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Gender gap among highly cited researchers, 2014–2021

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ABSTRACT

This study examines the extent to which women are represented among the world's highly cited researchers (HCRs) and explores their representation over time and across fields, regions, and countries. The study identifies 11,842 HCRs in all fields and uses Gender-API, Genderize.Io, Namsor, and the web to identify their gender. Women's share of HCRs grew from 13.1% in 2014 to 14.0% in 2021; however, the increase is slower than that of women's representation among the general population of authors. The data show that women's share of HCRs would need to increase by 100% in health and social sciences, 200% in agriculture, biology, earth, and environmental sciences, 300% in mathematics and physics, and 500% in chemistry, computer science, and engineering to close the gap with men. Women's representation among all HCRs in North America, Europe, and Oceania ranges from 15% to 18%, compared to a world average of 13.7%. Among countries with the highest number of HCRs, the gender gap is least evident in Switzerland, Brazil, Norway, the United Kingdom, and the United States and most noticeable in Asian countries. The study reviews factors that can be seen to influence the gender gap among HCRs and makes recommendations for improvement.

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1. INTRODUCTION

Research on the gender gap in science continues to receive substantial attention as barriers to the progress of women in science, technology, engineering, and mathematics (STEM) fields remain widespread (Bendels, Müller et al., 2018; Ceci, Ginther et al., 2014; Charlesworth & Banaji, 2019; Holman, Stuart-Fox, & Hauser, 2018; Huang, Gates et al., 2020; Larivière, Ni et al., 2013; Leslie, Cimpian et al., 2015; Maliniak, Powers, & Walter, 2013; Sheltzer & Smith, 2014; West, Jacquet et al., 2013). According to Aguinis, Ji, and Joo (2018), many factors have been shown to contribute to the underrepresentation of women in STEM and other fields, but nothing plays a stronger role than gender discrimination, which creates imbalances in the opportunities presented to and barriers encountered by women compared with men. These include bias in peer review (Helmer, Schottdorf et al., 2017; Murray, Siler et al., 2018), disproportionate resource allocation for men (Duch, Zeng et al., 2012), reviewers and colleagues' undervaluing the quality of women's research (Knobloch-Westerwick, Glynn, & Huge, 2013; Merton, 1968; Rossiter, 1993), stereotypes (Wang & Degol, 2017), favoritism (Abramo, D'Angelo, & Soldatenkova, 2017), sexual harassment (National Academies of Sciences, Engineering, and Medicine, 2018), poor mentorship (Aguinis et al., 2018), and lack of role models (Bell, Chetty et al., 2019; Botella, Rueda et al., 2019; Lockwood, 2006), among others.

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Gender discrimination and other concepts and phenomena, such as leaky pipelines (Blickenstaff, 2005; Carr, Gunn et al., 2015; Griffith, 2010; Shaw & Stanton, 2012), demographic inertia (Hargens & Long, 2002; Marschke, Laursen et al., 2007; Meho, 2021; Shaw & Stanton, 2012; Thomas, Poole, & Herbers, 2015), the Matthew Effect (Bol, de Vaan, & van de Rijt, 2018; Botella et al., 2019; Dion, Sumner, & Mitchell, 2018; Merton, 1968; Rossiter, 1993), and the Matilda Effect (Dion, Sumner, & Mitchell, 2018; Knobloch-Westerwick, et al., 2013; Lincoln, Pincus et al., 2012; Rossiter, 1993), are often correlated and mutually reinforcing, contributing to women publishing less (Bendels et al., 2018; Larivière et al., 2013), being undercited (Knobloch-Westerwick et al., 2013), underfunded (Bol et al., 2018; Ceci et al., 2014; Witteman, Hendricks et al., 2019), underpaid (Freund, Raj et al., 2016), underpromoted (Weisshaar, 2017), underrecognized (Lincoln et al., 2012; Ma, Oliveira et al., 2019; Meho, 2021), having shorter research careers (Elsevier, 2017, 2020; Huang et al., 2020), and having few progressing to senior and leadership positions compared to men (Ceci et al., 2014; Huang et al., 2020).

A main indicator of the gender gap in science is women's representation among elite scientists—researchers who made their mark in science largely through their publications and citation performance (Chan & Torgler, 2020; Kwiek, 2016; Sá, Cowley et al., 2020). Publications represent the primary means of disseminating knowledge and the principal measure of research productivity, which influences career prospects and visibility (Holman et al., 2018; Ioannidis, 2014). Citations also play a central role in assessing researchers' influence and attaining recognition from the scientific community (Carpenter, Cone, & Sarli, 2014; Sá et al., 2020). Elite scientists are generally highly cited researchers (HCRs), and being relatively highly cited, especially in fields where citations serve as symbolic capital, is a compelling sign of research impact. It can put scientists on the radar of their peers, funding agencies, and research award committees, help them advance further in their careers, and encourage them to produce more pioneering work (Chan & Torgler, 2020; Chatterjee & Werner, 2021; Ha, Lehrer et al., 2021; Kwiek, 2016; Sá et al., 2020). Institutions benefit, too, as having HCRs bestows prestige and impact in national and international rankings and helps attract more funding and high-quality students and faculty (Hazelkorn, 2015; Rauhvargers, 2013). In this study, we examine the extent to which women are represented among the world's HCRs and explore their representation over time and across fields, regions, and countries.

It is important to examine the gender gap among HCRs because productivity, research impact, and reputation in science are highly skewed (Chan & Torgler, 2020). Therefore, documenting women's representation among HCRs can be informative for addressing the gender gap in science (Aguinis et al., 2018). A key advantage of studying HCRs is that they are a relatively homogeneous group of scholars in terms of capacity to produce successful and innovative ideas (Chan & Torgler, 2020). Examining the gender gap among HCRs is also important because these researchers greatly influence individuals around them and often serve as role models and mentors who enrich their colleagues' and students' social and intellectual capital (Malhotra & Singh, 2016). Thus, understanding the gender gap among HCRs and the factors that influence this can be useful in planning interventions to help close the gap.

2. FACTORS THAT INFLUENCE THE GENDER GAP AMONG HCRS

We did not collect data to identify the root causes of the gender gap among HCRs; however, we briefly review here eight relevant factors or phenomena: research productivity and impact, publication venues, research collaboration, coaffiliation, leaky pipelines, demographic inertia, the Matthew Effect, and the Matilda Effect. These and other factors (e.g., career length, author affiliation, author location, national and international mobility, article language, research quality, and research funding) have been comprehensively reviewed by Tahamtan, Afshar, and Ahamdzadeh (2016). These factors can considerably affect researchers' propensity to receive more citations (Beaudry & Larivière, 2016) and achieve stardom, including HCR status.

