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Bibliometrics in glass and other sciences: A Plea for reason

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Abstract

We show a scientometric analysis for glass researchers and compare it with those for researchers in two fashionable research topics, representing the science-push area "graphene" and the market-pull area "lithium ion battery (LIB)". We also present similar statistics for two widely different macro fields, "materials science" (which contains the other three) and "mathematics". While productivity (number of published articles) of a researcher and his/her *H*-index are found to be correlated, these correlations are very different for different research fields, depending on their size, fragmentation, interdisciplinarity, and on the community's publication and citation culture. We also explore the correlation between citation statistics and scientific quality and find it to be elusive. While certain bibliometric indexes indeed indicate how active, prolific, and visible a researcher (or a research group) is, we argue that quality—evaluated by the originality, strength, reproducibility and relevance of the findings of a researcher's publications (as judged by peer review)—is much more important than the number of published articles and citations, and this is where efforts must be concentrated by researchers and evaluating bodies.

KEYWORDS
bibliometrics, citations, glass, *H*-index, quality

1 | INTRODUCTION

In 2005, an intelligent and well-written intellectual exercise entitled "An index to quantify an individual's scientific research output" conceived by the theoretical physicist J. E. Hirsch, was published in the Proceedings of the U.S. National Academy of Sciences.[1] Based on the number H of publications that have been cited at least H times, this *H-index* supposedly constitutes a means of rating a scientist's impact and relevance for the scientific community by a single number. Hirsch suggested that any physicist working for 20 years having achieved an H=20 was doing well. More than 10 years later, it can be argued that no other single publication has had such a profound influence on behavioral patterns of scientists, university administrators, and grant funding agencies. This is corroborated by the number of nearly 3000 citations to this article by December 2016, (which is far more than double of its author's most cited physics contribution on the Spin Hall Effect[2]). This article has irreversibly transformed the world of scientific inquiry, as well as university career advancement and grant funding policies. The worst consequence of this overall scenario has been its effect upon young scientists whose research attitudes are being shaped by excessive pre-occupation with numerical indicators such as *H*-index, citation numbers and journal impact factors.

Despite taking pride, or not, in their own individual citation statistics, most (if not all) leading scientists of any research field will readily admit that the citation numbers are indeed relevant and may be taken as a measure of visibility and popularity, but are certainly not by themselves being indications of intellectual value or scientific quality. To judge the latter, rigorous peer review and in-depth analysis of the scientific content of one's publications by experts in the field is indispensable. Unfortunately, in an imperfect world, such is frequently not possible, and scientific project reviews, grant funding decisions, and University career advancement steps are often based on decisive input from non-experts who can readily use such type of bibliometrics. In the past, such reviewers employed a more robust combination of criteria, such as the number of invited review papers, invited and plenary talks at prestigious congresses, celebrated awards granted, editorships of scientific periodicals, the number and value of research grants, the social or economic impact of the research, etc.,[3] on the basis of which scientific merit and reputation could be estimated. As it takes much more than a few mouse clicks to gather and evaluate such data, unfortunately, these holistic criteria have been forgotten or overridden by citation statistics as the ultimate measure of a researcher's effectiveness, quality, and reputation. In most science areas, the expectation is raised that their reputable scientists should achieve citation records comparable to those of the chemistry, physics, and biomedical sciences communities. We will show below that this is a misguided and unrealistic objective.

In the past 3 years we have been working to establish a world renowned Center for Research, Technology and Education in Vitreous Materials (CeRTEV, www.certev.ufscar.br) with 14 faculty and approximately 60 research students and post-docs. A substantial continuous funding from the São Paulo Research Foundation (FAPESP) for 11(5+6) years[4] backs up this effort. However, during the rigorously conducted written and oral annual review processes, FAPESP′s scientific advisors and funding administrators always bring up those questions about the number of citations and number of articles published by our researchers in high impact journals. In addition, they have been asking the same questions to the other 16 such centers, which focus on other fields.

