more concentrated in selected publications. Despite a higher number of publications in 2019, the number of citations is highly dispersed, having contributed to lower year-adjusted *h*-index values. Regardless, studies including countries from Cluster 2 tend to collect a higher number of citations. Dotted lines correspond to median and quartiles. Cluster 2 vs Cluster 1:  $p = 3.82 \times 10^{-6}$  (Welch's *t*-test); Cluster 2 vs Cluster 3:  $p = 2.45 \times 10^{-8}$  (Welch's *t*-test); Cluster 2 vs Cluster 4:  $p = 0.0008$  (Welch's *t*-test). (b) Probability distribution of collaboration share values in 2010 and mid 2019 for countries in each of the computed clusters. Cluster 1 countries have traditionally been highly collaborative, whereas Cluster 2 and Cluster 3 countries are now significantly more open to collaboration. Cluster 1, 2010 vs 2019:  $p = 0.771$  (Welch's *t*-test); Cluster 2, 2010 vs 2019:  $p = 0.0006$  (Welch's *t*-test); Cluster 3, 2010 vs 2019:  $p = 0.04$  (Welch's *t*-test); Cluster 4, 2010 vs 2019:  $p = 0.009$  (Welch's *t*-test). Dotted lines correspond to median and quartiles. Raw data from ref 27.

less developed countries, in the field of nanotechnology, to amend their national/institutional approaches to explore the full advantages of their research outcome.

**A Glimpse at the Nanomaterials Industry.** Nanomaterials have become ubiquitous in daily life and are now gradually commercialized as commodity products.<sup>31</sup> Those products have been exploited to tackle some of the world's most pressing needs in medicine, food, agriculture, and the environment.<sup>32</sup> However, with improvements in quality-of-life over the decades, nanotechnology also entered the fray in making consumer-based products that are being used in daily

