Proceedings of the
Estonian Academy of Sciences
2025, **74**, 4, 551–562

https://doi.org/10.3176/proc.2025.4.09

www.eap.ee/proceedings
Estonian Academy Publishers

SCIENTOMETRICS,
BIBLIOMETRIC INDICATORS

RESEARCH ARTICLE

Received 12 July 2025
Accepted 23 September 2025
Available online 10 November 2025

Keywords:
scientometrics, bibliometrics, research assessment, citation analysis, bibliometric indicators

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Citation:
Allik, J., Saarma, M. and Realo, A. 2025. How did Estonia become the world's fastest-growing country in scientific wealth? *Proceedings of the Estonian Academy of Sciences*, **74**(4), 551–562. https://doi.org/10.3176/proc.2025.4.09

How did Estonia become the world's fastest-growing country in scientific wealth?

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ABSTRACT

The concept of scientific wealth is defined as the average number of citations per paper published by scientists from a given country or territory over a fixed period. This analysis is based on data from *Essential Science Indicators* (ESI; Clarivate™), which ranks authors, institutions, countries, and journals according to publication and citation performance between 2014 and 2024. Twenty years ago, Estonia's scientific impact was 20% below the ESI world average. Today, the average citation rate of articles by Estonian researchers is 81.7% above the ESI world average, placing Estonia third globally, after Iceland and Singapore, and ahead of its Nordic neighbors and role models, Finland and Sweden. The rapid growth of Estonian science has yet to be fully explained. None of the four groups of factors analyzed – science policies, funding, foreign aid, and research ethos – can fully explain Estonia's success on its own, especially when compared to its Baltic neighbors, Latvia and Lithuania. Estonia is a prime example of how a fortunate combination of factors can lead to the fastest growth in scientific wealth worldwide, although this specific combination remains to be identified.

Introduction

About 30 years ago, Baron May of Oxford articulated the concept of *scientific wealth of nations*, which can be measured by the average number of citations received by publications from scientists in a given country or territory over a fixed period (May 1997). While citation counts are not the only measure of the quality of a country's scientific output, they remain a widely accepted proxy. As Eugene Garfield, visionary founder of the citation index, predicted even before citation tracking became technically feasible, citation statistics are not only sufficiently reliable but also the most practical means of assessing the quality of scientific work (Garfield 1955).

Although the average number of citations per article is a widely used indicator of scientific wealth (Rousseau and Rousseau 1998; Harzing and Giroud 2014; Prathap 2017; Rodríguez-Navarro and Brito 2022), it is not without limitations (Leydesdorff et al. 2014; Wagner et al. 2022). One drawback is that countries or territories may appear more successful if they do not surpass *Essential Science Indicators* (ESI; Clarivate™) inclusion threshold in weaker scientific fields, thus avoiding the dilution of their average citation impact. To address this limitation, a high-quality science index was proposed, which considers whether a country or territory has met the ESI inclusion threshold across all scientific fields or only in some (Allik et al. 2020a, 2020b, 2020c).

Another shortcoming of average citation counts is their inability to distinguish between low-risk, incremental research and high-risk, potentially groundbreaking work (Leydesdorff et al. 2014; Wagner et al. 2022). Bibliometric experts increasingly agree that, in addition to average citation metrics, indicators capturing the top of the citation distribution, such as the number of "highly cited" or "top" articles, should also be included in the evaluations (van Leeuwen et al. 2003). Fortunately, ESI tracks publications that fall within the top 1% of citations in the field of science and year of publication. The number of such articles that fall within the top 1% of citations for their field can serve as an indicator of scientific breakthroughs – research that has been widely recognized and cited by peers (Allik et al. 2020a, 2020b, 2020c).

The post-Soviet science

The fall of communism in Eastern Europe in the early 1990s was not only one of the most significant geopolitical events of the 20th century but also a unique natural experiment in the development of science. In terms of bibliometric indicators, science in the Soviet and Eastern Bloc countries was far below even the world average (Garfield 1987, 1990a, 1990b; Graham 1992). Decades later, post-communist countries were still lagging far behind their EU counterparts, especially in the life and health sciences, partly because of focusing on the quantity rather than the quality of their publications (Jurajda et al. 2017; Chankseliani et al. 2021; Lovakov et al. 2022). After the collapse of the Soviet Union, it became possible to observe how science evolved across 15 newly independent states. Some of these countries transitioned into genuine democracies, while others became even more "evil" or authoritarian than before (Park 2009).[1] Among the successors of a totalitarian empire, Russia and Belarus have continued to experience a decline in the quality of their scientific output and have since fallen into the group of countries with the lowest levels of scientific wealth globally.

The Baltic states – Estonia, Latvia, and Lithuania – were similarly positioned in terms of scientific quality after regaining independence following 50 years of Soviet occupation, perhaps slightly above the average level of the former Soviet Union (Allik 2003, 2008; Zavadskas et al. 2011). While all three made remarkable progress in catching up with scientifically advanced democracies, Estonia's near-miraculous improvement in scientific quality stands out as a still-unresolved phenomenon (Lauk and Allik 2018; Schiermeier 2019).

One key observation is that exemplary science funding was not the primary driver behind Estonia's rise in scientific wealth. Although it might initially appear that scientific advancement is closely tied to investment levels, as suggested in early analyses of scientifically advanced countries (May 1997), later research revealed that, on a global scale, the amount of funding alone does not determine how effectively it is translated into scientific wealth (Allik et al. 2020a). Therefore, a fully comprehensive and convincing explanation for Estonia's scientific success over the past three decades has yet to be clearly identified. Nonetheless, science policymakers should not overlook the unique combination of factors that contributed to this exceptional growth, at least in this particular case.

The objective of this analysis is to evaluate the level of scientific wealth attained by Estonia by 2024, both in comparison to its Nordic and Baltic neighbors and within a global context. Although the three Baltic countries – Estonia, Latvia, and Lithuania – began from comparable starting points after regaining independence, they have since experienced differing levels of success in advancing their scientific wealth. By analyzing the distinct strategies and developments in each of the three countries, this comparison may offer insights into the factors or approaches that can effectively accelerate the growth of scientific wealth.