The objective of this opinion article is to evaluate these scientometric measures for the 100 most prolific researchers of the glass community, and compare them with those of the fashionable "graphene" and "lithium ion battery" (LIB) fields, and also the much larger multidisciplinary "materials science" field, which includes many researchers from chemistry, physics, and medical sciences and contains the other three fields among many others. Finally, we analyse another macro-field, "mathematics", which is known to have a unique publication and citation culture.

2 | METHOD

We used the Scopus database, which indexes more than 22 000 serial scientific titles, to find the most prolific scientists in the specific fields of glass, graphene, and lithium ion battery. We searched Scopus in the subject area of physical sciences for publications from 1815 up to December 31, 2015 using the keywords glass* or glass-ceramic* or vitreous* or non-cryst* in the article title and excluding the keywords metal* or alloy* or steel* or organic or polymer* or macromolecule* or macro-molecule*. This search was repeated for the keyword "graphene" and "lithium ion battery" (LIB) in the article title. In a separate search, the time span was narrowed to 10 years from January 1, 2006 up to December 31, 2015 to "analyse" (in the sense stated above) the younger generation of glass scientists.

Then, we listed the 100 most prolific scientists based on the number of publications related to glass, graphene, and LIB. For each scientist, the total number of publications, *H*-index, total number of citations, as well as the first and last publication year were also extracted. Scientists who stopped publishing 5 years ago were excluded and, finally, the average number of citations per publication (CPP) was calculated for each scientist. Furthermore, in a separate but related analysis of macro-fields, the list of the 100 most-highly cited materials science scholars and mathematicians in 2015 was obtained from Thomson Reuters's newsletter, and then all the above-mentioned bibliometric data were extracted from Scopus for each scholar.[5,6] The selection of the highly cited researchers was taken from Essential Science Indicators (ESI) in the period 2003-2013, which included 128 887 highly cited papers. Each of these papers ranked in the top 1% by total citations according to their ESI field assignment and year of publication. All papers were assigned to one of 22 broad science fields. A ranking of author names in each ESI category by the number of highly cited papers produced in that period determined the identification and selection of the most cited researchers. Please refer to ref.[7] for more information on the methodology used. Finally, the bibliometric data were also determined for the prestigious Abel Prize winners in mathematics. This is unquestionably the most important award for mathematicians.

3 | RESULTS

The *H*-index vs number of publications for the 100 most prolific "glass", "graphene", and "lithium ion battery" researchers, and the most cited "materials" scientists are illustrated in Figure 1A-E. It should be stressed that the number of articles in the *x*-axis refers to the total number of articles published by a given researcher of a given field, which often includes papers on other subjects.

For all these four research communities, one can identify upper (green points) and lower (red points) boundary trend lines. They were all fit to power law equations, shown in the graphs. The power law equations were chosen to ensure that the fits would pass through the origin, as