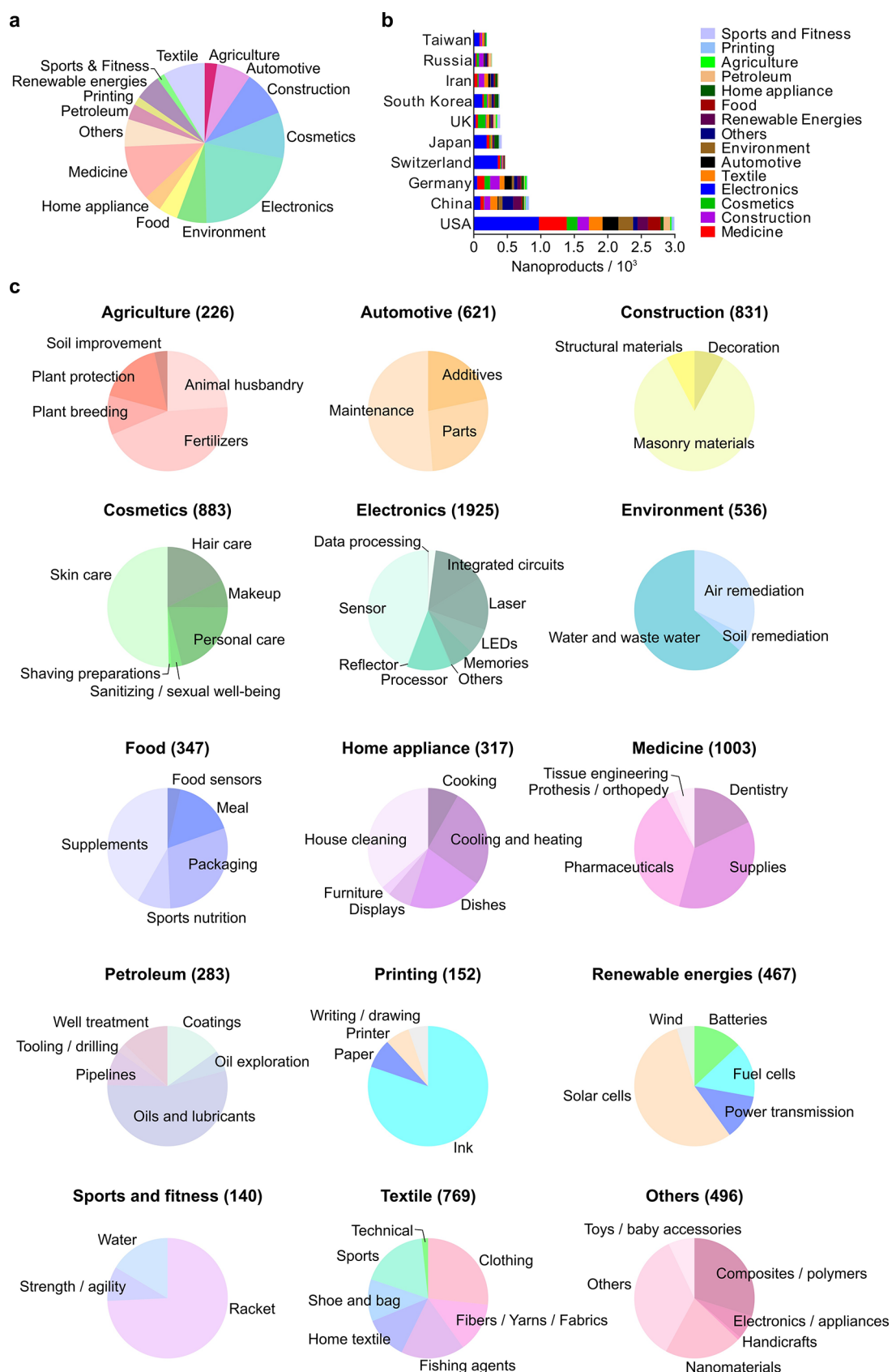


**Figure 7.** Overview on the nanotechnology industry. (a) Top contributors to national and international standards. Thickness of connection is proportional to the contribution, and values in parentheses correspond to the total number of documents per category. Data show that China, UK, and Iran are the top contributors to product specifications, and test methods are the most regulated. (b) Evolution of nanomaterial patents grouped by dimensionality (1D, 2D, 3D, or nanostructures) in the 2001–2018 period. Data show an exponential growth in patents of 3D nanomaterials. 1D nanomaterials: borophene, graphene, graphyne, Langmuir–Blodgett, nanocoating, nanofilm, nanolayer, nanoplate, nanoribbon, quantum well, and self-assembled layer. 2D nanomaterials: nanofiber, nanorod, nanowire, and quantum wire. 3D nanomaterials: dendrimer, diamondoid, fullerene, nanocapsule, nanocluster, nanohorn, nanoliposome, nanomicelle, nanoion, nanoparticle, nanopore, nanoshell, nanosphere, nanostar, and quantum dot. Nanostructures: aerogel, nanocolloid, nanocrystalline, nanoelectromechanic, nanofluid, nanofluidics, nanofoam, nanoporous, porous silicon, qubit, and supermolecule. (c) Distribution of nanomaterial dimensionality in commercialized products. Data show that 3D nanomaterials are the most abundant (85% of all materials), in particular nanoparticles, which are currently present in 78% of all nanoproducts. (d) Nanomaterial distribution according to industrial sector. Bars denote the prevalence of nanoparticles among all products in each of the 15 sectors. Red dots denote the percentage of nanoproducts in each sector. Blue dots denote the percentage of different nanoparticle morphologies in each sector. Data show a high prevalence of nanoparticles in all sectors, excluding electronics (for which data are absent) and sports. (e) Top contributors to medicinal nanoproducts and their share at the national level. Data show that the US, Germany, and Iran place higher emphasis than normal on health nanotechnologies.

life,<sup>2</sup> including cosmetics, sports and fitness, textiles, and home appliances. By the end of 2018, available nanoproducts were produced by 61 countries and spanned 15 different industry branches (Figure 7).<sup>33</sup>

As in any industry, standards and codes of practice have been established and are continuously updated both at national

and international levels (e.g., ISO) to ensure homogeneous and high-quality nanotechnology-based products. Again, countries in Cluster 2 (cf. Figure 4) have been the most active in regulating the nanotechnology field through the establishment of product specifications, definition of standard test methods, and guidelines (Figure 7a). Less expected, however, and in



**Figure 8.** Global nanoproducts stats by the end of 2018, including (a) different industry branches with their share of nanoproducts, (b) number of nanoproducts in industry branches by country, and (c) share of nanoproducts in each industry branch by their subdivisions.

light of our previous discussion, is the smaller contribution of the US relative to China, where product specifications and test

methods are highly regulated. Again, Iran emerged as a curious case with a fine balance between all standard categories

analyzed herein, demonstrating the increasing importance of nanomaterials and their serious commitment to advancing the field as a foundation for economical growth.

