

# Normalized results of Latin America's mycological visibility: are they a good proxy of potential impact?

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**Abstract:** In the context of scientific research, a valid sociopolitical argument of evaluation is the impact of studies. Scientists and policy makers tend to differ on their opinion about the role of science to prioritize collective needs, and the social validation of scientific activities has become a leverage tool for both parties. In this context, we wondered whether or not simple online queries could be used as tools to address potential scientific impact, which in the case of fungal research in Latin America, might allow the visualization of patterns that otherwise are obscured by gross scientific productivity.

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In the modern world, we rely on the internet for many tasks. Sometimes it is hard to believe that this human invention has been publicly available for only a few decades. There are entire generations, such as the baby boomers and even the generation x, for which childhood consisted of playing outdoors most of the time. Children in the current century, though, enjoy the benefits of the worldwide web in pretty much the same way as anybody else. Today, our devices, known as “clients”, interact all the time with computers, known as “servers”, and those interactions are modulated by data availability and routing processes.

Science has been heavily impacted by the development of the internet and by the level of interaction and thematic appropriation of human groups worldwide. This impact, however, has not necessarily been positive. As explained by Legg et al. (2021), in recent decades, science has been corrupted by corporate interests ultimately looking for profitability as the only optimized result of the scientific

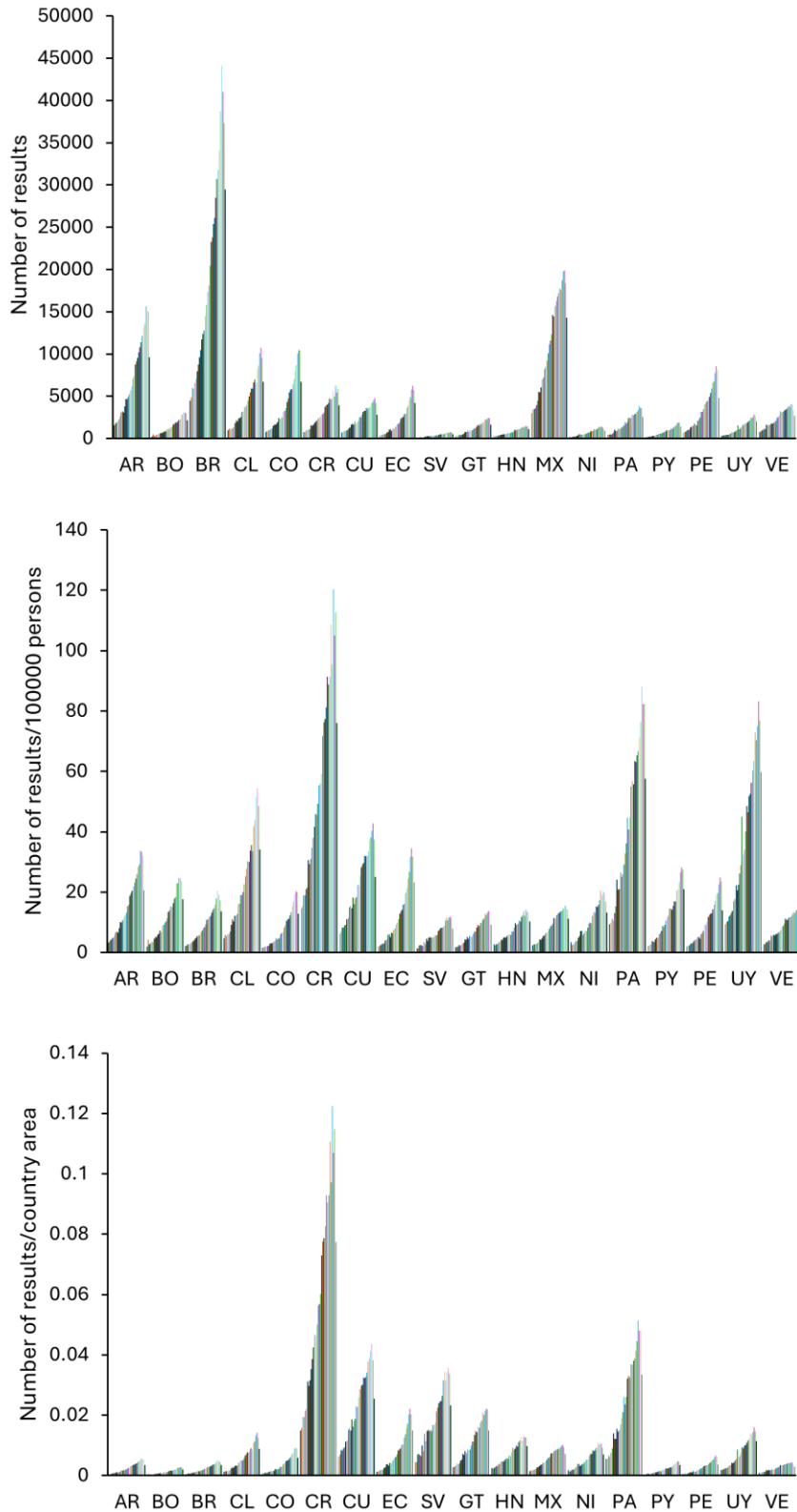
work. The internet has been a huge asset for such tasks as the visibility of scientific research has greatly expanded since the invention of the web. In the scientific world, consequently, the use of the “impact factor”, a popular bibliometric estimator, has become very attractive for evaluating either individual or institutional performance. Its inventor, Eugene Garfield, however, noted early on that “the use of journal impacts in evaluating individuals has its inherent dangers” (Garfield 2006). Even so, many academic institutions and scientists alike customarily build their career reputations on such metrics.