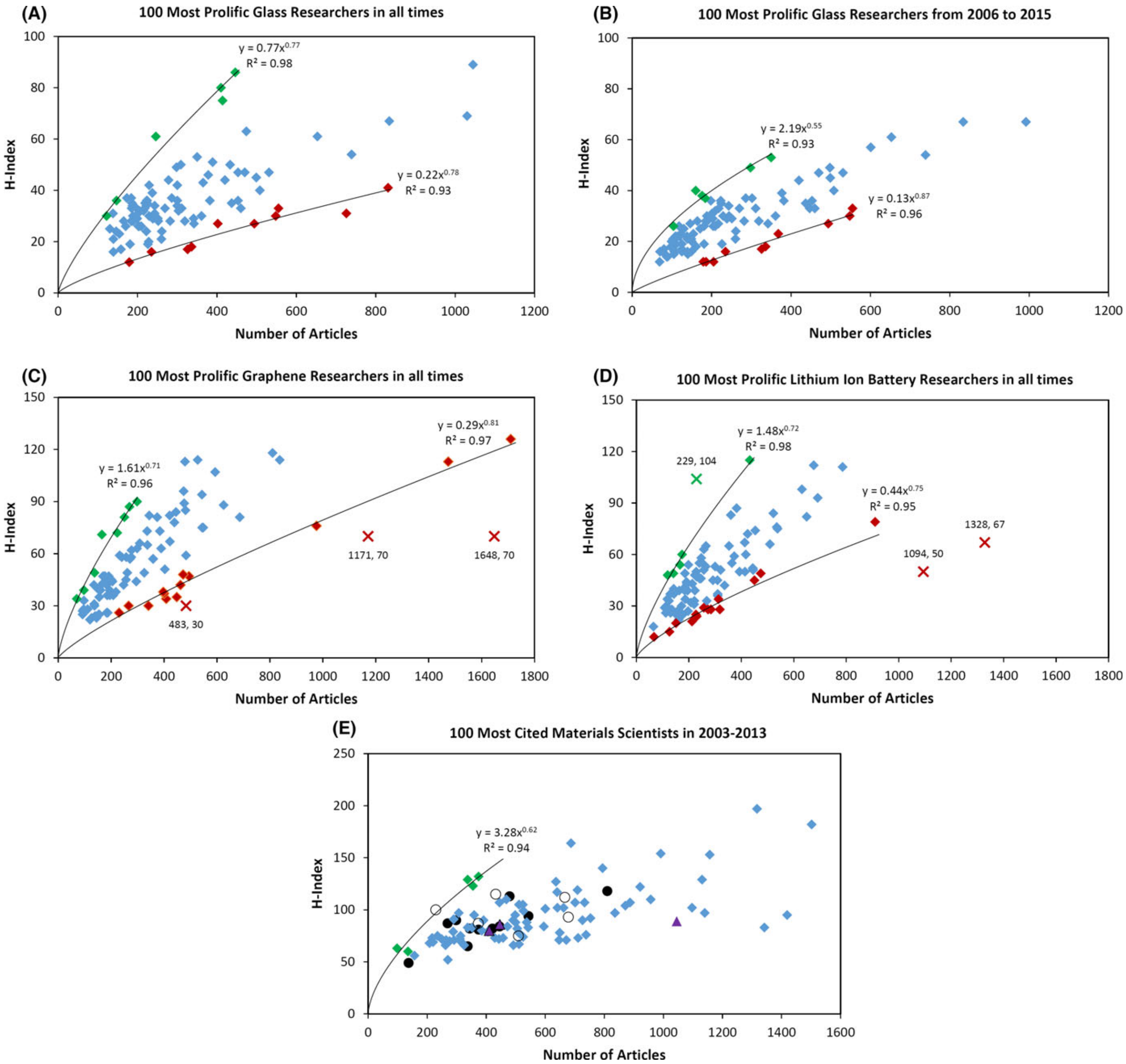

FIGURE 1 *H*-index vs number of publications for the 100 most prolific researchers in the fields of glass, graphene, lithium ion battery; and for the 100 most cited researchers in the macro-field of materials science in 2003-2013 (Sources: Scopus and Thomson Reuters's newsletter 2015). The green and red data points represent researchers who stand in the upper and lower boundaries respectively. (A) 100 most prolific glass researchers in the entire time span, (B) 100 most prolific glass researchers from 2006 to 2015, (C) 100 most prolific graphene researchers in all times, and (D) 100 most prolific lithium ion battery researchers in all times. The crosses, ×, show outliers. (E) 100 most cited materials scientists in 2003-2013. The solid circles, ●, open circles, ○, and purple triangles, ▲ show graphene, LIB, and glass researchers respectively

they should. We also tested linear fits and found that they do not describe well the *H*-index vs # articles. To justify this point, we extrapolated the trend lines showing that the power law fits indeed pass very close to the origin. The researchers standing in the upper boundary tend to publish fewer papers, but attract more citations per paper than the most prolific of all. For example, one LIB researcher in Figure 1D (green cross) has an *H*-index of 104 with "only" 229 articles. On the other hand, the *H*-indexes of the scientists in the lower boundary increase more slowly with the number of articles published, and this group usually has a smaller CPP. Three data points (red crosses) in Figure 1C and two data points in Figure 1D are outliers that fall well below the "smooth" low boundary line. The statistics of the majority of (the 100 most productive) scientists rest between these two limits.