Naturally, different classes of nanomaterials possess unique physical, chemical, and biological properties, which make them highly customizable and adaptable for specific applications. Although nanomaterials can be broadly categorized based on their morphology, composition, and mode of synthesis,<sup>34</sup> here we adopted a classification system based on dimensionality to streamline our analyses. Specifically, we considered materials in one-dimensional (1D) nanoscale (e.g., graphene and quantum wells), two-dimensional (2D) nanoscale (e.g., nanofibers and nanotubes), three-dimensional (3D) nanoscale (e.g., nanoparticles and quantum dots), and nanostructures, as multiphase materials where one of the phases has at least one dimension in the nanoscale (e.g., nanoporous materials and nanocomposites). Accordingly, by the end of 2018 all nanomaterial types presented a growth in number of corresponding patents when compared to that of 2001 (Figure 7b). Yet, anomalies were detected in patent number progression for 2D and nanostructures, where the former gradually ascended to second place, while the latter descended to last place by the end of 2018. This could be due to continuing emergence of 2D nanomaterials that contributed to a wide range of applications, such as supercapacitors, fuel cells, electrochemical batteries, water purification, nanotheranostic agents, and others.<sup>35</sup> This included 2D nanomaterials such as nanotubes, nanofibers, nanorods, and nanowires. Propelled by nanoparticles, the number of 3D nanomaterial patents represented 35.5% of all patents as of 2018,<sup>36</sup> which mirrors their widespread application (85%) in consumer products (Figure 7c). In fact, the nanomaterial distribution can be considered bipolar, with nanoparticle technologies being present in 78% of all products; all remaining nanomaterials have a representation of 22%. This could stem from a variety of factors including longer history of nanoparticles, easier and cheaper production methods, and wider availability of their building compounds (metals, polymers, ceramics, etc.).<sup>37,38</sup>

Three-dimensional nanomaterials most prevalently used in nanoproducts include nanoliposomes and various kinds of nanocapsules and nanoparticles. Having established that nanoparticles are the key driver of nanotechnology in consumer products, we then analyzed their prevalence in various product sectors in the hope of identifying differences in utility. Our data analysis suggests that nanomaterials seamlessly integrated different sectors and have the potential for massification, yet further progress is attainable in some cases. With the exception of medicine (12%) and electronics (22%), nanoproducts—a total of 8860—are evenly distributed across the analyzed sector panel, with each of the remainder groups incorporating an average  $6.6 \pm 5.1\%$  of all currently available products (Figure 7d, red dot, and Figure 8 for breakdown of each sector). This is in line with the different nanoparticle morphologies that can be found in each sector, with the exception of electronics, where information is absent (Figure 7d, blue dot). Moreover, it became evident that nanoparticles are the preferred technology platform (median 78%), supporting their versatility for myriad applications (Figure 7d bars), with the exception of the sports industry, where 1D nano-objects and nanofibers have found more utility. Particularly, the application of nanoparticles in medicine and biology is noteworthy, covering a broad range of uses that include drug and gene delivery, biomolecule detection,

antimicrobial coatings, and diagnosis.<sup>39</sup> In fact, nanoparticles are currently playing an important role in delivering various mRNA constructs, including both Pfizer-BioNTech and Moderna COVID-19 vaccines.<sup>40–43</sup> Along similar lines, we identified that medicine is the most diverse group in terms of technology adoption, currently commercializing products harnessing up to 12 different nanomaterial morphologies. Their most notable contributors include Cluster 2 countries, such as the US, China, Germany, and Switzerland (cf. Figure 7e), where up to 14.6% of all country-specific nanoproducts lie in the medicine field. In our analysis, Iran again stood out with a contribution of around 13% to the medicine field, which effectively establishes their industry as world-leading.