Likewise, the visibility and potential impact of science over the internet has reached human groups that are not part of the scientific world. Social media platforms and media creation techniques have boosted the impact of science on non-scientists (Bik and Goldstein 2013). Over the internet, an influencer could use science to make a point in a narrative, thus expanding scientific knowledge to people that otherwise would not be impacted. Unfortunately, the opposite is also true. Such dilemma has generated the request from scientists to moderate social media posts (Morrow et al. 2022) with the idea that such content curation can help contain the potential spread of scientific misinformation over social media platforms.

In that complex ecosystem, a new interactive tool has gained a lot of attention in the last years. Even though generative artificial intelligence, or generative AI, is an academic field that started in the 1950s, it was not until after the last pandemic (2020-2022) that everybody started talking about it. The current algorithms are so good that a user can create an image based on a prompt, obtain an explanation about a phenomenon based on a question or even design technology without much previous training. Some scientists are fearful of fake data creation and potential negative uses, but as Bago and Bonnefon (2024) explained, generative AI can also be used to counterbalance social biases. In the field of science, with a clear accumulation of imbalances produced by both the male/Caucasian-dominated and the for-profit models, generative AI interaction could be an interesting tool for exploration of unbiased patterns.

Within all that context, our objective herein was very simple. We wanted to test the idea of internet visibility as a metric of potential social impact since a large percentage of the world's population look at data online. For that reason, we carried out one simple, non-scientific, non-rigorous exercise that, albeit these two premises, would also be very realistic in terms of the daily interactive experience from any layperson. For that reason, we used the academic platform of a very popular search engine, Google Scholar, and defined a simple query to obtain data.

Based on our experience and feedback from colleagues, we knew that Latin American countries such as Brazil, Mexico and Argentina were the productivity leaders of mycological research in the region. These three countries, along with Colombia, are the most populated regional areas and it would make perfect sense to see their names standing on top of gross scientific productivity. If, for example, there was one regionally recognized mycologist per one million people in Latin America, there would be 617 mycologists in the region, from which the 204 Brazilians would be the most prominent group, and the 127, 48 and 43 professionals from Mexico, Colombia and Argentina, respectively, would follow. In other words, it makes sense that Brazil, Mexico and Argentina are hubs of scientific productivity because they are very populated countries. For this reason, when we looked for the number of results obtained in Google Scholar, as a proxy of scientific productivity, for the query fungi AND “country”, the latter being one of the respective jurisdictions in Latin America during the period 1994-2024 (Fig 1, top), not surprisingly, the countries with the highest number of results were Brazil, Mexico and Argentina, in such order. Interestingly, if gross mycological productivity in Latin America was a function of population, we would see a high correlation between both aspects.



**Figure 1.** Google Scholar results on a simple query about fungi and Latin American countries during the 1994-2024 period. Top: raw data. Medium: data normalized by population (rate by 100000 persons). Bottom: data normalized by country area (in thousands of km<sup>2</sup>).

In our case, the analysis showed exactly this result. We found with a very high coefficient of correlation ( $r=0.97$ ) for the total number of results per country and their population size. In simple words, more people, higher overall values. To create an analogy, if we thought of the gross domestic product (GDP) as something like mycological productivity we would expect a similar distribution pattern, with the most populated countries being the richest overall. However, gross GDP is not as good an estimator to visualize economic wellbeing as GDP per capita, which provides a better idea of the individual and collective impact of economic strength. For this reason, we thought of normalizing the previous results in a similar manner.