The average, median (middle value), and mode (most frequent value) of *H*-index for the most prolific 100 glass scientists of all times are approximately 36 and 33 and 33 respectively (Figure 1A). For the most prolific glass scientists in the last 10 years (2006-2015), these numbers reach 28, 27, and 16 respectively (Figure 1B). The corresponding values for researchers working on graphene are notably higher: 56, 47, and 47 respectively (Figure 1C), and the records for researchers working on lithium ion batteries are also higher and reach 48, 46, and 28 (Figure 1D). With regard to the much larger area that contains the former three fields, the 100 most cited materials science scholars have much higher records: 92, 87, and 73 respectively (Figure 1E). Eleven, six, and three researchers from the fields of graphene, lithium ion battery, and glass, respectively, are among the most cited materials scientists (Figure 1E).

Figure 2A shows the frequency distribution for *H*-index and average number of citations per publication (CPP) among the 100 most prolific scholars in the glass, graphene, and LIB fields. Figure 2B compares corresponding *H*-index and CPP distributions.

The most frequent *H*-index (Figure 2A) for glass scientists is between 25 and 30. For the graphene and LIB communities we note significantly higher numbers and a tendency toward a bimodal distribution. The most frequent CPP (47%) (Figure 2B) for the most prolific glass scientists is between 10 and 20. The scientists working on graphene and LIB also received most frequently 10-20 citations/article but the distributions include many more scientists with higher numbers.

One concern might be that these distribution curves are not directly comparable because of the different sizes of each community, as obviously the top 100 within an ensemble of 100 000 individuals is a more selective group than the top 100 within an ensemble of 1000 individuals. Thus, ideally one should not compare the top 100 most productive scientists in each field but rather a top percentage (eg top 1% most productive) of each community. Unfortunately, such a normalization is very difficult, as it is hard to estimate the number of researchers in each group, and any alternative measure defining the size of a community (e.g., number of papers published in a certain period, total number of references cited in those papers, or