Method

The analysis presented here is based on data from the ESI, a tool that identifies top-performing research within the *Web of Science Core Collection* (Clarivate™), or simply WoS. ESI surveys more than 11 000 journals (out of a total of 22 619 indexed by WoS) worldwide to rank authors, institutions, countries, and journals across 22 broad research fields, based on publication and citation performance. The most recent update (March 2025), covering an 11-year period from January 1, 2014, to December 31, 2024, was used for this analysis. Only research articles are included in the ESI calculations; letters, editorial materials, corrections, and retracted papers are excluded.

ESI covers 22 broad scientific disciplines, excluding the arts and humanities due to their relatively minor role in journal-based scientific communication. Each journal is assigned to a single field, and all research published in that journal inherits that field classification. The fields included are: agricultural sciences, biology & biochemistry, chemistry, clinical medicine, computer science, economics & business, engineering, environment/ecology, geosciences, immunology, materials science, mathematics, microbiology, molecular biology & genetics, multidisciplinary, neuroscience & behavior, pharmacology & toxicology, physics, plant & animal science, psychiatry/psychology, social sciences (general), and space science. While the division into 22 fields helps account for substantial differences in publication and citation intensity across disciplines, it can disadvantage researchers who publish across multiple fields, as their work is counted only within the field assigned to each journal.

Because only citations from indexed journals are considered for the ESI, the arts and humanities that rely heavily on books were excluded. Each journal is assigned to one of the ESI's 22 scientific fields, and all research published in that journal is attributed to that field. Only citations from journals indexed in the *Science Citation Index Expanded*, *Social Science Citation Index*, and *Arts & Humanities Citation Index* are included. Citations from books, conference proceedings, or journals listed in the *Emerging Sources Citation Index* are excluded.

Inclusion in the ESI is determined by meeting specific citation thresholds. Only the most highly cited individuals, institutions, journals, countries, and papers qualify. Researchers and institutions must rank among the top 1% in their field, while countries and institutions must be in the top 50%. To be recognized as a highly cited researcher, a researcher's total number of citations in a given field over the past 11 years must place them among the top 1% of all researchers in that field. All co-authors on a paper receive equal credit. Citation thresholds vary significantly by discipline. For example, to

[1] Only two former Soviet bloc countries – Estonia and the Czech Republic – are classified among the 21 fully democratic countries according to the *Economist Democracy Index* 2024 (https://www.eiu.com/n/global-themes/democracy-index/).

reach the top 1% in mathematics, a researcher needed 506 citations to articles published in mathematics journals over the past 11 years. In physics, the threshold was much higher – 14 557 citations, nearly 29 times more. These thresholds also depend on the year of publication, since older papers have had more time to accumulate citations. A 2014 mathematics article needed at least 88 citations to reach the top 1%, while a physics article from the same year required 216 citations. By contrast, for papers published in 2024, the thresholds were much lower – five citations in mathematics and 11 in physics. For a country or territory to rank in the top 50% in a given field, its mathematicians had to collectively accumulate at least 958 citations and its physicists at least 6600 citations.

In order for an article to reach the "highly cited" category, it must be in the top 1% of cited articles published in journals in its field and in a specific year of publication. Again, for a 2014 mathematics paper to reach the top 1% citation count, it needed 88 citations. In contrast, a 2014 molecular biology and genetics paper needed almost five and a half times more, at least 472 citations.

In the analysis conducted, the five most important bibliometric indicators were: (1) the number of publications from a country or territory that passed the ESI entry threshold in one of the 22 scientific fields, (2) the total number of citations to papers included in the ESI, (3) the average number of citations per paper – referred to as the scientific wealth, (4) the number of papers that reached the top 1% of citations within their age cohort, and (5) the percentage of top 1% papers out of all papers included in the ESI.

Results

Scientific wealth of countries in 2025

Table 1 presents 96 countries and territories that published a minimum of 8000 publications over the 11-year span from 2014 to 2024 and thus crossed the ESI entry threshold. This total publications criterion (the third column) excludes 55 countries and territories that surpassed the ESI threshold in at least one of the 22 fields but did not meet the required total number of publications. Several countries and territories, such as Gambia, Kyrgyzstan, Monaco, New Caledonia, and Panama, had a high average number of citations per article; however, the total number of articles entering the ESI over these 11 years was below the established threshold that guaranteed entry into the final list. Often, the success of these usually small countries or territories is due to participation in international consortia, which leads to strong performance in a few or even a single field of science, while weaker fields fail to pass the ESI entry threshold – thus preventing a dilution of their average citation rate (Allik et al. 2020a). The fact that as many as 96 countries and territories published at least 8000 articles in the essential set of 11 000 journals over the past 11 years suggests that the threshold was appropriately set to avoid significant bias in the analysis results.

Thus, the third column in Table 1 shows the number of articles published by each country or territory during the observation period. For example, Estonia, Latvia, and Lithuania published 25 820, 12 918, and 33 446 articles, respectively. These figures are, of course, minuscule compared to the 5.6 million articles from China and 4.8 million from the USA, the world's leaders in scientific productivity.

The fourth column of Table 1 presents the total number of citations received by the publications, while the fifth column shows the quotient of citations to publications, i.e., the average number of citations per article, which is defined as a measure of *scientific wealth*. On average, each article authored by researchers from Estonia, Latvia, and Lithuania received 30.7, 19.9, and 16.5 citations, respectively. For comparison, the global average citation rate among articles included in the ESI was 16.9. This means that, relative to the ESI world average, the citation rates of Estonian, Latvian, and Lithuanian publications were 81.7%, 17.8%, and –2.4% higher or lower, respectively. Based on this average citation impact – or article-level impact factor, aka scientific wealth – Estonia ranked 3rd, Latvia 41st, and Lithuania 69th among the 96 countries and territories included in the ranking.

Globally, Iceland (88.8%) and Singapore (83.9%) lead the list as the most scientifically wealthy countries, based on their average citation rates relative to the ESI world average. At the opposite end, Kazakhstan (–20.7%) and Russia (–31.4%) recorded the lowest impact. Notably, although China and the United States were the top producers of scientific publications, as already noted above, their average citation rates were 2.6% and 39.6% above the ESI average, placing them at 63rd and 23rd in the citation impact rankings, respectively. These findings highlight that a high volume of scientific output does not necessarily correlate with a proportionate increase in research quality or influence.