When we normalized the results of our mycological query by means of population size, the most outstanding pattern was that three small countries – Costa Rica, Uruguay and Panama – had the highest values. These nations were followed by Chile (Fig 1, medium). Interestingly, these smaller nations, collectively, have less than 2% of the overall population of Latin America. However, when we look at this result from a different perspective, the situation seemed clearer. In our GDP analogy, we were making the case that the normalization of a gross value could be a better indicator for the visualization of collective impact, whether this was economic or scientific. In the context of our results, it was interesting to note that, at the moment (November 2024), the top Latin American nations in GDP per capita were precisely Uruguay, Panama, Chile and Costa Rica, in respective order. This observation pointed out that besides population, economic wellbeing could be directly impacting mycological research in the region. A direct correlation between GDP per capita and mycological productivity did not take us anywhere ( $r=0.15$ ), but when we combined population size and GDP per capita, a multiple regression model yielded a higher correlation value than population size alone ( $r=0.98$ ).

An integrated analysis of these normalized results would imply that population size is a key predictor of mycological productivity in Latin America, and that economic wellbeing plays a secondary role. However, a third aspect, public investment in research and development, very likely has a strong impact on scientific activities as well. On this matter, data from the United Nations Economic Commission for Latin America and the Caribbean (CEPAL in Spanish) shows that Brazil, Chile, Mexico, Costa Rica and Uruguay are among the regional countries with more investment on such aspect. The data also demonstrates that research and development in Latin America is mainly financed by governments, thus making the topic a type of public investment. We did not attempt creating a model based on the three factors discussed herein – population size, economic wellbeing and public investment on research and development – but it cannot be a coincidence that in all the data presented in the current examination, the same countries, whether at the gross productivity or at the per capita level, show up at the top.

When the normalization was carried out at the spatial level, Chile disappeared from the discussion and both Cuba and El Salvador, much smaller nations, were now visible (Fig. 1, bottom). In a very similar way to the previous normalization per population, Costa Rica and Panama displayed high values. This meant that despite normalizing by population or area, the two Central American countries would take the top spots. From the known mycological activity in these areas, we were aware that the last two decades had been very important to boost the field of mycology in local academic institutions and that in the case of Costa Rica, mycological activities were now also taking place outside academic walls. In other words, we knew there had been recent activity in both countries – including hosting the Latin American Mycological Congress in both cases – and the results were not particularly surprising considering that the effect of these activities were very likely magnified much more in smaller nations. In this sense, we think

that the normalization by population could be more meaningful than the normalization by area, especially when the connection with other economic and social factors was clearer.

Overall, it seemed that Google Scholar results were indeed displaying that mycological research in Latin America is affected by intrinsic factors associated with general development. As such, any kind of potential impact at the social level should also reflect all the interactions among such factors. Specialized infrastructure, legislation affecting scientific research and bureaucracy stand among the most important of these relations. However, one key element of these interactions in Latin America should be the level of scientific independence reached by local researchers. In the field of mycology, this aspect has been slowly but steadily growing in smaller countries where fungi were not culturally or historically important before the establishment of the academic field. In fact, if we looked at the surnames associated with mycological research in these countries, every year there are more articles, books and workshops designed, developed and conducted by nationals. This is a pivotal characteristic of scientific development that in the field of mycology has played a significant role in creating a regional voice for smaller nations. In this sense, when we see the normalized results, it makes sense one more time, to see the comparatively high impact of research in smaller countries.

Could we infer similar conclusions from artificial intelligence? In a second exercise we attempted to do so by interacting with Gemini, a fairly new Google chatbot competing with the much more well-known ChatGPT. In this case we asked directly which were the most productive countries in Latin America in terms of mycological research and the results, not surprisingly, were Brazil, Mexico and Argentina. When asked about specific data from these countries, Gemini responded:

“Brazil is the Latin American country that produces the most mycological research. It has a long history of mycological studies, with numerous research institutions and universities dedicated to the field.”

“Mexico is a powerhouse of mycological research in Latin America. Some key factors contributing to Mexico's prominence in mycological research are diverse ecosystems, strong research institutions, an active mycological community and indigenous knowledge.”

“Argentina boasts several renowned mycologists and research institutions actively contributing to the field. Argentinian researchers have made significant contributions to the understanding of fungal diversity, ecology, and their impact on human health and the environment.”