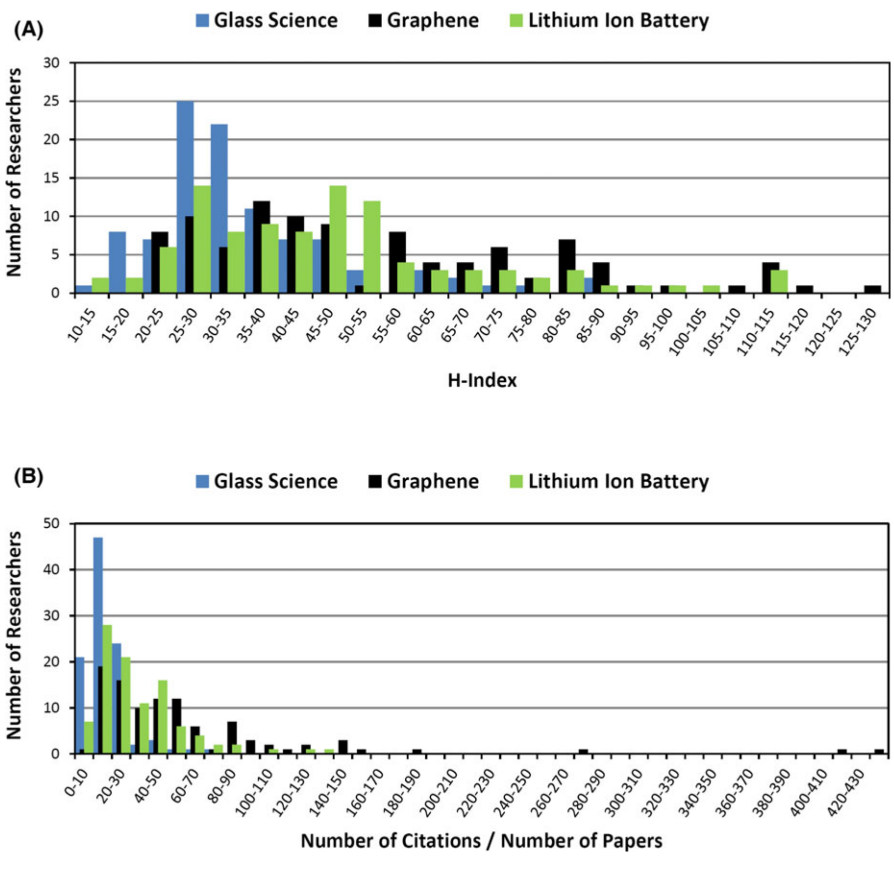

FIGURE 2 Frequency distribution of (A) *H*-index and (B) average number of citations per publication (CPP) among the 100 most prolific scholars in glass, graphene, and LIB. These statistics were taken over the whole time span covered by Scopus, but one should keep in mind that graphene was discovered only 12 y ago, in 2004, and lithium ion battery is also a "hot" new topic

some derived quantity based on a mathematical combination of these or other quantities) are somewhat arbitrary. However, as Figure 1A-D reveals that the 100 most prolific researchers in the glass, graphene, and LIB fields publish comparable numbers of papers, we assume that they represent groups of comparable selectivity within their respective community, even if the total sizes of the communities may vary. A more complicated issue results from the fact that these three (and other) communities are sub-divided into different subfields, across which fewer citations are made than within a given subfield. For instance, the glass community is divided into many distinct subfields (structure, relaxation, crystallization, properties—optical, electrical, mechanical, chemical, thermal, etc.). For such highly fragmented communities, the relevant "community size" should be that of each subfield!

Figure 3 compares the *H* and CPP distributions of the 100 most cited researchers in the two macro-fields materials science and mathematics. While it shows that some of the most cited scientists in each of these groups have achieved an extraordinarily high citation per paper index (CPP>200), the different publication and citation cultures between both macro-fields are clearly evident. The most frequent *H*-indexes differ widely: 70-75 and 20-25 for the materials scientists and the mathematicians, respectively. The research focuses of the top-cited materials scientists are mostly in the "fashionable" fields of graphene (the two scientists with top statistics in this ranking), nano-devices/materials and biomaterials, whereas the most cited mathematicians work on applied mathematics. The average CPP for the only three glass researchers that are among the most cited materials scientists (Figure 1E) is 59, and they work mostly in the multidisciplinary fields of materials chemistry, biomaterials, and semiconducting materials (not on "glass" subjects).

4 | DISCUSSION

Figure 1 reveals very interesting trends; the *H*-index scales with the total number of papers and article proliferation serves to enhance *H*-indexes much more efficiently in the fashionable graphene and lithium ion battery fields than in the glass field. As a result, it is obvious that *H*-indexes cannot be compared between different research fields, even if they are within the same macro-area of materials science. Our data clearly show that fashionable "science push areas" like graphene and "marked-pull" areas like LIB are