Overall, we explored different aspects of the nanomaterials industry by considering international contributors to standards, patents classified by their dimensionality, share of each type, and their distribution across different industry sectors. Accordingly, the more advanced countries (Cluster 2 in Figure 5) contributed the most to nanotechnology standards, both at the national and international levels. Appropriate documentary standards and reference materials are crucial building blocks for the development of innovative products,<sup>44</sup> and high-volume standardization initiatives by advanced countries may have contributed to their later success in commercialization of nanoproducts. Next, our analysis of various nanomaterial types implemented in nanoproducts showed clear dominance of 3D nanomaterials over 1D and 2D counterparts, as well as nanostructures. This sort of information could be critical to researchers, potential investors, and the regulatory entities. Particularly, a complete life cycle assessment requires analysis not only of the manufacture of a specific nanoproduct but also of its application and end-of-life options.<sup>45</sup> Furthermore, a survey of nanomaterial distribution across different industrial sectors confirmed that nanomaterials are now part of a mass rather than a niche market as they perhaps were until a few years ago.<sup>46</sup> Our analysis showed that the field of medicine is the most diverse industry in adopting different types of nanomaterials in their corresponding commercialized nanoproducts. This is not surprising due to the typically favorable risk–benefit assessment of nanotechnology made by healthcare stakeholders<sup>47</sup> and stems from the potential of nanomedicine in combating some of the most notorious human diseases such as cancer and infectious, neurological, musculoskeletal, and cardiovascular diseases.<sup>15,48</sup> Lastly, we have shown that the US is the top contributor to medicinal nanoproducts, a testament to recent success of this country in introducing two COVID-19 nanomediated vaccines (Pfizer-BioNTech and Moderna) into the market. The US dedication to development and commercialization of medicinal nanoproducts has proven to be rewarding, namely, when considering the staggering financial revenue that will continue to be generated for this country just from the COVID-19 vaccines.<sup>49</sup>

## CONCLUSIONS

Nanotechnology has become a familiar name among academic, government, and industry branches over the last two decades. Considerable national- and regional-level investment efforts led to not only significant scientific breakthroughs but also economic gain on a global scale. This prompted us to analyze nanotechnology progress and investment from a computational vantage point and using orthogonal heuristics. Our analyses revealed both well-established and surprising correlations in the nanotechnology field and its actors, including the interplay

between the number of research institutes—industry, publications—patents, collaborative research, and top contributors to nanoproducts. In brief, we have identified the US as the global leader in number of nanotechnology institutes (38% of total) and companies (45% of total). The US also holds one of the lowest values required to start a nanotech company (\$81/capita). Put together, these factors placed the US as the frontrunner in gross revenue generated from nanotechnology (\$903 million) by the end of 2018. Further analysis on the number of nanotechnology publications and patents over the last 10 years revealed a growing effort in translating research—particularly in the US—as there is an increasing tendency to patent research findings. Simultaneously, our unsupervised ML model clustered countries according to publication evolution, identifying commonalities between unexpected countries (e.g., pairing Iran with the US and EU members). Upon further investigation, the US was determined as one of the top contributors to the establishment of standards (product specifications and test methods). The cumulative effect of all US initiatives in nanotechnology was reflected in the analysis of industry, producing the highest number of nanoproducts (more than 3000 different types) worldwide across different sectors. Taking the US as an example, it seems clear that proper incentive programs, set out by the stakeholders (researchers, funding agencies, policy makers, and industry), can lead to exponential growth of nanotechnology to a point where it becomes a centerpiece for economical welfare. Investment in nanotechnology seems worthy, considering its steady development over the last years, virtually immune to the reminiscences of the not-so-long-ago international financial crisis and past and present meager global economic growth.<sup>50</sup> Nanoproducts have been increasingly entering the consumer market over a broad spectrum of applications, and expectations are high for the years to come.<sup>51</sup> This calls for global action to further expand standards, certifications, and regulations for the upcoming wave of nanoproducts in order to ensure their reliable and safe use. Also, given the importance of financial investment in the discovery of nanotechnologies, public and private sectors are urged to continue funding nanosciences at academic and research facilities, as our analyses strongly support that this will ultimately lead to sustainable economy expansion. A strong global economic growth and job creation is expected to emerge and strengthen in the coming decades. Specifically, such an effort will allow the subsequent emergence of nanoproducts with improved performance and impending benefit to the public. The COVID-19 mRNA nanovaccines from Moderna and Pfizer/BioNTech are just two excellent examples of how nanotechnology-enabled products can dramatically impact our lives today, particularly in an issue as sensitive as human health. To date hundreds of millions of people worldwide were already vaccinated for COVID-19 with these nanovaccines. These will inevitably increase public awareness and trust in nanotechnology and further boost developments in the field. The hereby presented approach also sets the foundations for future analyses on the impact of this and other specific achievements of nanotechnology. Lastly, a stronger relationship between universities, government, and industry will further facilitate the transfer of knowledge from discovery to industry implementation, which can allow sustained growth of nanoproducts in the consumer market. We have only just begun to scratch the surface of nanotechnology and its massive potential. Nanomaterials and resulting nanoproducts are no longer potential assets to the