2.1. Research Productivity and Impact

Research productivity and impact measured by publications and citations are key factors for attaining HCR status. Female researchers, however, for various reasons, generally publish and get cited less than men in most fields (Chan & Torgler, 2020; Holman et al., 2018; Larivière et al., 2013; Nygaard, Aksnes, & Piro, 2022). In a study of 59,278 researchers in science, technology, engineering, mathematics, and other scientific fields, Aguinis et al. (2018) found a considerable gender productivity gap among star performers in favor of men across fields. They also found that the underrepresentation of women is more extreme as we consider more elite ranges of performance (i.e., top 10%, 5%, and 1% of performers), suggesting that women may have to accumulate more scientific knowledge, resources, and social capital to achieve the same level of increase in total outputs as their male counterparts. In another study of 943 elite researchers and their peers in the United States, Canada, and South Africa, Sá and colleagues (2020) found that among the elites, men published 30% more articles and were cited 64% more than women. However, the difference in publication activity between men and women in the peer group was insignificant. Sá and colleagues also found that elite male scientists are significantly more frequently cited than their female peers. Madison and Fahlman (2021) examined the publication metrics of 1,345 full professors at the six largest universities in Sweden between 2009 and 2014. They found that men had significantly more publications and citations in medicine and the social sciences. They concluded that women have to reach higher levels of scholarly achievement than men to achieve similar career success.

2.2. Publication Venues

Another factor that can influence the gender gap among HCRs is that women publish fewer articles in top journals than men. In a study examining 293,557 research articles published in 54 Nature journals covering the categories of life sciences, multidisciplinary, earth and environmental sciences, and chemistry, Bendels and colleagues (2018) found that 39% of women contributed 30% of all authorships. In another study of the top 10 political science journals, Teele and Thelen (2017) found that female authors are well below the proportion of women in the field (e.g., 11% authors vs. 23% full professors). According to the Scopus database, articles published in top quartile journals attract, on average, more than twice, four times, and 15 times as many citations as articles published in second, third, and fourth quartile journals, respectively[1]. Given that top journals are much more frequently cited than others (Holman et al., 2018), the gender gap in HCRs may shrink if women's publishing in these journals is facilitated through such initiatives as having journals and publishers switch from single to double-blind review and increasing women's representation among journal editors and reviewers (Cho, Johnson et al., 2014; Gottlieb, Krzyzaniak et al., 2021; Lerback & Hanson, 2017; Lincoln et al., 2012; Murray et al., 2018).

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[1] https://www.scopus.com/ (accessed July 4, 2022).

2.3. Collaboration with Large and International Teams

A third factor that can contribute to the gender gap among HCRs can be linked to women's lower participation rates in large and international collaborative teams and projects. Larivière, Gingras et al. (2015) provide a historical analysis of the relationship between collaboration and scientific impact using three indicators of collaboration (number of authors, number of addresses, and number of countries) derived from 32,500,000 articles published between 1900 and 2011. They found that an increase in the number of authors leads to an increase in research impact and that the increase was not due to self-citations. A similar trend was also observed for the number of addresses and countries represented in an article's byline. They concluded that larger and more diverse (in terms of institutional and country affiliations) teams are necessary to realize a higher research impact. Abramo, D'Angelo, and Di Costa (2019) studied differences in collaboration behavior between 11,145 male and female top scientists covering the period 2006–2010. The main significant difference between the two groups was international collaboration, where the propensity for collaboration is greater among male professors. Similar results were found among Norwegian researchers (Aksnes, Piro, & Rørstad, 2019). Kwiek and Roszka (2021) examined the gender collaboration practices of all internationally visible Polish university professors ($N = 25{,}463$) based on their 158,743 journal article publications between 2009 and 2018. They found that most male scientists collaborate solely with men; most female scientists, in contrast, do not collaborate with women at all. Across all age groups studied, all-women collaboration is marginal, while all-men collaboration is pervasive.

At the discipline level, Jadidi, Karimi et al. (2018) investigated gender-specific differences in collaboration patterns of more than one million computer scientists worldwide from 1970 to 2017. Their results highlight that successful male and female scientists reveal the same collaboration patterns: They tend to collaborate with more colleagues than other scientists, seek innovations as brokers, and establish longer-lasting and more repetitive collaborations. However, on average, women are less likely to adopt the collaboration patterns related to success and more likely to embed into ego networks devoid of structural holes. Zhang, Zhang et al. (2020) investigated the effect of the international collaboration of 3,118 chemists from 38 universities and the Chinese Academy of Sciences on male and female scientists' academic performance. The results indicated that, compared to male scientists, female scientists performed better and significantly improved their academic performance through international collaboration, mainly because it permits them to overcome the lack of social capital and better integrate into the academic environment (Abramo, D'Angelo, & Murgia, 2013). Similar results were found among chemistry professors in Pakistan (Badar, Hite, & Badir, 2013).

2.4. Dual Affiliations

A fourth factor that can affect the gender gap among HCRs is multiple affiliations. Women hold fewer dual affiliations than men, denying them resources for participation in high-impact research (Safaei, Goodarzi et al., 2016). In a study of authors in biology, chemistry, and engineering, Hottenrott and Lawson (2017) found that authors with multiple affiliations have higher citation numbers and are more often found in high-impact publications or publish more articles in the top 10% journals than other authors. Hottenrott and Lawson also found that multiple affiliations are widespread and increasing in all fields and countries. In this study, we found that 24% of the 1,855 female HCRs have affiliations with two or more institutions and 6% have institutional affiliations in more than one country compared to 30% and 10%, respectively, among male HCRs. These differences would probably have been much greater if we were examining and comparing all female and male researchers and not only HCRs, as star performers tend to have more access to such resources (Aguinis et al., 2018; Hottenrott & Lawson, 2017).

2.5. Leaky Pipelines, Demographic Inertia, the Matthew Effect, and the Matilda Effect

These concepts or phenomena have been widely used to explain or identify causes of gender-based differences in science. The leaky pipeline analogy is used to show the extent and impact of women's dropping out of STEM fields at various stages of their careers on the gender gap in science (Blickenstaff, 2005; Carr et al., 2015; Griffith, 2010; Shaw & Stanton, 2012). For example, in the United States, women make up nearly 45% of all assistant professors, yet their proportion drops significantly to 28% among full professors (National Science Foundation, 2022). As described below, this can influence the number and proportion of female HCRs. Demographic inertia is primarily used to explain the role of low numbers and proportions of female authors in the past on their future competition for positions, status, and recognition (Hargens & Long, 2002; Marschke et al., 2007; Meho, 2021; Shaw & Stanton, 2012). It essentially assumes that, given enough time, the gender gap in science (including HCR representation) will be minimized (Thomas et al., 2015). Relevant examples of the Matthew Effect are where men as the predominant authors in a field receive more citations, stature, influence, and resources (Bol et al., 2018; Botella et al., 2019; Dion et al., 2018) and where women's publishing and citation networks are more isolated and have fewer ties than men's networks (Yu, Krehbiel et al., 2020)—these and other factors affect the propensity of women to accumulate scientific capital to achieve HCR status. As for the Matilda Effect, it is when women's research is viewed as less important than men's research or when women's ideas are attributed to male scholars, even as a field becomes more diverse, resulting in the loss of science capital by women (Dion et al., 2018; Lincoln et al., 2012).