Pretty accurate? Right? Well, what about countries that we knew were at the bottom of the gross productivity chart that we had already created? On these, Gemini said:

“The level of mycological research and expertise in Nicaragua is limited compared to other Latin American nations. Nicaragua has fewer dedicated research institutions and universities focusing on mycology compared to larger countries.”

“Paraguay has a growing interest and contribution to the field of mycology. However, compared to its neighbors, Paraguay has fewer dedicated mycological research institutions and a smaller community of mycologists.”

Again, a quite accurate depiction. Finally, about the nations that were favored by the normalized approach, Gemini responded:

“Costa Rica has made significant strides in the field, particularly in recent decades. It's recognized internationally for its contributions to mycology, especially considering its relatively smaller size and resources compared to larger countries.”

“Panama has a significant presence in mycological research within Latin America. Overall, Panama's mycological research is on the rise and the country has the potential to make substantial contributions at the regional level.”

“Uruguay's mycological research is steadily progressing. The country has a solid foundation and a growing community of researchers contributing to the field. Uruguay has a group of dedicated mycologists who are actively studying the country's fungal diversity.”

“Chile's mycological research is on the rise. The country's diverse ecosystems, growing interest, and dedicated researchers position it as a promising player in the field of mycology within Latin America.”

At this point, we asked Gemini to help us determine the Latin American countries with the highest mycological research output per capita. This is exactly the exercise that we had already carried out, step by step, at an earlier moment. This time, the chatbot replied:

“To determine this, we would need to consider several factors including total research output, population size, research infrastructure and international collaboration. Unfortunately, a precise quantitative analysis of mycological research output per capita for all Latin American countries is not readily available. However, based on the available information and general trends, countries like Argentina, Chile, and Costa Rica are likely to have a relatively high mycological research output per capita.”

Of course, as we know, generative AI is based on data available on the internet and being Gemini Google's current chatbot, it makes sense that both the results from a manual analysis and those from simple questions in the AI environment were very similar. However, we were impressed with the level of accuracy and complexity of the answers. It would have been hard to infer some of the specific patterns observed in the manual analysis only using AI-based information, but the general trends were certainly very similar in both exercises.

Going back to the development of the internet and its deep impact on modern science, it seems clear that any information that is currently not present in digital form is relegated to invisibility. In the field of Latin American mycology, researchers, institutions and countries must make an effort to digitize information, whether this means raw data, obscure reports or mycological collections. What needs to be considered is the curation of the data, just like in the case of social media. At that level, the presence of a critical mass of highly trained researchers can make a difference. The last two authors of this note, for instance, are working on the creation of an online portal containing information for all the fungi and slime molds deposited at the Luis Fournier Origgi herbarium of the University of Costa Rica.

When it comes to research and development, the gap between rich countries and the Latin American region is very visible. For instance, Brazil, Argentina and Chile, the regional countries with the highest investment, allocate less than 10% of the levels observed in rich nations. This pattern has a clear impact on scientific visibility, but it should not be an obstacle for our region to show up more conspicuously in the map of mycological research worldwide. The recent history of mycological activity in the smaller regional nations demonstrates that visibility is possible when the potentiality of scientific impact drives the effort.

In many ways, Gemini could have the answers. Brazil, Mexico and Argentina are regional mycological powerhouses. Research in Uruguay, Chile, Costa Rica and Panama is on the rise. Paraguay and other nations have a growing interest in the field of mycology.

Latin America seems to be a region with a lot to say when it comes to fungi. We just have to put it online in this moment in history for the data to be located.

Now, let's take some time to analyze the situation of one large country that did not show up, as expected, in the analysis carried out herein. Colombia is a nation with 48 million people and ranks third, regionally, in population size. In Fig 1 (top), the expected value of gross mycological productivity for the 1994-2004 period should have been about 10% higher and the normalized results by population were expected to be 50% higher, based on countries with similar populations.

We think that these results are the partial effect of armed conflicts, political crises and drug trafficking impacts on the overall performance of Colombia during the period of study. For context, Colombia's GDP per capita is currently between 30-40% that of the top four Latin American countries and its research and development investment oscillates between only a quarter and half of what other regional countries allocate. However, even with this panorama, Colombia is on the rise, and mycological activity is growing fast, just like many other socioeconomic indicators are in this nation.

### **The Antioquia case**

From outside Colombia, during the last few decades, the loudest voices on mycological research came from the region of Antioquia. Perhaps even today, mycological research in Colombia has a core of action centered in this region. However, as briefly explained, a number of sociopolitical issues during the 1990s and the first two decades of the current century have slowed down the scientific activity of this nation, and along with that, the productivity of mycological research.