complex global consumer market but well-established enhancers of value.

## METHODS/EXPERIMENTAL

**Data Sets.** We collected and manually curated publicly available data on nanotechnology research and development in the past 20 years. Databases that were mined include the US National Nanotechnology Initiative (US NNI; <https://www.nano.gov/>), Web of Science and Scopus (patents and primary research publication data), StatNano (<https://statnano.com/>), Nanowerk (<https://www.nanowerk.com/>), Nano.nature (<https://nano.nature.com/>), and the Trending Economics (gross domestic product data).

**Data Analyses.** Data were analyzed in Python 2.7 and/or 3.6 and KNIME. Statistics were performed with SciPy 1.1.0, data wrangling was performed with Pandas 0.23.4 and NumPy 1.15.4, ML/AI was implemented with Scikit-learn 0.20.3, and model interpretation was assisted by SHAP 0.36.0. Data were plotted with Matplotlib 2.2.5 or Seaborn 0.7.1, and figures were compiled in Inkscape 1.0.

**Machine Learning.** Publication data for 105 countries across all continents in the 2000–2019 period were collected from nanostat. The difference in number of publications was calculated between consecutive years for each of these countries. The engineered features were normalized with the MinMaxScaler function. Using the transformed features, dimensionality reduction was performed with the *t*-distributed stochastic neighborhood embedding (*t*-SNE) algorithm using perplexity = 50 and learning\_rate = 100. All remaining hyperparameters were kept as default. We subsequently clustered the publication data in *t*-SNE space with *k*-means. An appropriate number of clusters was studied with the elbow method and, alternatively, with the silhouette score. On the basis of those computations, we elected to use *k* = 4, which avoids aggregating in one cluster many countries with dissimilar publication records. All other *k*-means hyperparameters were kept as in the default implementation. To interpret the cluster assignment, we built a random forest classifier using the engineered descriptor set as features and the clustering-derived labels as target variables. The model was assessed through repeated (10 times) stratified 10-fold cross-validation, while using accuracy as scoring metric. All hyperparameters were used as default, with the exception of n\_estimators = 100. A *Y*-randomization control was performed similarly. For outlier detection, an isolation forest heuristics<sup>52</sup> was implemented with default settings, using percentage of publications, on a yearly basis for each country, as features. SHAP analyses were performed with the TreeExplainer function with default settings. All code and data sets are available at [https://github.com/tcorodrigues/nanotech\\_analyses](https://github.com/tcorodrigues/nanotech_analyses).

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## Notes

T.R. and J.C. are co-founders and shareholders of TargTex S.A. For a list of entities with which R.L. is involved, compensated or uncompensated, see [www.dropbox.com/s/yc3xqb5s8s94v7x/Rev%20Langer%20COI.pdf?dl=0](http://www.dropbox.com/s/yc3xqb5s8s94v7x/Rev%20Langer%20COI.pdf?dl=0). All the other authors declare no financial conflict of interest.