The global ranking of scientific wealth clearly illustrates the long-term impact of the Soviet Union's collapse on its former republics. Among these, only Estonia (3rd) and Georgia (7th) have attained a high level of scientific wealth. Latvia (41st), Armenia (50th), and Lithuania (69th) have achieved a solid mid-tier standing, comparable to that of several former Eastern Bloc countries, with Slovenia (44th) and Hungary (47th) performing among the best in this group. In contrast, Belarus (75th), Azerbaijan (90th), Ukraine (94th), Kazakhstan (95th), and Russia (96th) produced a sufficient number of publications to surpass the ESI threshold over the past 11 years, yet their average citation rates place them at the bottom of the global ranking. Notably, Russia ranked as the lowest-performing country in the world in terms of scientific wealth. Although Moldova and Kyrgyzstan met the ESI threshold, the total number of their publications remained too small for inclusion in the main comparative table, and their average impact scores were similarly low.

In 2007, the United States ranked second globally in terms of scientific impact, following Switzerland, with an average citation rate 49% above the ESI world average. By 2025, although the United States still maintains a 40% advantage over the ESI average, this is sufficient only for 23rd place in the global ranking. While the relative impact of U.S. science has declined over the years, China's scientific influence has

Table 1. Countries and territories publishing at least 8000 publications, exceeding the ESI threshold between 2014 and 2024, ranked by impact (average citations per article, 5th column)

Rank	Countries/regions	No. of Web of Science documents	No. of citations	Average citations per article	No. of top articles	Percentage of top articles
1	ICELAND	14 898	475 024	31.89	389	2.61
2	SINGAPORE	181 119	5 630 077	31.08	5594	3.09
3	ESTONIA	25 820	792 400	30.69	708	2.74
4	SWITZERLAND	395 954	11 555 395	29.18	10 279	2.60
5	SCOTLAND	199 220	5 713 987	28.68	5201	2.61
6	WALES	68 416	1 952 693	28.54	1655	2.42
7	REPUBLIC OF GEORGIA	9046	256 817	28.39	230	2.54
8	NETHERLANDS	513 421	14 484 503	28.21	12 570	2.45
9	DENMARK	246 685	6 877 475	27.88	5938	2.41
10	LUXEMBOURG	16 929	460 356	27.19	412	2.43
11	BELGIUM	285 090	7 578 807	26.58	6630	2.33
12	HONG KONG	220 816	5 835 093	26.43	5981	2.71
13	NORTHERN IRELAND	36 525	951 160	26.04	863	2.36
14	SWEDEN	355 905	9 213 739	25.89	7587	2.13
15	ENGLAND	1 332 101	34 435 936	25.85	29 283	2.20
16	QATAR	33 782	869 232	25.73	780	2.31
17	IRELAND	119 520	3 032 425	25.37	2756	2.31
18	AUSTRALIA	834 505	21 023 222	25.19	17 986	2.16
19	FINLAND	170 868	4 198 329	24.57	3298	1.93
20	AUSTRIA	211 748	5 134 311	24.25	4504	2.13
21	SRI LANKA	14 936	354 868	23.76	338	2.26
22	NORWAY	189 089	4 469 416	23.64	3804	2.01
23	USA	4 837 637	114 230 491	23.61	82 042	1.70
24	CANADA	870 981	20 557 055	23.60	16 449	1.89
25	NEW ZEALAND	125 255	2 937 094	23.45	2407	1.92
26	COSTA RICA	9269	214 424	23.13	147	1.59
27	GERMANY	1 350 883	31 142 707	23.05	22 951	1.70
28	FRANCE	885 153	20 293 347	22.93	14 858	1.68
29	CYPRUS	21 812	493 599	22.63	491	2.25
30	ISRAEL	182 839	4 095 408	22.40	3397	1.86
31	KENYA	29 343	653 864	22.28	503	1.71
32	GREECE	147 168	3 201 956	21.76	2790	1.90
33	LEBANON	27 854	605 862	21.75	776	2.79
34	PHILIPPINES	23 098	499 642	21.63	530	2.29
35	ITALY	922 769	19 900 317	21.57	14 692	1.59
36	PERU	23 503	504 263	21.46	424	1.80
37	PORTUGAL	201 431	4 234 950	21.02	3111	1.54
38	SPAIN	768 930	16 102 744	20.94	11 996	1.56
39	MACAU	24 850	513 257	20.65	552	2.22
40	NEPAL	13 969	284 033	20.33	256	1.83
41	LATVIA	12 918	257 453	19.93	204	1.58
42	MALAYSIA	167 589	3 324 205	19.84	2865	1.71
43	OMAN	15 511	307 115	19.80	334	2.15
44	SLOVENIA	51 782	1 005 975	19.43	806	1.56
45	SOUTH AFRICA	183 651	3 563 480	19.40	3016	1.64
46	BANGLADESH	46 885	909 226	19.39	1023	2.18
47	HUNGARY	95 681	1 848 240	19.32	1537	1.61
48	TANZANIA	16 178	310 843	19.21	200	1.24
49	CAMEROON	15 322	293 928	19.18	181	1.18