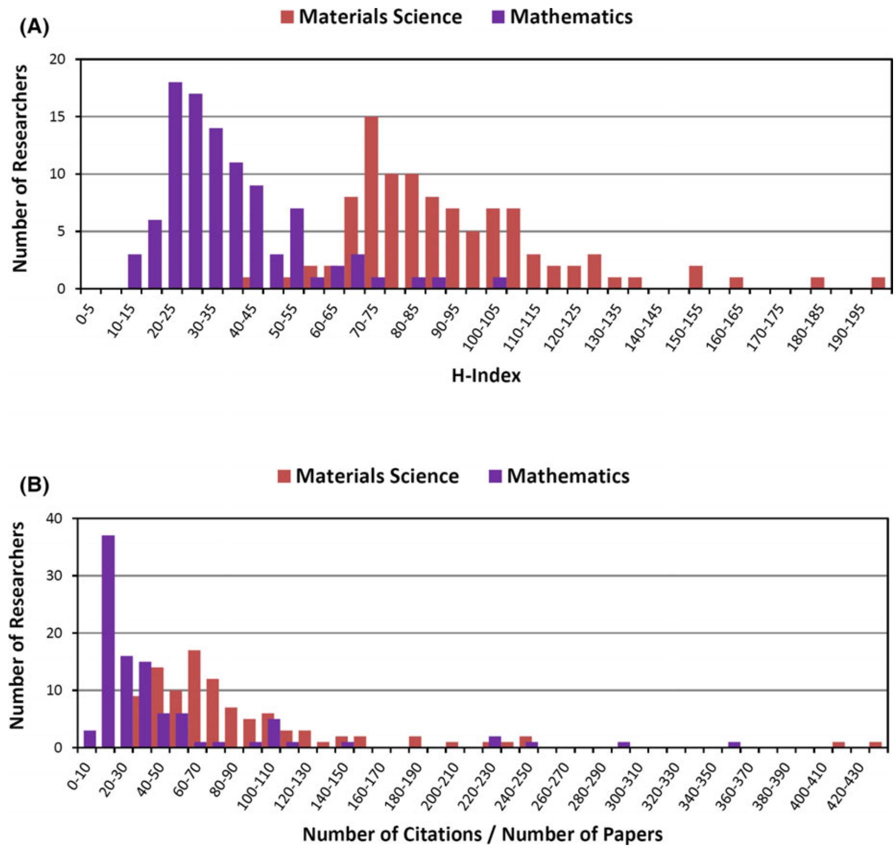

FIGURE 3 Frequency distribution of (A) *H*-index and (B) average number of citations per publication (CPP) for the 100 most cited scientists in two macro-fields in 2003-2013: materials science and mathematics

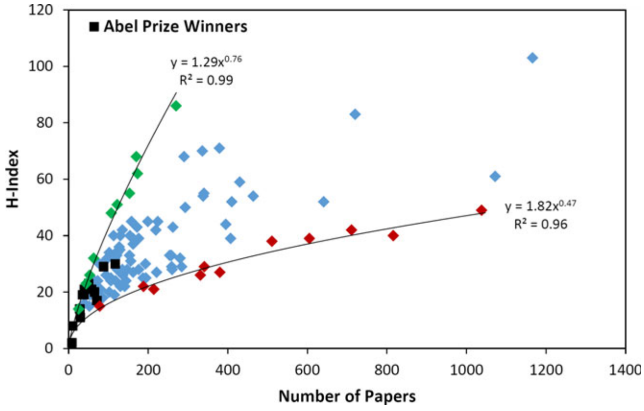

FIGURE 4 *H*-index of the 100 most cited mathematicians in 2003-2013 (Sources: Scopus and Thomson Reuters's newsletter 2015) vs their number of papers. The prestigious Abel Prize winners' data are also included (black squares ■)

intrinsically favored by the *H*-index metric. Aside from differences in the total number of papers published within the entire community, a strong contributing factor for these differences may also be the extent of cohesion or fragmentation of the latter. For instance, the "glass" community, which is the focus of this article, is clearly sub-divided into many small subfields, and these small sub-communities of glass do not frequently cite each other's articles. Therefore, essential factors, which are not taken into account by the *H*-index, are the fragmentation and resulting size of a research community, as well as its publication and citation culture.