3. METHODS

Similar to Shamsi, Lund, and Mansourzadeh (2022), we use the lists of HCRs generated annually since 2014 by Clarivate to identify highly cited researchers in all 21 Essential Science Indicators (ESI) subject categories (see below)[2]. We also identify HCRs classified by ESI under a category named cross-field—researchers who did not make it as HCRs in a specific subject category but have multiple highly cited papers in several fields that together qualify them as HCRs. The lists of HCRs include the names of the researchers and their subject category(ies), primary affiliation, and secondary affiliation, if any. According to Clarivate, HCRs are researchers who have demonstrated significant and broad influence through the publication of multiple highly cited papers during the last 11 full calendar years (e.g., the 2021 HCR edition is based on papers published and cited between 2010 and 2020). The source of the papers is the Science Citation Index Expanded and the Social Sciences Citation Index. Highly cited papers are those that rank in the top 1% of citations in their respective subject categories and year of publication. The 2014–2020 editions of HCRs exclude papers with more than 30 institutional addresses, and the 2021 edition excludes papers with more than 30 authors. Authors qualify as HCRs based on the number of highly cited papers they published in one or more subject categories. The number of HCRs selected in each category is based on the population of authors in each subject category. For more details on the HCRs methodology, see Clarivate (2022).

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[2] https://clarivate.com/webofsciencegroup/solutions/essential-science-indicators/.

Table 1. Subject categories used in classifying HCRs

Science-Metrix classification	ESI subject categories included
Agriculture and Biology	Agricultural Sciences; Plant & Animal Science
Chemistry	Chemistry
Computer Science	Computer Science
Earth & Environmental Sciences	Environment & Ecology; Geosciences
Economic & Social Sciences	Economics & Business; Social Sciences
Engineering	Engineering; Materials Science
Health Sciences	Biology & Biochemistry; Clinical Medicine; Immunology; Microbiology; Molecular Biology & Genetics; Neuroscience & Behavior; Pharmacology & Toxicology; Psychiatry & Psychology
Mathematics & Statistics	Mathematics
Physics & Astronomy	Physics; Space Science
Total	**All above + Cross-Field**

Note: Agriculture and Biology is a merger of the two Science-Metrix categories "Agriculture, Fisheries & Forestry" and "Biology." Engineering is a merger of the two Science-Metrix categories "Engineering" and "Enabling & Strategic Technologies" (which includes the following subfields: Bioinformatics, Biotechnology, Energy, Materials, Nanoscience & Nanotechnology, Optoelectronics & Photonics, and Strategic, Defence & Security Studies). We use Computer Science for Science-Metrix's "Information & Communication Technologies," which includes the following subfields: artificial intelligence & image processing, computation theory & mathematics, computer hardware & architecture, distributed computing, information systems, medical informatics, networking & telecommunications, and software engineering.

From 2014 to 2021, the database includes 38,352 HCRs from 76 countries, or 1,855 female and 9,987 male unique HCRs after manually correcting errors in author names (e.g., the same author listed with and without middle initials) and accounting for researchers listed in more than 1 year and subject category. Because of the relatively small number of female HCRs per year per subject category, we collapsed ESI's 21 subjects into nine broad fields using the Science-Metrix (2018) classification as shown in Table 1: Agriculture and Biology, Chemistry, Computer Science, Earth & Environmental Sciences, Economic & Social Sciences, Engineering, Health Sciences, Mathematics & Statistics, and Physics & Astronomy.

To identify the gender of HCRs, we first used the Gender-API, Genderize.Io, and Namsor online gender detection tools. These tools rely on extensive, often openly available, name repositories (e.g., those of the US Census and US Social Security) and refine the results by using additional information (e.g., names and country of origin) obtained from the web and social media profiles. Santamaría and Mihaljević (2018) and Sebo (2021a) extensively review these and other gender detection tools. In Genderize.Io, we used the technique recommended by Sebo (2021b) to improve accuracy. Generally, these tools report the proportion and number of times a name is associated with men or women, alongside the number of examples checked. As in Thelwall (2020), we used evidence of gender if a name was 100% one gender with at least 10 examples, increasing the evidence requirements as the percentage decreased, eventually falling to 90% one gender needing 500 examples. Using this method, we identified the gender of 9,577 (81%) HCRs. We searched the web to identify the gender of all remaining 2,263 HCRs, consulting Wikipedia pages and other sources (e.g., personal and institutional web pages and CVs) that provide gender information (based on pronouns used in the text).

When necessary, we relied on images. A limitation of this method and the study is that we used only a binary gender classification (men-women) and did not consider other genders or groups (Kozlowski, Murray et al., 2022).

We use primary affiliations of the HCRs when analyzing data by geographical region and country. Approximately 10% of all HCRs have a secondary affiliation in another country. To estimate the extent of the gender gap among HCRs, we follow a logical conclusion that the proportion of female HCRs should be close to the proportion of female authors (Lincoln et al., 2012). For this reason, we identify the pool of eligible candidates for HCR recognition by using the gender distribution of authors by field and country according to the comprehensive report published by Science-Metrix (2018), which is based on data from the Scopus database. Because HCR is annually based on papers published during the previous 11 years, we used the midpoint for every 11 years as the base for the proportion of female authors. For example, for the 2014 edition of HCR, which is based on papers published between 2003 and 2013, we used the proportion of female authors in 2008 as reported by Science-Metrix; for the 2015 HCR edition, which is based on papers published between 2004 and 2014, we used the proportion of female authors in 2009; and so on. Note that authors qualify for HCR recognition regardless of their position in the byline.

4. RESULTS

4.1. Extent of Improvement

From 2014 to 2021, women accounted for 1,855 or 15.7% of all 11,842 HCRs. This is similar to the study by Chan and Torgler (2020), in which they examined the gender of more than 94,000 of the world's top-cited scientists in 21 fields across 43 countries and found that 15% of these scientists are women. Annually, women's share of HCRs improved from 13.1% in 2014 to 14.0% in 2021 (Figure 1). These annual figures are lower than the 15.7% in total representation because there is a higher HCR turnover among women than men (see Section 4.3). These findings on HCRs reveal a more pervasive indicator of the gender gap in science compared with the gap in the proportion of female authors in general, where women account for 33.9% of all authors globally (Science-Metrix, 2018). In short, considering their proportion among authors, women's share of HCRs would need to increase by over 142% (or from 14.0% to 33.9%) to close the gap with men. The data also show that between 2014 and 2021, the gender gap among HCRs has improved at a slower rate than women's representation among authors in general—7% (or from 13.1% to 14.0%) compared to 12% (or 29.5% to 33.9%), respectively (Figure 1).