Continued on the next page

Table 1. *Continued*

Rank	Countries/regions	No. of Web of Science documents	No. of citations	Average citations per article	No. of top articles	Percentage of top articles
50	ARMENIA	9762	183 363	18.78	134	1.37
51	BULGARIA	30 309	568 909	18.77	496	1.64
52	CHILE	119 644	2 226 152	18.61	1673	1.40
53	VENEZUELA	8862	164 689	18.58	115	1.30
54	URUGUAY	14 269	264 228	18.52	179	1.25
55	UNITED ARAB EMIRATES	63 179	1 164 238	18.43	1458	2.31
56	SAUDI ARABIA	300 370	5 521 509	18.38	5756	1.92
57	UGANDA	17 872	323 654	18.11	241	1.35
58	CZECH REPUBLIC	169 689	3 071 626	18.10	2367	1.39
59	VIETNAM	80 205	1 439 643	17.95	1277	1.59
60	GHANA	24 599	439 566	17.87	346	1.41
61	SOUTH KOREA	756 153	13 278 497	17.56	8464	1.12
62	ARGENTINA	111 783	1 953 281	17.47	1398	1.25
63	CHINA MAINLAND	5 560 044	96 388 533	17.34	75 434	1.36
64	COLOMBIA	72 529	1 257 056	17.33	999	1.38
65	CROATIA	50 272	867 675	17.26	722	1.44
66	KUWAIT	16 249	278 617	17.15	268	1.65
67	JAPAN	958 057	16 089 727	16.79	9668	1.01
68	TAIWAN	327 751	5 433 325	16.58	3576	1.09
69	LITHUANIA	33 446	552 180	16.51	406	1.21
70	NIGERIA	56 193	920 976	16.39	787	1.40
71	PAKISTAN	199 474	3 250 732	16.30	3560	1.78
72	JORDAN	34 646	558 650	16.12	536	1.55
73	IRAN	459 645	7 381 392	16.06	4166	0.91
74	EGYPT	206 340	3 284 224	15.92	2456	1.19
75	BELARUS	13 519	211 538	15.65	153	1.13
76	SLOVAKIA	49 790	778 818	15.64	544	1.09
77	ECUADOR	22 597	352 266	15.59	331	1.46
78	IRAQ	38 881	602 468	15.50	588	1.51
79	SERBIA	65 550	1 015 514	15.49	800	1.22
80	THAILAND	125 230	1 924 768	15.37	1307	1.04
81	POLAND	376 724	5 731 568	15.21	3981	1.06
82	CUBA	9078	138 003	15.20	75	0.83
83	TURKEY	320 880	4 814 870	15.01	2512	0.78
84	ROMANIA	108 249	1 619 169	14.96	1505	1.39
85	INDIA	1 017 537	14 982 237	14.72	9383	0.92
86	ETHIOPIA	41 147	605 253	14.71	412	1.00
87	MEXICO	197 523	2 892 072	14.64	1859	0.94
88	MOROCCO	41 597	608 199	14.62	500	1.20
89	BRAZIL	593 539	8 648 553	14.57	4676	0.79
90	AZERBAIJAN	9691	139 990	14.45	186	1.92
91	INDONESIA	57 628	819 709	14.22	598	1.04
92	TUNISIA	55 350	769 858	13.91	407	0.74
93	ALGERIA	47 438	647 856	13.66	487	1.03
94	UKRAINE	53 740	722 490	13.44	513	0.95
95	KAZAKHSTAN	18 588	249 422	13.42	229	1.23
96	RUSSIA	443 814	5 145 635	11.59	3204	0.72

grown substantially (Wagner et al. 2022). In 2007, the average citation rate of Chinese scientific publications was 56% below the ESI world average (cf. Allik 2008). Since then, China's position has improved markedly. Over the past 11 years, Chinese researchers have published approximately 5.5 million articles that met the ESI threshold, with an average citation rate of 17.3 citations per paper, equivalent to 3% above the ESI world average.

Top 1% of most-cited articles

The sixth column of Table 1 shows the number of articles from each country or territory that reached the top 1% of most-cited articles within their respective fields and time of publishing during the 11-year period. The seventh and final column presents the percentage of total articles that achieved this elite status. According to these figures, 2.7% of Estonian publications ranked the top 1%, compared to 1.6% for Latvia and 1.2% for Lithuania. These results placed Estonia, Latvia, and Lithuania at 3rd, 51st, and 74th in this ranking, respectively. Among the 96 countries and territories analyzed, Singapore ranked first, with three out of every hundred articles (3.0%) falling into the top 1% most-cited globally. For comparison, the United States saw 1.7% of its articles reach this category (ranked 42nd), while China achieved 1.36% (66th). Russia again ranked at the bottom, with just 0.72% of its publications reaching the top citation percentile.

There is a strong positive correlation between the average number of citations per paper (fifth column) and the percentage of papers that reach the top 1% of most-cited articles globally (seventh column), $r = 0.88$, $N = 96$, $p < 0.0001$. This strong relationship suggests that countries producing highly cited papers are also more likely to contribute to the top tier of global research. However, discrepancies between these two indicators may reveal inconsistencies in scientific impact. Leydesdorff et al. (2014) have noted that the proportion of papers reaching the top 1% relative to a country's average citation rate may serve as an indicator of a temporal lag in research quality. Lauk and Allik (2018) proposed using this discrepancy as an "index of mediocrity," highlighting countries that publish fewer top 1% papers than expected based on their average citation performance.

Among major scientific nations, this index reveals notable underperformance in the United States (–19 ranks), Japan (–18), and Portugal (–18). In contrast, Estonia maintains a strong position, ranking third in both the average citation rate and share of top 1% articles, indicating a balanced and impactful research output. Latvia and Lithuania, however, show moderate declines on the index: –10 and –5 ranks, respectively. These shifts suggest that, despite respectable average citation counts, both countries fall short of their expected number of top-performing papers.

In addition to the articles that have reached the top 1% of citations, it is also worth looking at how many articles have been published in the two leading journals, *Nature* (IF 2023 = 50.5) and *Science* (IF 2023 = 44.7), over the past 11 years. According to data from the WoS, between 2014 and 2024, Estonian scientists published 131 articles in these journals, while Latvian and Lithuanian researchers published 25 and 47 articles, respectively. The average number of citations per article during this period was 538 for publications by Estonian, 595 by Latvian, and 387 by Lithuanian researchers. These figures underscore Estonia's relative success in not only contributing to *Nature* and *Science*, but also in achieving a significant citation impact. Although articles by Latvian researchers in these journals had a slightly higher citation rate on average, the substantially greater number of publications by Estonian researchers highlights a broader and more consistent pattern of high-impact research output.

Estonia's rise in scientific wealth

To understand Estonia's ascent in global rankings of scientific wealth, it is instructive to examine Fig. 1, which traces changes in the average citation rate of Estonian publications relative to the ESI world average since 2006. Unfortunately, systematic data on the impact of Estonian, Latvian, and Lithuanian science immediately following the restoration of independence in 1991 is not available. However, by coincidence, researchers from each of these three countries published approximately 300 papers in WoS-indexed journals in the early years of regained independence (Allik 2003, 2008). By 2006, the number of WoS-indexed publications had grown substantially in Estonia and Lithuania, reaching over 900 and 1300 publications, respectively, while Latvia lagged behind with around 400 publications (Allik 2008).