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## REFERENCES

- (1) Schaming, D.; Remita, H. Nanotechnology: From the Ancient Time to Nowadays. *Found. Chem.* **2015**, *17* (3), 187–205.
- (2) Nasrollahzadeh, M.; Sajadi, S. M.; Sajjadi, M.; Issaabadi, Z. *An Introduction to Green Nanotechnology*; Elsevier Science Publishing Co Inc: San Diego, 2019.
- (3) Cheng, H.; Doemeny, L. J.; Geraci, C. L.; Grob Schmidt, D. *Nanotechnology Overview: Opportunities and Challenges*; American Chemical Society: Washington DC, 2016.
- (4) The National Nanotechnology Initiative to the President's Budget. *The US National Science and Technology Council* 2017.
- (5) Nanowerk.com; Nanotechnology Company & Research Labs Directory. [https://www.nanowerk.com/nanotechnology/research/nanotechnology\\_links.php](https://www.nanowerk.com/nanotechnology/research/nanotechnology_links.php) (accessed 12/06/2021).
- (6) Dong, H.; Gao, Y.; Sinko, P. J.; Wu, Z.; Xu, J.; Jia, L. The Nanotechnology Race between China and the United States. *Nano Today* **2016**, *11* (1), 7–12.
- (7) Gabellieri, C.; Frima, H. Nanomedicine in the European Commission Policy for Nanotechnology. *Nanomedicine* **2011**, *7* (5), 519–520.
- (8) Horizon 2020. <https://ec.europa.eu/programmes/horizon2020/en/h2020-section/nanotechnologies> (accessed 12/06/2021).
- (9) Zubaşcu, F. Leaders Agree on Slimmed-Down €80.9B for Horizon Europe. <https://sciencebusiness.net/framework-programmes/news/leaders-agree-slimmed-down-eu809b-horizon-europe> (accessed 12/06/2021).

(10) Nature Springer. An Overview of the State of Chinese Nanoscience and Technology. <https://media.springernature.com/full/springer-cms/rest/v1/content/15302926/data/v3> (accessed 12/06/2021).

(11) UNESCO Nanotechnology is a Growing Research Priority. [http://www.unesco.org/new/en/media-services/single-view/news/nanotechnology\\_is\\_a\\_growing\\_research\\_priority/](http://www.unesco.org/new/en/media-services/single-view/news/nanotechnology_is_a_growing_research_priority/) (accessed 12/06/2021).

(12) Crawley, T. Commercialisation of Nanotechnology—Key Challenges, *Report on the Workshop Organised by Nanoforum*, Helsinki, 2007.

(13) Flynn, H. Nanotechnology Update: Corporations up Their Spending as Revenues for Nano-Enabled Products Increase; 2017.

(14) Gender Ratio. <https://ourworldindata.org/gender-ratio> (accessed 7/28/2021).

(15) Martins, J. P.; das Neves, J.; de la Fuente, M.; Celia, C.; Florindo, H.; Günday-Türelı, N.; Popat, A.; Santos, J. L.; Sousa, F.; Schmid, R.; Wolfram, J.; Sarmiento, B.; Santos, H. A. The Solid Progress of Nanomedicine. *Drug Delivery Transl. Res.* **2020**, *10* (3), 726–729.

(16) Inshakova, E.; Inshakov, O. *World Market for Nanomaterials: Structure and Trends, MATEC web of conferences*; EDP Sciences, 2017; p 02013.

(17) Roco, M. C. Overview: Affirmation of Nanotechnology between 2000 and 2030. *Nanotechnology commercialization: manufacturing processes and products* **2017**, 1–23.

(18) Chen, H.; Roco, M. C.; Son, J.; Jiang, S.; Larson, C. A.; Gao, Q. Global Nanotechnology Development from 1991 to 2012: Patents, Scientific Publications, and Effect of NSF Funding. *J. Nanopart. Res.* **2013**, *15* (9), 1951.

(19) Bornmann, L.; Daniel, H.-D. The State of H Index Research. *EMBO Rep.* **2009**, *10* (1), 2–6.

(20) Laverde-Rojas, H.; Correa, J. C. Can Scientific Productivity Impact the Economic Complexity of Countries? *Scientometrics* **2019**, *120* (1), 267–282.

