

## From academic curiosity to industrial reality: A detailed bibliometric analysis of the growth in research on 4D Food Printing

José A Téllez-Morales

División de Ciencias de la Salud, Biológicas y Ambientales, Universidad Abierta y a Distancia de México (UnADM), Mexico City, Mexico

### Abstract

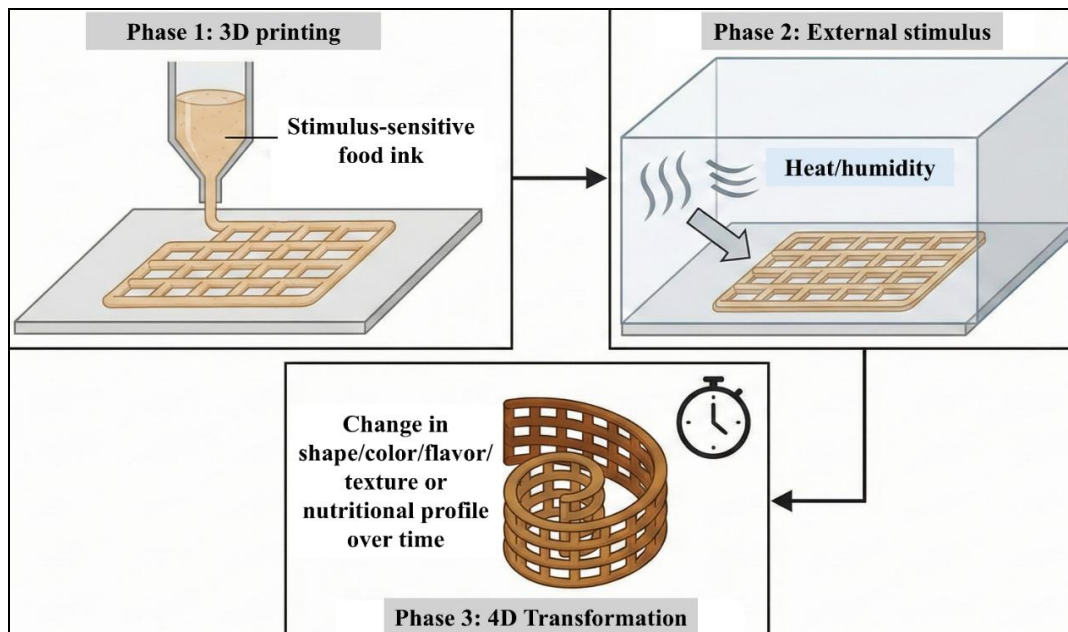
4D food printing represents an evolution in additive manufacturing that integrates the temporal dimension, allowing products to change shape, color, or flavor in response to predetermined external stimuli. A detailed bibliometric analysis was conducted on the growth of research in this field. The results reveal an exponential increase in scientific output since 2020, led overwhelmingly by China, Jiangnan University, and researcher Zhang, M. However, the predominance of review articles (50.9%) suggests that the field is still in an early stage of theoretical definition and technological exploration. Keyword analysis identifies thematic clusters focused on smart materials (hydrogels), stimulation methods (microwave/pH), and industrial applications. Despite progress, critical challenges to real-world adoption remain, including nutrient stability after printing, rheological limitations of edible inks, and food safety. In conclusion, 4D printing is rapidly transitioning from an academic curiosity to a potential industrial reality through interdisciplinary approaches.

**Keywords:** Process, 4D Food Printing, Stimulus-responsive

### Introduction

4D food printing (Fig 1) is an evolution of additive manufacturing that integrates the dimension of time into conventional 3D printing. While 3D printing creates static

objects, 4D printing uses smart or "stimulus-responsive" materials that allow the final product to change its shape, color, flavor, texture, or nutritional profile in a predetermined manner after the printing process [1-4].



**Fig 1:** Schematic representation of the 4D food printing process, where a 3D-printed structure changes shape and/or property under external stimulation over time.

4D food printing presents significant challenges in the nutritional field, with four important points highlighted below.