One might assume that such post-independence growth had roots in comparatively strong scientific infrastructure during the Soviet era. However, this assumption is not supported by evidence. On the contrary, Estonian, Latvian, and Lithuanian science did not markedly exceed the average quality of Soviet science overall. In a notable study, Eugene Garfield (1990a) identified the 100 most influential Soviet scientists based on global citation data from 1973 to 1988;

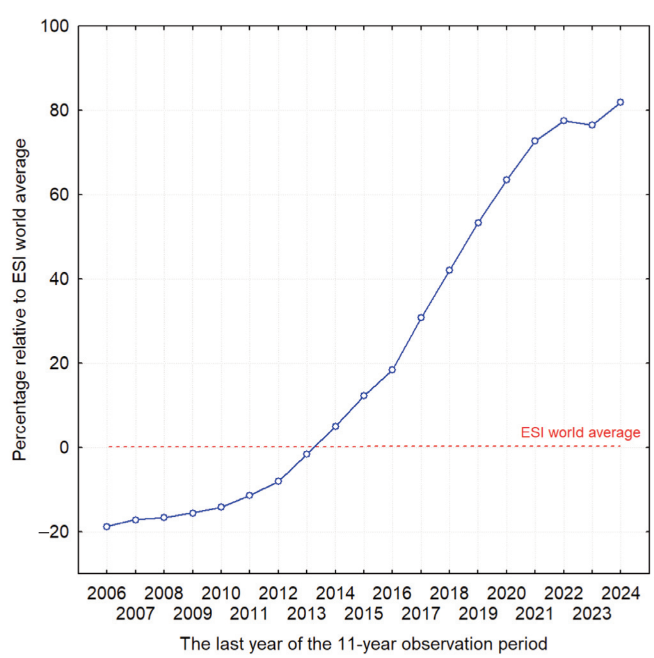

Fig. 1. Percentage impact of articles by Estonian researchers (citations per article) compared to the ESI world average, 2006–2024.

Table 2. Twenty-two fields of Estonian science ranked by their impact relative to the ESI world average (percentage) in 2025

Rank	Research fields	No. of Web of Science documents	No. of citations	Citations per paper	Relative to ESI average	Top papers
1	CLINICAL MEDICINE	2506	175 066	69.86	337.72	184
2	MOLECULAR BIOLOGY & GENETICS	1075	101 117	94.06	225.35	80
3	BIOLOGY & BIOCHEMISTRY	971	53 161	54.75	154.18	31
4	NEUROSCIENCE & BEHAVIOR	618	27 946	45.22	114.82	23
5	COMPUTER SCIENCE	619	16 621	26.85	100.37	3
6	IMMUNOLOGY	352	15 822	44.95	99.25	17
7	PLANT & ANIMAL SCIENCE	2175	49 876	22.93	84.47	79
8	MICROBIOLOGY	505	17 816	35.28	77.91	17
9	PHYSICS	2558	65 570	25.63	74.83	54
10	SPACE SCIENCE	467	16 785	35.94	69.93	12
11	MULTIDISCIPLINARY	73	2632	36.05	65.44	2
12	ENVIRONMENT/ECOLOGY	2259	66 559	29.46	54.65	64
13	PSYCHIATRY/PSYCHOLOGY	796	16 652	20.92	35.58	22
14	PHARMACOLOGY & TOXICOLOGY	445	9083	20.41	24.53	6
15	SOCIAL SCIENCES, GENERAL	2392	27 710	11.58	9.45	37
16	GEOSCIENCES	1390	25 724	18.51	9.07	28
17	AGRICULTURAL SCIENCES	588	9152	15.56	1.04	3
18	ENGINEERING	1954	28 160	14.41	–3.09	21
19	CHEMISTRY	1910	35 079	18.37	–6.75	17
20	MATHEMATICS	385	1959	5.09	–13.87	1
21	MATERIALS SCIENCE	1302	25 114	19.29	–15.87	7
22	ECONOMICS & BUSINESS	480	4796	9.99	–31.81	0
0	ALL FIELDS	25 820	792 400	30.69	81.92	708

the list included four Estonian scientists (Endel Lippmaa, Märt Mägi, Valdur Saks, and Ago Samoson) but none from Latvia or Lithuania (Garfield, 1990a). The only scholar from the region to be recognized among the most cited humanities scholars of the 20th century was Juri Lotman from the University of Tartu (Garfield 1986).

Broadly speaking, Soviet science lagged significantly behind the global research frontier (Graham 1992). For instance, U.S. researchers published 171 231 papers in 1978 indexed in the *Science Citation Index (SCI)*, which received 975 632 citations within five years – an average of 5.7 citations per article. In contrast, Soviet researchers published 21 158 papers in the same year, garnering only 31 574 citations, or 1.5 citations per article (Garfield 1987). Notably, researchers from the Netherlands accumulated more citations (32 568) than the entire Soviet Union, despite publishing only 5327 articles, resulting in an average citation rate of 6.1 per article. Given that the global average in 1978 was 4.8 citations per article, Soviet science trailed by approximately 68% in citation impact. By 2006, as shown in Fig. 1, Estonia had closed much of this gap. With an average citation rate only 20% below the ESI world average, the country had managed to reduce its citation deficit by more than threefold compared to the Soviet-era baseline, marking a remarkable transition in the quality and impact of Estonian science.

In 2007, the citation impact of Estonian science ranked 27th globally, while Latvia and Lithuania ranked 78th and 106th, respectively (Allik 2008). By 2014, the average citation rate of Estonian publications had reached parity with the ESI world average for the first time. Over the subsequent decade, the impact of Estonian scientific articles grew at an annual rate approximately 8% higher than the global average. As a result, by 2024, Estonian publications were cited 81.7% more per article than the ESI world average, as indicated above, marking a remarkable trajectory of growth in the country's scientific influence.