4.2. Gender Gap by Field

Similar to previous studies on elite researchers (e.g., Bendels et al., 2018; Chan & Torgler, 2020; Holman et al., 2018; Larivière et al., 2013), our data show that the gender gap among HCRs is greatest in chemistry, computer science, engineering, mathematics, and physics and astronomy where women account for 4–7% of all HCRs although they make up 25–35% of the fields' authors (Science-Metrix, 2018). This is followed by agriculture and biology as well as earth and environmental sciences, where women account for 11–14% of all HCRs, although they make up 31–36% of the fields' authors. Women's greatest representation is in the economic, social, and health sciences, where they constitute 17–21% of all HCRs (Figure 1). Considering their numbers among authors worldwide, women's share of HCRs would need to double in economic, health, and social sciences; triple in agriculture, biology,

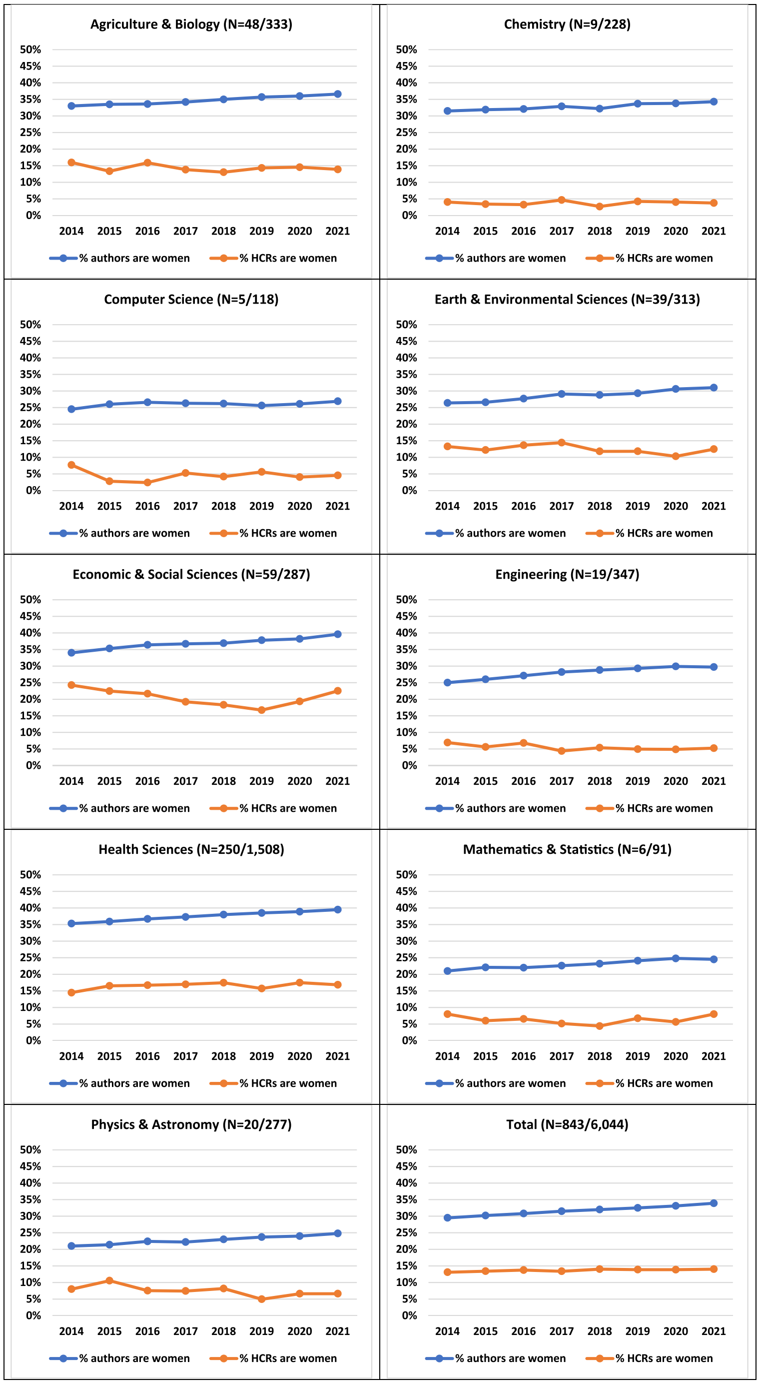

Figure 1. Proportion of female HCRs vs. proportion of female authors, by field. We use the gender distribution of authors as reported by Science-Metrix (2018). Because HCR is annually based on papers published during the previous 11 years, we used the midpoint for each 11-year period as the base for the proportion of female authors. For example, for the 2014 edition of HCR which is based on papers published between 2003 and 2013, we use the proportion of female authors in 2008; for the 2015 HCR edition, which is based on papers published between 2004 and 2014, we use the proportion of female authors in 2009; and so on. The figures in parentheses refer to the average number of HCRs per year from 2014 to 2021 (women/total). In the Total chart, we report the average number of HCRs per year from 2018 to 2021 (and not from 2014 to 2021) because in 2018 Clarivate Analytics added a new subject classification named *Cross-Field*—which includes researchers who did not make it as HCRs in a specific subject category but have multiple highly cited papers in several fields that together qualify them to be classified as HCRs. Without Cross-Field, the average number of HCRs per year during 2014–2021 would have been 447/3,435 in total. The sum of HCRs by field (455/3,502) is greater than the total (i.e., 447/3,435) because of overlap.

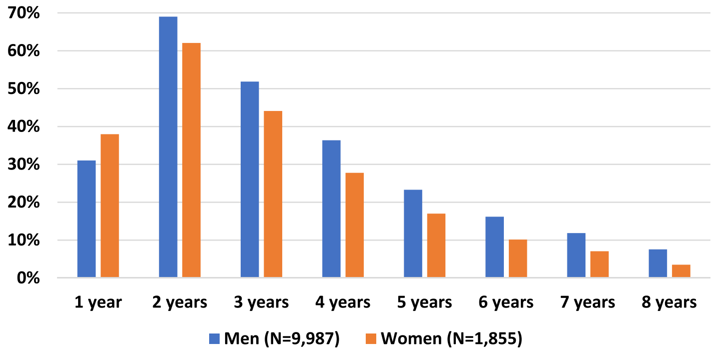

Figure 2. Proportion of researchers maintaining their HCR status by the number of years between 2014 and 2021. An example of how to read this figure: 36% of the male HCRs maintained their HCR status for 4 years compared to 28% among female HCRs.

and earth and environmental sciences; quadruple in mathematics, physics, and astronomy; and increase more than fivefold in chemistry, computer science, and engineering to close the gap with men.