An open question of considerable interest is whether citation metrics can be used to discriminate quality from quantity of scientific output. This issue is highly controversial and has been a subject of several publications in recent years, eg.[8-10] These studies have clearly shown that impact metrics are strongly biased by many factors[10-12] and various corrections to moderate biases due to discipline, the number of authors, and academic age have been proposed.[13-16] Here, we try to address this point by illustrating the *H*-indexes of the 100 most cited scientists working in a very different field and publication culture, such as the macro-field of mathematics (Figure 4). Again, we can differentiate between a small group of scientists contributing to the upper-boundary, a small group contributing to the lower-boundary, and the large majority in-between these limits.

The 100 most cited mathematicians received most frequently 10-20 citations/article. They reached an average *H*-index of 36, which (coincidentally) is equal to that of the most prolific glass researchers, but far lower than the average of the most cited materials scientists ($<H>=92$). Despite the fact that the whole mathematics community is likely much larger than the glass community, their average bibliometric indexes coincide, which clearly show the strong dependence of these indexes to the publication and citation culture of each community. Among the most cited mathematicians, most work on applied mathematics and only a few focus on theoretical subjects. And it is relevant to note that none of the prestigious Abel Prize winners, who have undoubtedly done outstanding fundamental discoveries, is included in this list of the 100 most cited mathematicians in 2003-2013. Their numbers of publications are much smaller and so are their *H*-indexes. But these outstanding scientists usually publish (or have published) some very influential ground breaking papers that are not as highly cited as those of the most prolific applied mathematicians because in their community (pure mathematics) the publication culture is very different from that of applied mathematics.

It is known that most scientific papers typically have a finite lifetime: their citation rates peak a few years after publication, and then steadily decline.[17] However, there are some exceptions: papers whose relevance is not being recognized for decades, but then suddenly become highly influential and cited. These papers are called "Sleeping Beauties" in science.[17] The Einstein, Podolsky & Rosen "EPR"-paradox paper is an example.[18] This highly cited paper (6827 citations up to December 2016) was published in 1935 and had received only four citations 35 years later, in 1970, when Einstein had already passed away for 15 years. Clearly the citation history of this paper is vivid evidence for the absence of a correlation between scientific quality and citation frequency.

In another search for this elusive correlation, Kaur et al.[19] introduced a new method to assess the universality of any scholarly impact metric, and applied it to evaluate a number of established metrics. The authors concluded that none of the various corrections suggested to citation statistics is effective against the whole spectrum of potential biases.[19]

Additionally, Wildgaard et al.[20] reviewed 108 bibliometric indicators that could potentially be used to measure the performance of scientists. The authors of this very comprehensive review did not identify a single indicator that captures the overall quality of a researcher. Their categorization illustrated clearly that author-level indicators can only partially identify individual impact (citations), as they indicate impact over time, impact normalized to field, impact of a selected number of publications, or impact normalized to the researchers' age, seniority and productivity. Only when several indicators are used in combination they can give a fair idea of the overall impact of a researcher. The study also concluded that there is no agreement on which combination of indicators best expresses the impact of a researcher's body of work. The clearest message is that using just one indicator is inadequate to gauge a researcher's impact (not to say quality).

Furthermore, Kaur et al.[21] proposed and evaluated a method based on the generation of a statistical baseline specifically tailored for the academic profile of individual researchers and demonstrated the effectiveness of their approach (*Z* factor) in decoupling the roles of quantity and quality (once more associated with the number of citations) of publications to explain how a certain level of impact is achieved. As an illustration, they used their model to capture the high quality work of Nobel laureates in physics, chemistry, medicine, and economics irrespective of the number of publications, academic age, and discipline, even when the standard metrics suggested low impact in absolute terms, as did our Figure 4 for the Abel Prize winners. But in the end, Kaur′s model extends a similar technique that has been previously applied to the ranking of research units and countries in specific disciplines.[22] In our opinion, their approach is indeed capable of an improved evaluation of a scientist's visibility compared to his peers than simple metrics (such as *H*-index), but as it is still based on citation statistics, it says little about the quality of his/her work.