One of the most significant contributors to the rapid advancement of Estonian research has been the strong influence of Finland and Sweden, where many Estonian researchers pursued doctoral studies, collaborated in joint research projects, or received research training (Lauk and Allik 2018). As recently as 2007, the quality of Finnish and Swedish science appeared far beyond Estonia's reach. At that time, Sweden ranked 11th globally with a citation impact 34% above the ESI world average, and Finland ranked 13th with a 27% advantage. In comparison, Estonia held the 31st position, with a citation impact just 17% above the global benchmark average (Allik 2008). Remarkably, by 2025, Estonia has surpassed both Finland and Sweden in scientific impact, ranking third ahead of Sweden, now 15th with a 53% surplus over the ESI average, and Finland, 17th with a 46% surplus. This development marks a striking achievement in Estonia's ongoing ascent in scientific wealth.

Table 2 ranks 22 Estonian research fields by their citation impact relative to the global field-specific averages reported by the ESI. The leading drivers of Estonian scientific performance are clinical medicine, molecular biology and genetics, biology and biochemistry, neuroscience and behavior, and computer science – fields in which publications by Estonian researchers are cited more than 100% above the ESI world average. In total, Estonian-authored papers exceed the global citation average in 17 of the 22 fields. The only area where Estonia falls significantly below the benchmark is economics and business, with a citation rate 31.8% lower than the ESI average. By comparison, Latvia has entries in 17 ESI fields, while Lithuania is represented in all 22. Since the number of ESI fields in which a country or territory is represented correlates strongly with its ranking in scientific wealth, this count can serve as an additional indicator of a nation's research impact (Allik et al. 2020c).

Discussion

It may come as a surprise to many that Estonia – a small country of just 1.3 million people – has risen from a scientifically underdeveloped state to one of the most scientifically wealthy nations in the world in only 30 years (Schiermeier 2019). The rise to the third science-wealthiest country in the world has been the fastest. Sceptics might argue that such a dramatic transformation must be the result of a statistical error or bias, as stories of this kind typically belong to the realm of fairy tales. However, there is no evidence to suggest that Estonia's scientific wealth indicators are artificially inflated or skewed. Comparative analysis using WoS, Scopus, and Google Scholar reveals that Estonia's performance is consistent across databases (Martín-Martín et al. 2018). Nor does the proportion of articles published in the 11 000 core journals selected to represent essential science, relative to the total number of articles indexed by WoS, significantly affect the scientific wealth of a given country or territory (Allik et al. 2020a).

Unlike some other countries or territories, Estonia's high average citation rate is not the result of excluding weaker scientific fields that failed to meet ESI thresholds – a strategy that can artificially boost national citation averages (Allik et al. 2020a, 2020c). Estonian papers do not receive more citations than those from other countries conducting similar research, as Estonia is not viewed as a leading nation in this field (Gomez et al. 2022). Researchers have credited Estonia's success to its involvement in large international consortia (Hirv 2018, 2022); this argument is unconvincing, especially given the global trend toward increased collaboration in fields such as physics and clinical medicine, where Estonia's successes have only been possible through consortium-level efforts.

Estonia's position at the top of global scientific wealth rankings is further reinforced by a steady growth trajectory, which began around 2010 and has shown no significant setbacks since 2006 (see Fig. 1). Today, Estonia joins Iceland and Singapore among the top three countries in terms of scientific reputation, as measured by average citations per paper (see Tabel 1). While Panama demonstrates a comparable citation impact, its performance is largely driven by one outstanding institution, which is the Smithsonian Tropical Research Institute, whose internationally renowned scholars contribute a disproportionately large share of the country's high-impact scientific output (Christen 2002; Allik et al. 2020c).

This presents a fascinating question: how has Estonia managed not only to catch up with but even surpass its role models, Finland and Sweden, from whom it lagged significantly just 20 years ago? Estonia's remarkable success is particularly notable when compared to its neighbors, Latvia and Lithuania, with which it shared nearly identical starting positions in 1991. By comparing the development of scientific wealth across the three Baltic countries over the past 30 years, it may be possible to identify factors that have particularly supported – or hindered – the growth of scientific wealth.

The key drivers of scientific excellence in Estonia, or in any country, can be broadly grouped into four categories: (1) science policy decisions, (2) research funding, (3) foreign aid, and (4) the research ethos of scientists, which we will discuss below.

Science policy decisions

First, there is little doubt that several science policy decisions made by Estonia, Latvia, and Lithuania following the restoration of independence in 1991 have significantly influenced the development of scientific wealth in these countries (Kristapsons et al. 2003; Martinson 2015; Dagiene et al. 2024). Some reforms were both necessary and broadly similar across all three states. For example, the Soviet two-tier system of academic degrees – Candidate of Sciences and Doctor of Sciences – was replaced by a single doctoral degree (PhD), aligning with international standards in higher education. Equally important was the restoration of universities' autonomy in awarding academic degrees, transferring this authority from centralized national committees back to individual institutions, as is the norm in most democratic countries.

One particularly radical decision that may ultimately explain part of Estonia's scientific success was the requirement that, instead of submitting a traditional thesis several hundred pages long, doctoral candidates must publish at least three articles in internationally recognized journals indexed by WoS or other major scientific databases. Each article undergoes critical evaluation by at least two reviewers before publication, meaning that every doctoral thesis effectively receives scrutiny from a minimum of six internationally recognized experts who validate the work's quality and originality. This mandate, adopted collectively by all Estonian universities, has substantially reduced the relevance of local publications. As a result, local journal publishers have been compelled to seek inclusion in major indexing databases such as WoS.

Fortunately, this shift coincided with WoS's efforts to address criticism of being overly centered on English-language mainstream journals by expanding the range of indexed journals, including many local ones. Currently, WoS indexes 47 journals published in Lithuania, while Estonia and Latvia have 18 and 13 local journals indexed, respectively.[2] Paradoxically, the relatively large number of Lithuanian journals indexed in WoS may partly explain why Lithuania's scientific wealth is the smallest of the three Baltic countries. Since local journals – often published in the local language – generally have lower impact factors than mainstream international journals, this can reduce researchers' motivation to publish

[2] https://mjl.clarivate.com/search-results

in higher-impact journals, which are considerably more competitive.