4.3. Gender Gap in HCR Status Retention

Abramo et al. (2017) examined all professors in Italy, identified the top ones based on research productivity, tracked their performance, and concluded that women were less successful than men in maintaining their stardom over time. In this study, we similarly found that 62% of women maintained their HCR status for more than 1 year compared to 69% of men. We also found that the difference in success rate in maintaining HCR status over time increases in favor of men as more elite ranges of performance are considered (e.g., scientists with 3, 4, 5, 6, 7, and 8 years of HCR status). For example, 4% of women maintained their HCR status in all 8 years between 2014 and 2021, compared to 8% among the 9,987 male HCRs (see Figure 2 for more examples). One could attribute these differences to women's shorter career and publication history or because women leak out of STEM fields before progressing further in their careers more than men (Carr et al., 2015; Ceci et al., 2014; Diamond, Thomas et al., 2016; Elsevier, 2017, 2020; Huang et al., 2020; Sheltzer & Smith, 2014). We, however, attribute these differences to three other or additional considerations: The study covers a short period, 2014–2021; the number of female HCRs is far smaller than men to allow accurate gender comparisons here; and a higher proportion of woman than men were more recently classified as HCRs—for example, of all female HCRs, 13% were first classified as HCRs in 2021 compared to 10% among men (Figure 3). These results suggest that it will become more pertinent to accurately assess gender differences in HCR status retention as time passes.

4.4. Gender Gap by Region

North America, Oceania, and Northern, Southern, and Western Europe are home to 1,656 (or 89%) of the world's 1,855 female HCRs. Women's representation among all HCRs in these five regions ranges from 15% to 18%, compared to the world average of 13.7%. Although in Latin America and the Caribbean (where 8% of the world's population resides) women represent over 26% of all HCRs in the region, they account for only 1% or 19 of the world's 1,855 female HCRs. Similarly, in Sub-Saharan Africa (where 15% of the world's population resides), women represent over 19% of all HCRs in the region, but they account for only 0.3% or six of the world's 1,855 female HCRs. Women's gender gap among HCRs is most pronounced in

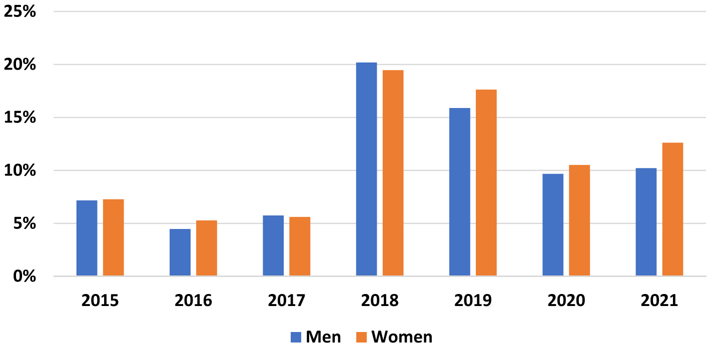

Figure 3. Proportion of HCRs entering the list for the first time by year. The year 2014 is excluded because it marks the beginning of the period covered in the study.

South Asia, East Asia, the Middle East and North Africa, and Eastern Europe, where women's representation among all HCRs in their respective regions ranges from a high 10% to a low 6% (Figure 4). These results corroborate those of Bendels and colleagues (2018), who found that women's representation among the authors of articles in 54 of the highly prestigious Nature journals is highest in Latin America (36%), followed by North America, Oceania, and Europe (30–33%), and a distant last Asia (20%).

4.5. Gender Gap by Country

At the individual country level, we find a wide-ranging or highly disproportionate distribution of women's representation among HCRs, extending from 0% (in 26 countries) to 100% (Figure 5). Of the 50 countries with at least one female HCR, 33 exceed the world average of 13.7% in women's proportion among the total population of HCRs; the number of countries rating above the world average is high largely due to the relatively small number of male and female HCRs in most countries. Indeed, of the 50 countries with female HCR representation, only 16 have more than 1% of the world's share of all HCRs, and only 13 countries have more than 1% of the world's share of female HCRs. Countries with sizeable numbers of HCRs but

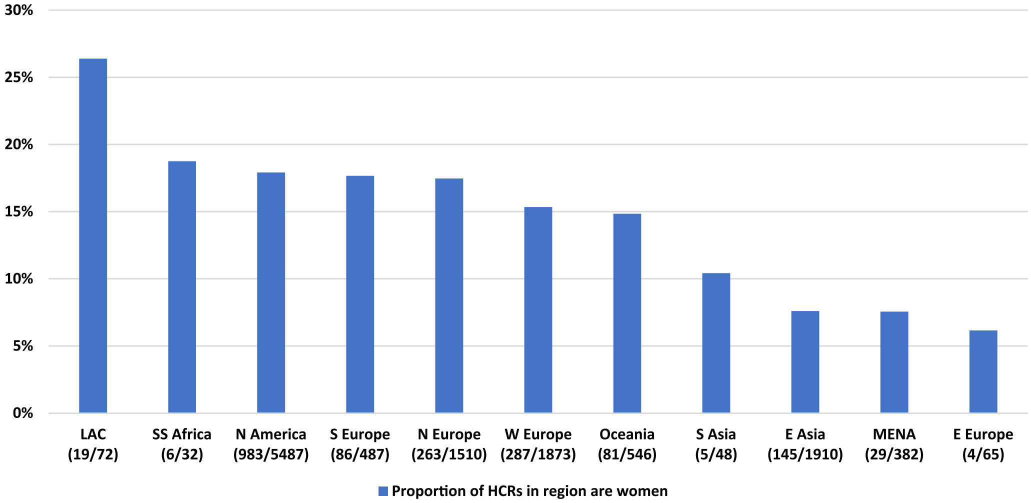

Figure 4. Proportion of female HCRs by geographical region. Figures in parentheses refer to the number of female HCRs in the region over the total number of HCRs in the region. The world average proportion of female HCRs during 2014–2021 is 13.7%. The sum of all regions is higher than the total number of HCRs and higher than 100% due to researchers' mobility between 2014 and 2021.

highly disproportionate representation of women include Taiwan (4/73), South Korea (5/94), and Iran (1/40). Our data revealed several important observations among the 16 countries with over 1% of the world's HCRs (Figure 6):

- The great majority are countries with mature and open scientific systems, strong scientific output, and high support for science and research and development (Nature Index, 2014; Wagner & Jonkers, 2017).