In structural terms, Fernandez (2011) stated that the greatest impediments to carry out biological work in Colombia were the high load of paperwork and general bureaucracy. Based on our own experience, this is likely to be the case. The result of such obstacles is the comparative lag with other nations. For instance, in 2018, a general regional assessment estimated that the genomic diversity associated with life forms in Colombia was more incomplete than comparable data from other Latin America countries, placing the former in an unfavorable position. We are aware of the great efforts made by local mycologists to project the mycological research of this country during the last decades, but the structural limitations still in place represent constraints to collaborative work, a great catalyst of research activity.

When asked about the strengths of Colombian mycology, Gemini responded:

“Some key points about Colombia's mycological research are the increasing research output and its focus on applied mycology. Research in Colombia focuses on applied aspects of mycology, such as the use of fungi in bioremediation, agriculture, and medicine.”

From our own experience, it is a fact that Colombian researchers started to look at fungi from an applied point of view. This activity, though, is much more a result of an increasing multidisciplinary approach favored by both the agendas of the public and private sector, rather than an increment in the productivity of pure mycological research. The latter is still carried out by an increasing group of individuals with primary training on fungal taxonomy and phylogeny, and with a strong link to Antioquia.

Our data, this time obtained from a query on “fungi and Antioquia” for the 1994-2024 period, showed that the relationship between these results and those obtained for Colombia, an approximation to the relative frequency of results coming from this area, has grown up over time. During the first decade, the average percentage of results from Antioquia relative to those from Colombia was 5.94%. This value increased to 8.99% for the second decade and to 10.18% for the 2015-2024 period. These numbers represent an increment of 51% between the first two decades, 13% between the last two, and 75% overall during the entire period of study. In simple words, the visibility of mycological research from Antioquia has increased at a great rate during the last three decades. We believe that these data very likely reflect the real pattern of mycological activity in Antioquia relative to the rest of the country.

The rate of results per 100000 people for Antioquia resulted in a current value of about 14.5. This is very comparable to the observed values for Brazil and Mexico since 2010, calculated as 13.9 and 12.8, respectively. The impact of mycological research from Antioquia is therefore far from being negligible and its visibility over the internet is good and still increasing.

In this case, Gemini was also able to provide details associated with this impact. When asked about the contribution of Antioquian mycology to the visibility of Colombian mycological research, the chatbot responded:

“Antioquia has a dedicated research group and numerous publications in the field. Antioquian researchers have played a pivotal role in elevating the visibility of Colombian mycological research on the global stage.”

We know, of course, that the contribution of many researchers to the development of mycology in Antioquia is substantial. Any Latin American mycologist would know that. As such, this response from an AI-based service works as evidence of the point that we are trying to make herein. Data must be online to be retrieved.

### **Social impact based on online visibility**

It is believed that about 67% of the world population currently have access to the internet. This value represents a 26% increase in just eight years from the 53% calculated during 2018. The current internet coverage will likely continue increasing. As part of this trend, the AI industry is expected to increase at an annual rate of 36% between 2024 and 2030, and AI-based devices seem to have come to



stay. Currently, about 97% of mobile devices use AI-powered tools and it is calculated that 40% of people worldwide use them every day.

In simple terms, if the scientific trend of visibility on the internet continues to take place – as it has been favored by academic institutions and researchers during the last few decades – the real social impact of scientific research will rely more and more on whatever data are available online. From the moment when scientific publishers started posting papers online, the lifetime of an article –the number of years that a scientific article is considered valuable by the scientific community – has decreased from the values observed in the previous century. In 2023, this lifetime, for life sciences, oscillated between 36 and 48 months only, meaning that a mycological paper published in a well-known journal has a very short temporal window to impact the scientific community and the general population.

Most of the algorithms used by search engines and AI services would likely perform a similar pattern and ponderate in different manners data obtained at different times or scientific articles published at different moments. The result of this process is that newer information is likely to show up more obviously on searches of any kind. As such, the task of establishing a voice on the internet by means of posting curated mycological data should be a priority in Latin American countries. The tasks of modern researchers also include these activities, unlike those that the previous generation of mycologists had to do to increase the impact of their research. The case of smaller countries in Latin America and the region of Antioquia in Colombia serve as evidence, perhaps not scientifically rigorous but very realistic, to observe the visibility of mycological activities on the internet, and perhaps, they really represent a measure of social impact.

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