Most recently, a study by Sinatra et al.[23] assigns a unique individual parameter to each scientist, which is stable during a whole career, and predicts the evolution of his/her individual "impact". The proposed individual parameter, *Q*-factor, captures the scientist's sustained ability to publish highly cited papers, and is independent of career stage. This is in contrast with the *H*-index, which is cumulative. However, their *Q*-factor has the same flaw as the previous indexes; it also focuses on citation numbers and—at least in its most reductionist application (which unfortunately is the one that is likely going to be the one most widely used)—it does not offer normalization by research field! And, therefore, the ultimate message of this article can be even more dangerous than the idea of the *H*-index: it basically states that if you don't gather enough citations per paper in the first ~20 articles of your career, all hope is lost and you might as well give it up! What will be the consequence? Everybody will want to work on graphene or lithium ion battery, or any other fashionable new topic?

An anonymous reviewer of this article suggested that other negative consequences of assigning a too high importance on the *H*-index include: (i) Driving some scientists, especially the younger, to scientific misconduct. For instance, it is known that some researchers attempt to increase their citation numbers and *H*-index as quickly as possible, by conducting non-relevant self-citations, by writing low quality review articles, and by making deals with colleagues to cite each other. Obviously, in such cases, the *H*-index is a fake one; (ii) suppressing the ultimate motivations of doing research, eg, curiosity, pleasure in discovery, advancement of the frontiers of knowledge, responsibility for a sustainable society, etc.; (iii) creating scientific bubbles by overheating and exaggerating on the so called "hot" topics, eg, graphene, and finally, (iv) encouraging journals to favor "hot" papers that potentially increase their impact factor, but avoid "cold", exotic, but highly original findings, that might prove to be highly relevant many years ahead. We are in complete agreement with these points.

5 | CONCLUSION

The *H*-index creator, J. Hirsch, recently suggested that "... *h*-index can lead to unfair results and should therefore be used with care. We should always bear in mind that an *h*-index in a field or subfield is often not comparable with *h*-indices in other fields or subfields. The *h*-index should never be used as the only factor to evaluate a researcher. There are many "typical" researchers whose *h*-index provides a true picture of their quality and position in their field compared to other researchers, but there are also many "atypical" researchers whose *h*-index can provide a distorted image".[24] These statements are in full agreement with our findings. Still, we must disagree with Hirsch's final message in that same article[24] stating " . . . . .considering the h-index should result in better decisions pertaining to hiring and promotion of scientists, granting of awards, election to membership in honorary societies and allocation of research resources by agencies that have to decide between different competing proposals".

The message we wish to extend to university administrators, funding agency officers, and especially to the younger generation of scientists, is the following: Citation numbers, *H*-index,[1] *Q*-factor,[23] *Z*[21] and other indexes are indeed important measures of how prolific and trendy a scientist is and how successful (s)he is in attracting attention to his/her published work. But they are not a measure of quality. While many of the very prolific individuals are indeed extremely motivated and of exceptionally high level, we must never forget that the goal of research is advancement of knowledge or technology. Equating the latter with high bibliometric scores is a contemporary aberration (some would rather call it a perversion), we currently have to contend with.[25] If—for the time being—it is unavoidable to use such numbers, this must be done very judiciously with appropriate normalization by subfield size and research area, and within the context of a more holistic evaluation approach.

Quality—evaluated by the originality, strength, reproducibility and relevance of the findings of a researcher's publications (as judged by peer review) is much more important than the number of published articles and citations, and this is where researchers and evaluating bodies must focus their efforts. In the glass (and all the other science fields) we must look for real advances in pushing the frontiers of knowledge or technology.[26] The research communities are sufficiently astute to identify such contributions and do not need citation statistics to recognize the young and senior authors who keep publishing first-rate research in their field. New fundamental insights, true innovation, and advanced technology are of the essence, not the numerically specified level of external perception. We pledge for quality, not quantity!

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