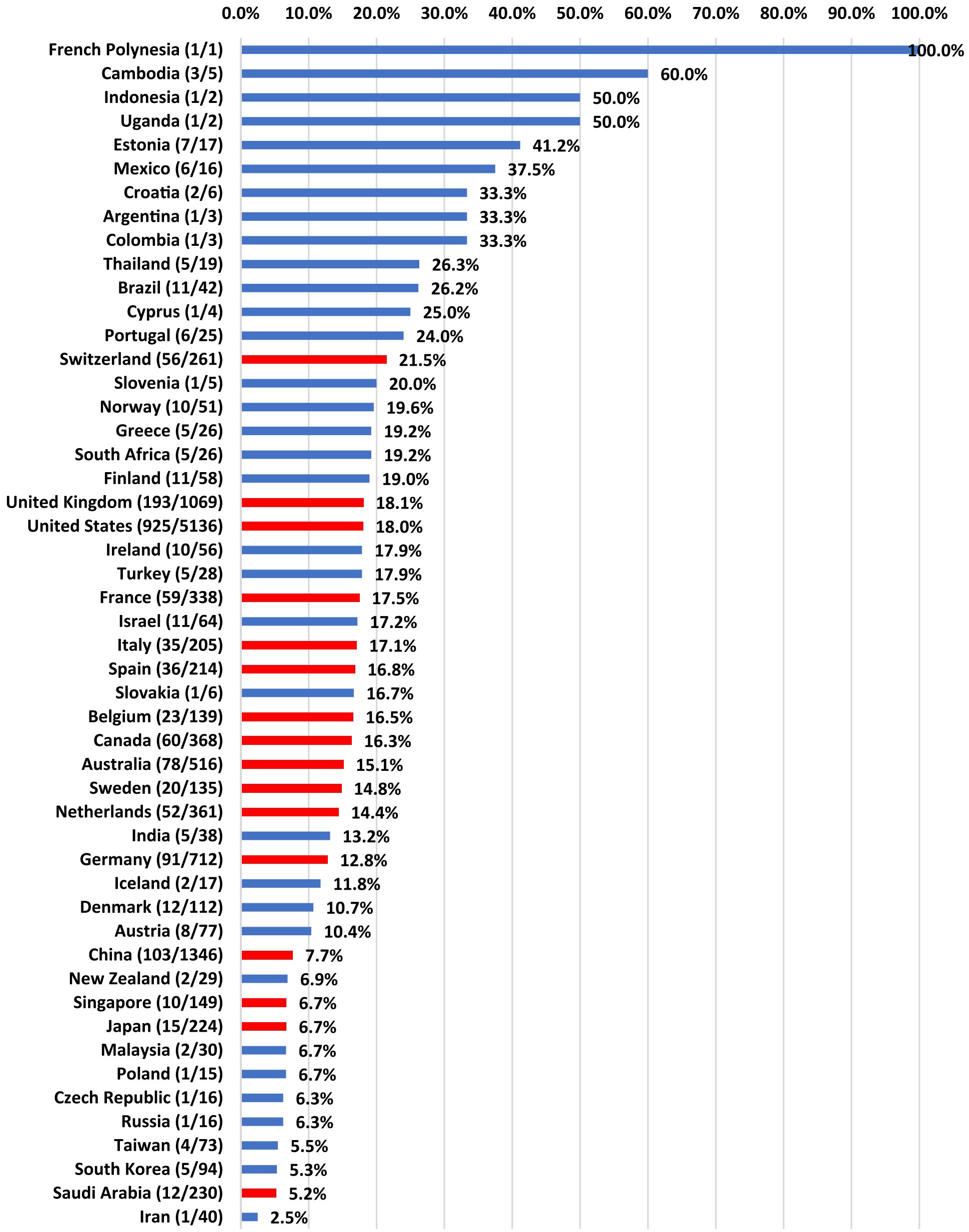

Figure 5. Proportion of female HCRs by country. Figures in parentheses refer to the number of female HCRs in the country over the total number of HCRs in the country. Highlighted in red are countries with more than 1% of the world's share of HCRs.

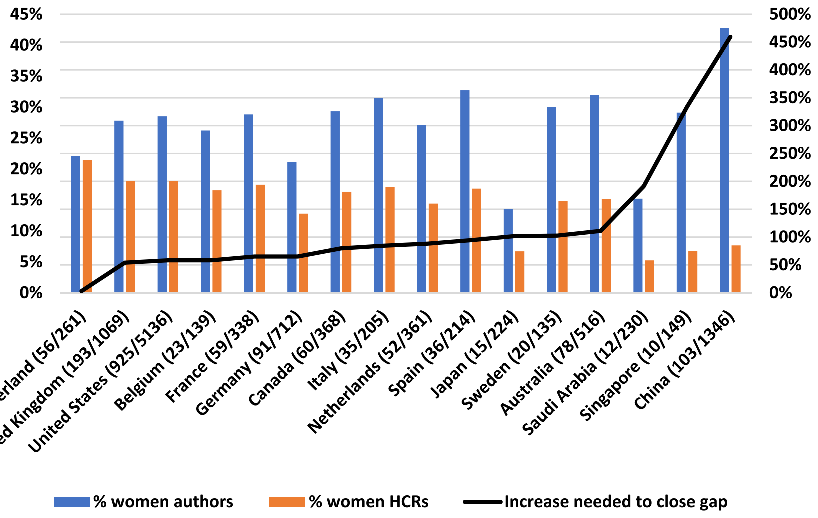

Figure 6. Gender gap among HCRs by country. The chart is limited to the 16 countries with over 1% of the world's share of HCRs. Figures for the proportion of female authors are from Science-Metrix (2018).

- China: Although women make up over 40% of all authors (Science-Metrix, 2018), they lag far behind in representation among HCRs. The situation is so grim that women's share of HCRs needs to increase by 450% to close the gap with men. According to Tang and Horta (2021a, 2021b), despite the legal assurance of gender parity in China and even though women make up more than half of all the country's authors, Chinese female academics still encounter many obstacles in terms of promotion, participation in institutional and research leadership positions, and access to resources; are more likely to be part of networks or collaborative dynamics that are less visible, less impactful, or farther from the centers of authority in the field and institutions; and their imbalanced representation in the higher academic ranks (i.e., full professor), as leaders of departments, faculties, or universities, and in the most research-oriented universities creates many challenges for them.
- Germany: In the past two decades, Germany has introduced several programs to increase women's participation in science, such as the "Women Professorship Programme" and the "Pact for Research and Innovation." Despite the positive impact of these programs (Bührer & Frietsch, 2020), women in Germany still constitute only 21% of the country's authors, one of the lowest proportions in Europe. However, because of this low representation of women among authors, Germany ranks the sixth closest to bridging the gender gap among HCRs compared to the other 15 countries. Women's share of HCRs in Germany would need to increase by 65% to close the gap with men (compared to 142% globally).
- Japan: Although women in Japan account for only 6.7% of all HCRs in the country, the gender gap in HCRs is lower than in most other countries, mainly because Japan has one of the world's lowest proportions of female authors (13.5%). Women's share of HCRs in the country would need to increase by 102% to close the gap with men (compared to 142% globally). Japan's gender gap in science is essentially a result of its patriarchal society (Bendels et al., 2018), stagnation in research productivity, and few opportunities for permanent jobs for early-career scientists (Fuyuno, 2017). In 2020–2021, women's share of HCRs in the country increased by three (or 20%) against a world average of 23%.
- Saudi Arabia: It has not only one of the world's lowest proportions of female authors and female HCRs but also all of its 12 female HCRs are expatriates, and 11 of them are

affiliated with a single institution—King Abdulaziz University, which is historically known for hiring international HCRs with minimal duties on campus (Bhattacharjee, 2011; Biagioli, Kenney et al., 2019; Pachter, 2014). The lack of home-grown female HCRs in Saudi Arabia can largely be attributed to cultural reasons (e.g., patriarchal society) and the fact that the country has one of the world's widest gender gaps in employment (OECD, 2019).