(21) Kumar, R. R.; Stauvermann, P. J.; Patel, A. Exploring the Link between Research and Economic Growth: An Empirical Study of China and USA. *Quality & Quantity* **2016**, *50* (3), 1073–1091.

(22) Pedregosa, F.; Varoquaux, G.; Gramfort, A.; Michel, V.; Thirion, B.; Grisel, O.; Blondel, M.; Prettenhofer, P.; Weiss, R.; Dubourg, V. Scikit-learn: Machine Learning in Python. *J. Machine Learning Res.* **2011**, *12*, 2825–2830.

(23) Soltani, A. M.; Tabatabaeian, S. H.; Hanafizadeh, P.; Bamdadsoofi, J. Outcome and Impact Indicators for Nanotechnology Policies. *J. Sci. Technol. Policy Management* **2020**, *11*, 563.

(24) Lundberg, S. M.; Nair, B.; Vavilala, M. S.; Horibe, M.; Eisses, M. J.; Adams, T.; Liston, D. E.; Low, D. K.-W.; Newman, S.-F.; Kim, J.; Lee, S.-I. Explainable Machine-Learning Predictions for the Prevention of Hypoxaemia during Surgery. *Nature Biomedical Engineering* **2018**, *2* (10), 749–760.

(25) Lundberg, S. M.; Erion, G.; Chen, H.; DeGrave, A.; Prutkin, J. M.; Nair, B.; Katz, R.; Himmelfarb, J.; Bansal, N.; Lee, S.-I. From Local Explanations to Global Understanding With Explainable AI for Trees. *Nature machine intelligence* **2020**, *2* (1), 2522–5839.

(26) Rodrigues, T. The Good, the Bad, and the Ugly in Chemical and Biological Data for Machine Learning. *Drug Discovery Today: Technol.* **2019**, *32–33*, 3–8.

(27) StatNano.com Nanotechnology Indicators, <https://statnano.com/indicators/nano> (accessed 12/06/2021).

(28) Cao, C.; Appelbaum, R. P.; Parker, R. Research is High and the Market is Far Away: Commercialization of Nanotechnology in China. *Technology in Society* **2013**, *35* (1), 55–64.

(29) Unesco. *UNESCO Science Report: Towards 2030*; Unesco Publishing, 2015.

(30) Kishi, T.; Bando, Y. Status and Trends of Nanotechnology R&D in Japan. *Nat. Mater.* **2004**, *3* (3), 129–131.

(31) Sudha, P. N.; Sangeetha, K.; Vijayalakshmi, K.; Barhoum, A. *Emerging Applications of Nanoparticles and Architecture Nanostructures*; Elsevier Inc: Amsterdam, 2018.

(32) Salamanca-Buentello, F.; Persad, D. L.; Martin, D. K.; Daar, A. S.; Singer, P. A. Nanotechnology and the Developing World. *PLoS Med.* **2005**, *2* (5), No. e97.

(33) StatNano.com Nanotechnology products. <https://product.statnano.com/> (accessed 12/06/2021).

(34) Marques, M. R. C.; Choo, Q.; Ashtikar, M.; Rocha, T. C.; Bremer-Hoffmann, S.; Wacker, M. G. Nanomedicines - Tiny Particles and Big Challenges. *Adv. Drug Delivery Rev.* **2019**, *151–152*, 23–43.

(35) Zhou, X.; Liu, B.; Chen, Y.; Guo, L.; Wei, G. Carbon Nanofiber-Based Three-Dimensional Nanomaterials for Energy and Environmental Applications. *Materials Advances* **2020**, *1* (7), 2163–2181.

(36) StatNano.com Nanomaterials morphologies. <https://statnano.com/nanomaterials> (accessed 12/06/2021).

(37) Niederberger, M. Multiscale Nanoparticle Assembly: From Particulate Precise Manufacturing to Colloidal Processing. *Adv. Funct. Mater.* **2017**, *27* (47), 1703647.