One key factor behind the success of Estonian science was the establishment of the Estonian Science Foundation (*Eesti Teadusfond*), independent of the state. Its history is detailed by its first director, Helle Martinson, in the book *From Isolation to Academic Capitalism: The Estonian Science Foundation 1989–2011* (Martinson 2015). Thanks to this foundation, Estonia – unlike Latvia and Lithuania – became a member of the European Union Research Organizations Heads of Research Councils (EUROHORCs, founded in 1992), which represents the majority of scientific research organizations across Europe.

To protect its independence from political influence, the foundation wisely mandated that all grant applications be submitted in English and evaluated by foreign experts, whose involvement was compulsory. This policy proved to be an excellent training ground, not only teaching researchers how to write competitive articles but also how to apply effectively for external grants. While some nationalist politicians initially viewed the English-language requirement as merely replacing the previously mandatory Russian with another bureaucratic language, Estonia's high success rate in securing European Science Foundation and other European Union grants suggests the decision had overwhelmingly positive consequences.[3] In contrast, Latvia made a critical error by introducing a grant system that led to the loss of stable, basic funding for science. The resulting lack of consistent funding, reliant instead on one-off decisions, triggered a significant brain drain (Hazans 2019), which significantly weakened Latvian science (Kristapsons et al. 2003).

It was also a wise decision to invite the Royal Swedish Academy of Sciences to evaluate Estonian science right from the outset in 1992 (Martinson and Martinson 1999; Martinson 2015). By the end of that year, the Academy presented a comprehensive report on the state of Estonian science. While some regarded the "benefits" of the Swedish evaluation, especially those influencing administrative decisions, as relatively modest, the moral impact of this assessment should not be underestimated. Although it is difficult to measure how much of an advantage this large-scale international evaluation gave Estonia over Latvia and Lithuania, it was undoubtedly an important factor in Estonia's integration into the global scientific community. The overall positive evaluation not only dispelled early doubts about weak or ideologically compromised scientific groups and fields but also served as a powerful encouragement for further progress in Estonian science.

Thus, it is challenging to identify a single policy as the main driver behind the rapid rise of Estonian science's influence. More importantly, it became clear that the governance system of a country or territory may play an even greater role in fostering high-quality science. As recently argued by Moody (2025), Estonia is the most successful small European country of our lifetime. Since 1991, it has increased its GDP per capita by 2500%, built what is considered the best education system in Europe according to PISA results (Boman 2020), and ranks 13th on the latest perceived corruption index by Transparency International[4] – placing it ahead of Canada and Germany (both 15), the United Kingdom (20), Lithuania (32), and Latvia (38). Estonia has successfully developed a digital society.[5] This has also contributed to advancements in various fields, likely including scientific wealth (Kattel and Mergel 2019). Good governance involves the careful and deliberate exercise of state authority, characterized by the absence of violence and corruption, a strong commitment to the rule of law, and respect for citizens' rights. It also requires the ability to formulate and implement sound policies that benefit society as a whole rather than privileging a select few (Allik et al. 2020a). Notably, good governance has positively influenced the growth of generalized social trust, which has increased at an unprecedented rate in Estonia, Latvia, and Lithuania, mirroring, at least in part, the growth of their scientific wealth (Beilmann et al. 2021).

Research funding

The amount of research funding and money invested in science is clearly not the primary driver behind Estonia's surge in scientific wealth. According to Eurostat data, Finland and Sweden invested 3.1% and 3.6% of their GDP into R&D in 2023, respectively. In contrast, Estonia surpassed both in scientific wealth despite a more modest R&D investment of only 1.8%, which is even below the EU average. However, these figures can be misleading, as most Estonian funding is allocated to basic research, while a significant portion of Finnish and Swedish investments goes toward applied research within companies. Furthermore, salaries for Estonian professors and researchers are far from competitive compared to their Nordic counterparts. The average gross salary for a professor in Estonia is €35 357 (approximately €17 per hour), whereas professors in Finland and Sweden earn an average of €77 707 (€37 per hour) and €63 261 (€30 per hour), respectively.[6] It is worth noting that Estonia's salary system is more flexible, allowing professors to increase their earnings through grants. Clearly, it is neither superior scientific infrastructure nor financial incentives that have driven the production of highly influential scientific papers in Estonia.

One peculiarity of Estonian R&D funding is that, unlike Sweden and Finland, much of the budget is allocated to basic research, with only a negligible portion directed toward applied science – often conducted by non-academic institutions. While this focus supports foundational knowledge, it also represents a significant shortcoming that threatens the long-term sustainability of Estonian research funding. This imbalance is unlikely to have contributed to the rapid growth

[3] https://researchinestonia.eu/rwp/wp-content/uploads/2023/07/ETAG_onepager_2023_A4_3mmbleed.pdf

[4] https://www.transparency.org/en/cpi/2024

[5] https://www.newyorker.com/magazine/2017/12/18/estonia-the-digital-republic

[6] https://www.salaryexpert.com/salary/browse/countries/professor

of Estonia's scientific wealth. Instead, it signals a risk: Estonian science may not be contributing enough to economic growth, which in turn jeopardizes future funding for fundamental research.[7]

Foreign aid

The contribution of foreign aid to the development of science in Estonia, Latvia, and Lithuania is difficult to overstate. As was noted above, in the first half of 1991, the Estonian government decided to commission an international evaluation of its scientific landscape, reflecting the widely held belief that a seriously ill patient can no longer diagnose themselves (Kristapsons et al. 2003; Martinson 2015). Furthermore, many Estonian researchers pursued doctoral studies, collaborated on joint research projects, or received research training in Finland and Sweden (Lauk and Allik 2018), as well as in other leading scientific countries such as the United States and the United Kingdom. Official statistics often overlook generous donations from international colleagues of equipment, chemicals, computer time, and other resources critical to conducting high-quality research. When the International Science Foundation allocated grants to newly independent post-Soviet countries, Estonia was by far the most successful relative to its size (Ilves 1994). Moreover, Estonian scientists' willingness to contribute to international projects – such as CERN and other consortia whose results often appear in multi-authored publications – can also be considered a form of foreign aid (Hirv 2019, 2022). However, participation in these consortia is not simply about collecting easy rewards; in fields such as physics, astronomy, genetics, and medicine, it is often the only way to conduct "big science."