- Singapore: Has been investing heavily in research as an engine for growth (Van Noorden, 2018). Nine of the 10 female HCRs in Singapore are located at the country's second and third most productive research institutions—Nanyang Technological University (5) and the Agency for Science, Technology & Research (4). The gender gap among HCRs in the country remains very high (over 300%), but the fact that 70% of Singapore's HCRs entered the list in 2020 and 2021 (against a world average of 23%) could be a sign that the heavy investment in research has just started to pay off among early-career female researchers in terms of their number and representation among the country's HCRs.
- Switzerland: Is the only country where the proportion of female HCRs is almost the same as that of female authors.

5. DISCUSSION AND CONCLUSION

The proportion of female authors worldwide has improved remarkably, with the great majority of countries currently exceeding 30% (Elsevier, 2017, 2020; Holman et al., 2018; Larivière et al., 2013; Science-Metrix, 2018). The number and proportion of women among senior professors (associate and full professors) have also increased considerably in the past few years; for example, in the United States, from 44,900 (or 28%) in 2010 to 61,700 (or 33%) in 2019 (National Science Foundation, 2022), in Canada from 8,049 (30%) in 2010 to 10,458 (36%) in 2020 (Statistics Canada, 2021), among European Union countries (including the United Kingdom) from 20% in 2010 to 26% in 2018 for full professors and from 36% to 40% for Grade B academic staff (European Commission, Directorate-General for Research and Innovation, 2013, 2021), and in India from 53,591 (28%) in 2010 to 73,016 (34%) in 2019 (AISHE, 2013, 2020). Despite these improvements, this study found a huge gender gap among HCRs. The proportion of female HCRs (i.e., those who train junior scientists or serve as role models) is worryingly low, considering women's numbers and proportions among the general population of authors and senior professors.

The time it would take to close the gender gap among HCRs depends greatly on initiatives taken and reforms made in policies, education, mentoring, funding, and publishing. Periodic and frequent assessments and evaluations of these reforms are also necessary to ensure success. As found in the study by Tang and Horta (2021a) on female academics in China, interest in the gender gap in science is largely triggered by governmental policy considerations and changes. It becomes relatively dormant during periods of lower policy activity.

Another worrying finding is that women have not been able to maintain their HCR status for as long as men. This could be due largely to women's shorter career and publication history and the fact that women leak out of STEM fields before progressing further in their careers more than men (Elsevier, 2020; Huang et al., 2020). Moreover, only 9% of all female HCRs are classified under chemistry, computer science, engineering, mathematics, physics, and astronomy compared to 22% in the case of men. Official reports, such as the one based on the 2018 large-scale global survey of mathematical, natural, and computing scientists (Guillopé & Roy, 2020), show evidence that women and men do not have the same experiences in science, and that women's experiences are less positive than men's regarding sexual harassment, fair and respectful treatment, career progression and discrimination, access to resources,

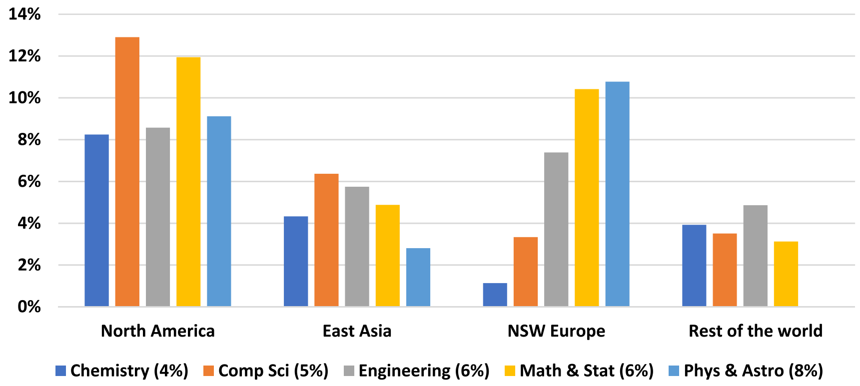

Figure 7. Women's HCR representation in chemistry, computer science, engineering, mathematics & statistics, and physics & astronomy (by geographical region).

and effect of children on the career. Even where women's HCR representation in these fields is relatively good (i.e., in North America and Northern, Southern, and Western Europe (Figure 7)) recent reports published by learned societies in these four regions indicate that the gender gap in science conditions is still very grim. For example, the Royal Society of Chemistry (2018) in the United Kingdom describes a context of funding uncertainty, an inflexible and unsupportive academic culture, and gender-stereotyped family and home care expectations as barriers that limit women's progress in the field. A report by the National Academies of Sciences, Engineering, and Medicine (2018) in the United States and another in Canada (Holroyd-Leduc & Straus, 2018) describe a pervasive, persistent, and damaging culture of harassment that limits the participation and advancement of women in STEM. All these reports recommend more effective policies and initiatives to reduce the gender gap in science.

Coe, Wiley, and Bekker (2019) mention that diversity within the scientific workforce brings unique perspectives, drives creativity and innovation, and provides new contexts for understanding and applying research findings. Leaders and practitioners in STEM continue to be unaware of and poorly educated about the nature, extent, and impact of barriers to the full participation of women in these fields. This lack of awareness and education results in the failure to fully mobilize the human capital of half the global population and limits technological and medical advances. This study shows that high levels of female author representation (such as those in China, South Korea, and Taiwan) are insufficient to diminish the gender gap among HCRs. The chronic lack of recruitment, promotion, and retention of female scientists, stars and otherwise, is due to systemic, structural, organizational, institutional, cultural, and societal barriers to equity, diversity, and inclusion. These barriers must be identified and removed through increased awareness of the challenges combined with evidence-based, data-driven approaches leading to measurable targets and outcomes (Coe, Wiley, & Bekker, 2019; Nielsen, Bloch, & Schiebinger, 2018).

We suggest that efforts to enhance women's representation among HCRs be wide-ranging, realistic, and include, among others:

- Reforms in academic publishing and peer review, and guarantees that women have equal access to professional networks, are afforded equal resources at work, are given better access to parental and personal support, and that the extra demands outside the workplace that traditionally fall on women are taken into account when assessing achievements

(Bates, Gordon et al., 2016; Ceci et al., 2014; Duch et al., 2012; Lerback & Hanson, 2017; Lutter & Schröder, 2020; Shaw & Stanton, 2012; Ward & Wolf-Wendel, 2012).