(38) Vance, M. E.; Kuiken, T.; Vejerano, E. P.; McGinnis, S. P.; Hochella Jr, M. F.; Rejeski, D.; Hull, M. S. Nanotechnology in the Real World: Redeveloping the Nanomaterial Consumer Products Inventory. *Beilstein J. Nanotechnol.* **2015**, *6* (1), 1769–1780.

(39) Rudramurthy, G. R.; Swamy, M. K. Potential Applications of Engineered Nanoparticles in Medicine and Biology: An Update. *JBIC, J. Biol. Inorg. Chem.* **2018**, *23* (8), 1185–1204.

(40) Florindo, H. F.; Kleiner, R.; Vaskovich-Koubi, D.; Acúrcio, R. C.; Carreira, B.; Yeini, E.; Tiram, G.; Liubomirski, Y.; Satchi-Fainaro, R. Immune-Mediated Approaches against COVID-19. *Nat. Nanotechnol.* **2020**, *15* (8), 630–645.

(41) Sahin, U.; Muik, A.; Derhovanessian, E.; Vogler, I.; Kranz, L. M.; Vormehr, M.; Baum, A.; Pascal, K.; Quandt, J.; Maurus, D.; Brachtendorf, S.; Lörks, V.; Sikorski, J.; Hilker, R.; Becker, D.; Eller, A.-K.; Grützner, J.; Boesler, C.; Rosenbaum, C.; Kühnle, M.-C.; et al. COVID-19 Vaccine BNT162b1 Elicits Human Antibody and TH1 T-Cell Responses. *Nature* **2020**, *586*, 594.

(42) Talebian, S.; Wallace, G. G.; Schroeder, A.; Stellacci, F.; Conde, J. Nanotechnology-Based Disinfectants and Sensors for SARS-CoV-2. *Nat. Nanotechnol.* **2020**, *15* (8), 618–621.

(43) Talebian, S.; Conde, J. Why Go NANO on COVID-19 Pandemic? *Matter* **2020**, *3* (3), 598–601.

(44) Halamoda-Kenzaoui, B.; Holzwarth, U.; Roebben, G.; Bogni, A.; Bremer-Hoffmann, S. Mapping of the Available Standards Against the Regulatory Needs for Nanomedicines. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology* **2019**, *11* (1), No. e1531.

(45) Şengül, H.; Theis, T. L.; Ghosh, S. Toward Sustainable Nanoproducts. *J. Ind. Ecol.* **2008**, *12* (3), 329–359.

(46) Hansen, S. F.; Hansen, O. F. H.; Nielsen, M. B. Advances and Challenges Towards Consumerization of Nanomaterials. *Nat. Nanotechnol.* **2020**, *15* (12), 964–965.

(47) van Dijk, H.; Fischer, A. R.; Marvin, H. J.; van Trijp, H. C. Determinants of Stakeholders' Attitudes Towards a New Technology: Nanotechnology Applications for Food, Water, Energy and Medicine. *Journal of Risk Research* **2017**, *20* (2), 277–298.

(48) Saxena, S. K.; Nyodu, R.; Kumar, S.; Maurya, V. K. Current Advances in Nanotechnology and Medicine. In *NanoBioMedicine*; Springer, 2020; pp 3–16.

(49) Castillo, J. C.; Ahuja, A.; Athey, S.; Baker, A.; Budish, E.; Chipty, T.; Glennerster, R.; Kominers, S. D.; Kremer, M.; Larson, G.; Lee, J.; Prendergast, C.; Snyder, C. M.; Tabarrok, A.; Tan, B. J.; Więcek, W. Market Design to Accelerate COVID-19 Vaccine Supply. *Science* **2021**, *371* (6534), 1107.

(50) Global Economic Prospects. <https://www.worldbank.org/en/publication/global-economic-prospects> (accessed 12/06/2021).

(51) Hansen, S. F.; Heggelund, L. R.; Besora, P. R.; Mackevica, A.; Boldrin, A.; Baun, A. Nanoproducts-What is Actually Available to European Consumers? *Environ. Sci.: Nano* **2016**, *3* (1), 169–180.

(52) Liu, F. T.; Ting, K. M.; Zhou, Z. In Isolation Forest. *2008 Eighth IEEE International Conference on Data Mining*; IEEE, 2008; pp 413–422.

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