The support of émigré scientists from Estonia, Latvia, and Lithuania – many of whom gained global recognition – was also crucial. They contributed by returning home or helping local researchers integrate into international networks. For example, Lithuanian archaeologist and anthropologist Marija Gimbutas (1921–1994) proposed the influential Kurgan hypothesis locating the Proto-Indo-European homeland in the Pontic Steppe. Estonian psychologist Endel Tulving (1927–2023) was a pioneer in memory studies, distinguishing episodic from semantic memory. Latvian folklorist and psychologist Vaira Vīķe-Freiberga, a student of Tulving, served as Latvia's sixth president (1999–2007). These and many other émigré scientists served as role models, showing that if they could succeed internationally, so could other Estonians, Latvians, and Lithuanians (Crowe 1988).

The research ethos

One of the key factors behind the success of Estonian science was a fundamental shift in research ethos – defined as the practices or values that distinguish one person, organization, or society from others. The shortcomings of the Soviet scientific system are well known: extreme centralization coupled with very low efficiency, pervasive ideological control, isolation from the global scientific community, a bias toward serving the military-industrial complex, an orientation toward the Russian language, and an unjustified sense of superiority over the rest of the world – attributes that earned it the label "empire of knowledge" (Balzer 1985; Graham 1992).

An essential step toward liberation from this "empire of knowledge" was a radical change in mindset and scientific ethos. This meant abandoning all Soviet-era practices and values in favor of new approaches. One of the most important shifts was orienting Estonian science toward the global scientific marketplace, aiming to publish in internationally respected journals such as *Nature* and *Science* rather than focusing on a narrow, parochial "local market."

This change in attitude was well captured by Jaan Einasto (Einasto 2018), one of Estonia's most prominent scientists and a key figure in the paradigm shift in cosmology (Peebles 2012, 2024). Einasto exemplifies how scientific ideas and discoveries gain serious recognition only once they are published in leading journals and when key figures in the field have engaged with you personally. It is also worth noting that another distinguished Estonian astronomer, Ernst Öpik, had earlier escaped both the physical terror of the Bolsheviks and their Marxist dogmas, allowing him to pursue his scientific career freely at the Armagh Observatory in Northern Ireland and later at the University of Maryland (Öpik 1977).

A common practice among leading Estonian researchers is the strategic use of scientific databases such as WoS, Scopus, and later Google Scholar to guide and refine their research activities. During the Soviet era, the *Current Contents* series, published by Eugene Garfield's Institute for Scientific Information, was essentially the only way for scientists behind the Iron Curtain to stay updated with new literature. Since the authors' addresses were included with each new title, requesting reprints directly from them was often the only way to access these publications (Baykoucheva 2019).

Today, nearly all Estonian research groups carefully monitor journal impact factors, recognizing the importance of publishing in widely read and highly cited journals. By analyzing the global response to their work, researchers can better refine their choice of research topics, interpret results, and select the most suitable outlets for publication. Although there is often public criticism that true science should not be driven solely by citation counts, there is strong evidence that reasonable use of bibliometric tools has been a key factor in Estonia's rapid scientific growth. This approach helps minimize wasted effort on activities that do not substantially contribute to the country's scientific wealth. As the saying goes, "Not rich enough to buy cheap things." Paraphrased for Estonian science, a fitting maxim might be: "Too small to publish papers without significant impact."

Conclusion

Neither any single factor nor any of the four broad groups of factors alone can fully explain the unprecedented growth of Estonia's scientific wealth over the past decades. The expo-

[7] Saarma, M. 2025. Akadeemia roll (The role of the academy). *Sirp*, 24.01.2025. https://www.sirp.ee/akadeemia-roll/

nential shape of the growth curve suggests the presence of a positive feedback loop, where each success fuels the next. Thus, the key to Estonia's remarkable achievements lies in the synergy of multiple factors working together. It also appears that a generally favorable environment – characterized by good governance, strong democratic institutions, and an excellent education system – plays a crucial role in fostering outstanding scientific achievement. However, the precise combination of factors that most effectively foster the production of high-impact scientific papers remains to be identified. Identifying the precise combination of these factors necessitates methods such as conducting in-depth interviews with participants, which is beyond the scope of this work.

Data availability statement

All data are available in the article.

Acknowledgments

The authors are members of the Estonian Academy of Sciences, with the second author (MS) currently serving as its President. The authors sincerely thank the scientists whose work has helped make Estonia the fastest-growing nation in scientific wealth worldwide. The publication costs of this article were covered by the Estonian Academy of Sciences.

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Kuidas sai Eestist maailma kõige kiiremini kasvava teadusjõukusega riik?

Jüri Allik, Mart Saarma ja Anu Realo

Teadusjõukuse mõiste on defineeritud kui keskmine viidete arv artikli kohta, mille on avaldanud konkreetse riigi või territooriumi teadlased kindlaksmääratud aja jooksul (May 1997). Käesoleva töö analüüs põhineb andmebaasil Essential Science Indicators (ESI; Clarivate™), mis reastab autorid, asutused, riigid ja ajakirjad viitamise tulemuslikkuse alusel aastatel 2014–2024. Kakskümmend aastat tagasi oli Eesti teadusartiklite mõjukus 20% madalam kui ESI maailma keskmine. Tänaseks, 2025. aastal, on Eesti teadlaste artiklite keskmine viitamissagedus 81,7% kõrgem kui ESI maailma keskmine, asetades Eesti Islandi ja Singapuri järel maailmas kolmandale kohale ning edestades oma Põhjamaade naabreid ja eeskujusid Soomet ja Rootsit. Eesti teaduse mõjukuse kiirele kasvule pole leitud ühte lihtsat seletust. Ükski neljast analüüsitud tegurirühmast – teaduspoliitika, rahastamine, välisabi ja eetos – ei suuda üksi täielikult seletada Eesti edukust, eriti võrreldes naabrite Läti ja Leeduga. Eesti on suurepärane näide sellest, kuidas tegurite unikaalne koosmõju võib viia teadusjõukuse kiireima kasvuni kogu maailmas, kuigi tegurite täpne kombinatsioon on veel kindlaks tegemata.