- Use of quotas or specific targets for the number and proportion of female STEM faculty or academic staff and requiring these methods within organizations and departments (Coe et al., 2019). The impact of such a requirement is best exemplified by the Swiss Institute of Bioinformatics (SIB), which strictly implements the principles of equality, diversity, and inclusion, aiming for gender-balanced representation among their academic and scientific staff. The result of this policy at SIB is a population of staff where nearly half (49%) are women, including software developers, computational biologists, scientists, managers, and data analysts. With 55 HCRs in total, it was not surprising that 24 (or 44%) of SIB's HCRs were women—ranking second in the world in terms of female representation among HCRs, behind the U.S. National Institute on Aging's 46% (or 6 out of 13 HCRs).
- Increase in the number of female role models in the scientific workforce of organizations and academic departments. This is a key factor in reducing the gender gap, as women receive more inspiration and aspiration from outstanding female role models than men (Bell et al., 2019; Botella et al., 2019; Lockwood, 2006). Increasing the pool of women top scholars (as researchers and mentors) within an institution or a country can have a snowball effect, as boasting more female scholars helps in increasing and producing top scholars (Aguinis et al., 2018; Chan & Torgler, 2020).
- Introduction of excellence initiatives to facilitate women's access to resources, networks, and research infrastructure (Hottenrott, Rose, & Lawson, 2021). Universities, for example, may wish to focus on identifying stars based on objective measures and then implement policies that guarantee more significant growth opportunities (e.g., reduced teaching load and greater allocation of research funds (Aguinis et al., 2018)).
- Development of gender-based national, regional, or international rankings or ratings of research institutions (universities and others) assessing the number, proportion, and status of female scientists they have. Such rankings can provide valid and valuable information for determining excellence in achieving gender-balanced representation among academic and scientific staff (see Table 2 as an example). Administrators could rely on these rankings or ratings as indicators of improvement over time, as methods to determine institutional priorities, and as benchmarking tools against peer institutions. Governments and funding agencies would use these rankings or ratings for information about the performance of their higher education institutions or other organizations in which they have invested resources.
- Have national academies, professional associations, and scientific societies use gender-based criteria in decision-making. For example, membership in the Association of American Universities (AAU) is considered one of the most prestigious honors in higher education in the United States. Among the criteria influencing the Association's decision to forward an invitation for membership are the number of HCRs and the number of national academy members an institution has. One could only imagine what aspiring institutions would do if AAU required, as a condition of membership, that institutions must meet certain gender-based thresholds, such as a minimum number and proportion of female scientists, HCRs, and national academy members (with a minimum number of service years at the institution with full-time status).

Efforts to enhance women's representation among HCRs must consider the social, cultural, economic, historical, and political contexts in which researchers conduct scientific research. Each country and institution should carefully study its contexts to facilitate women's success.

Table 2. Gender disparity among HCRs, by institution (top 50 institutions by total number of HCRs)

Institution	Total HCRs	Ranking by total HCRs	Female HCRs	Ranking by female HCRs	% of female HCRs	Ranking by % of female HCRs
Wellcome Sanger Institute, United Kingdom	80	27	22	T8	27.5	1
Mayo Clinic, United States	64	T44	17	T15	26.6	2
Johns Hopkins University, United States	101	12	26	4	25.7	3
National Institutes of Health (NIH), United States	173	5	43	2	24.9	4
King's College London, United Kingdom	61	47	15	T24	24.6	5
Duke University, United States	90	20	21	T10	23.3	6
Washington University in Saint Louis, United States	95	T18	22	T8	23.2	7
Cornell University, United States	98	T14	21	T10	21.4	8
University of Michigan, United States	73	T34	15	T24	20.5	9
Imperial College London, United Kingdom	79	T28	16	T18	20.3	10
Yale University, United States	84	24	17	T15	20.2	11
University of Texas M.D. Anderson Cancer Center, United States	60	T48	12	T37	20.0	12
Brigham & Women's Hospital, United States	76	T31	15	T24	19.7	13
University of North Carolina Chapel Hill, United States	72	T37	14	T31	19.4	14
University of California San Francisco, United States	85	23	16	T18	18.8	T15
University of Queensland, Australia	69	T39	13	T34	18.8	T15
University College London, United Kingdom	87	21	16	T18	18.4	17
Broad Institute, United States	115	10	21	T10	18.3	18
Utrecht University, Netherlands	62	46	11	T43	17.7	19
Harvard University, United States	542	1	95	1	17.5	20
University of Cambridge, United Kingdom	97	16	16	T18	16.5	21
Stanford University, United States	214	4	35	3	16.4	T22
University of Melbourne, Australia	73	T34	12	T37	16.4	T22
University of Washington Seattle, United States	113	11	18	14	15.9	24

Table 2. *(continued)*

Institution	Total HCRs	Ranking by total HCRs	Female HCRs	Ranking by female HCRs	% of female HCRs	Ranking by % of female HCRs
Columbia University, United States	96	17	15	T24	15.6	24
University of Pennsylvania, United States	99	13	15	T24	15.2	T26
University of Toronto, Canada	79	T28	12	T37	15.2	T26
University of California San Diego, United States	95	T18	14	T31	14.7	28
Massachusetts General Hospital, United States	82	T25	12	T37	14.6	29
Centre National de la Recherche Scientifique, France	78	30	11	T43	14.1	30
Max Planck Society, Germany	164	6	23	7	14.0	31
University of California Berkeley, United States	127	8	17	T15	13.4	32
Massachusetts Institute of Technology, United States	158	7	21	T10	13.3	T33
University of Maryland College Park, United States	60	T48	8	T65	13.3	T33
University of Oxford, United Kingdom	122	9	16	T18	13.1	35
Howard Hughes Medical Institute, United States	69	T39	9	T57	13.0	36
Dana-Farber Cancer Institute, United States	65	T42	8	T65	12.3	37
University of Texas at Austin, United States	74	33	9	T57	12.2	38
Memorial Sloan Kettering Cancer Center, United States	76	T31	9	T57	11.8	39
University of California Los Angeles, United States	98	T14	11	T43	11.2	40
Princeton University, United States	72	T37	7	T75	9.7	41
California Institute of Technology, United States	64	T44	6	T85	9.4	42
Chinese Academy of Sciences, China	260	2	24	T5	9.2	43
University of Chicago, United States	66	41	6	T85	9.1	44
Northwestern University, United States	59	50	5	+100	8.5	45
Tsinghua University, China	86	22	6	T85	7.0	46

Table 2. (*continued*)

Institution	Total HCRs	Ranking by total HCRs	Female HCRs	Ranking by female HCRs	% of female HCRs	Ranking by % of female HCRs
King Abdulaziz University, Saudi Arabia	232	3	16	T18	6.9	47
Nanyang Technological University, Singapore	73	T34	5	+100	6.8	48
National University of Singapore, Singapore	65	T42	1	+300	1.5	49
King Saud University, Saudi Arabia	82	T25	1	+300	1.2	50

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COMPETING INTERESTS

The author has no competing interests.

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DATA AVAILABILITY

The data used in this study is available in a repository (Lokman, 2022).

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