### Stability and degradation of nutrients

One of the biggest obstacles is maintaining the integrity of nutrients during and after the printing process. This often involves high temperatures or exposure to light, which can degrade heat-sensitive

vitamins and other bioactive compounds [5]. Unlike static 3D printing, 4D products are designed to change over time. However, nutritional and sensory properties may deteriorate during storage. For example, in space contexts, microgravity and radiation accelerate the degradation of vitamins and proteins [6]. Methods such as drying, baking, or frying, sometimes necessary to activate the change in form or cook the food, can reduce moisture content and alter nutritional density.

### Limitations on materials and ingredients

The formulation of edible inks that are both printable and nutritionally complete is complex, as there is a limited range of materials that meet printing requirements (rheology/viscosity) and are also nutritious. Often, inks based solely on vegetable proteins lack the necessary functional characteristics, requiring additives that could dilute the nutritional value [7,8]. It is difficult to create printed materials that mimic the complex nutritional properties and structure of real foods, such as meat, which is a barrier to their adoption as a complete dietary substitute [9,10]. There is a tension between the need for low viscosity for extrusion and high structural stability to maintain shape. Achieving this without compromising nutrient loading is a technical challenge [11].

### Accuracy in personalized nutrition

Although personalization is a key promise, achieving it with precision presents difficulties. This is because meeting personalized metabolic needs (e.g., for astronauts or patients with dysphagia) requires extreme precision in nutrient deposition that current technology still struggles to standardize [6,12]. It is not enough to simply print the nutrient; the 4D design must ensure that bioactive compounds (such as vitamins or probiotics) are released and absorbed correctly in the body (bioavailability) after consumption [13].

### Food safety and acceptance

Safety and consumer perception directly affect nutritional intake. Closed or long-term environments are prone to microbial contamination, compromising food safety and nutritional quality [13]. In isolation scenarios, dietary monotony and loss of sensory appeal (texture, taste) can lead to reduced food intake and, consequently, malnutrition [6]. 4D printing seeks to combat this by enhancing the sensory experience, but if the texture is unfamiliar or unpleasant, the nutritional benefit is lost if the user does not eat the product.

### Methods

In the Scopus database, the following Boolean operator and wildcard were used to search for and identify articles, yielding 167 documents: TITLE-ABS-KEY (("4D food printing") OR ("4D printing" OR "four-dimensional

printing") AND "food"). The data were exported in RIS format for further analysis in VOSviewer.

### Results and Discussion

Fig 2 shows significant and rapid growth in research on 4D food printing, especially since 2020. Research in this field was very nascent or almost nonexistent. In 2018, there was only one paper. Interest grew very slowly, reaching about two papers in 2019 and six in 2020. Growth continued at a very rapid pace until 2022, reaching 30 papers. In 2024, it reached the highest point in the series with 40 papers. Given that we are now in 2025, this indicates that the data for 2025 is partial or not yet complete. It is very common for databases to take time to index all publications for the current year.

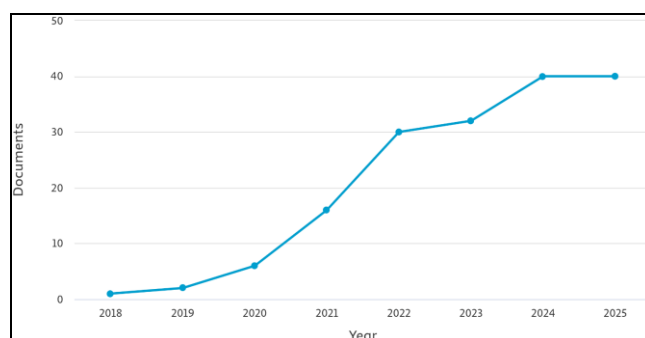


Fig 2: Evolution of the number of scientific publications on the topic of 4D food printing over time.

Fig 3 breaks down the information in Fig 2, showing which scientific journals are publishing articles on 4D food printing. This is a highly specialized topic, which means that no journal publishes extensively on the subject. The most any journal published in a single year was five articles (International Journal of Biological Macromolecules in 2024). This is typical of a very new and specific field of research. No single journal "dominates" this topic; leadership changes every year, and the types of journals on the list suggest that the topic is being approached from multiple angles. In 2025, there is a sharp decline in most journals, but Trends in Food Science and Technology (blue) and Food Research International (orange) seem to be off to a good start for the year.

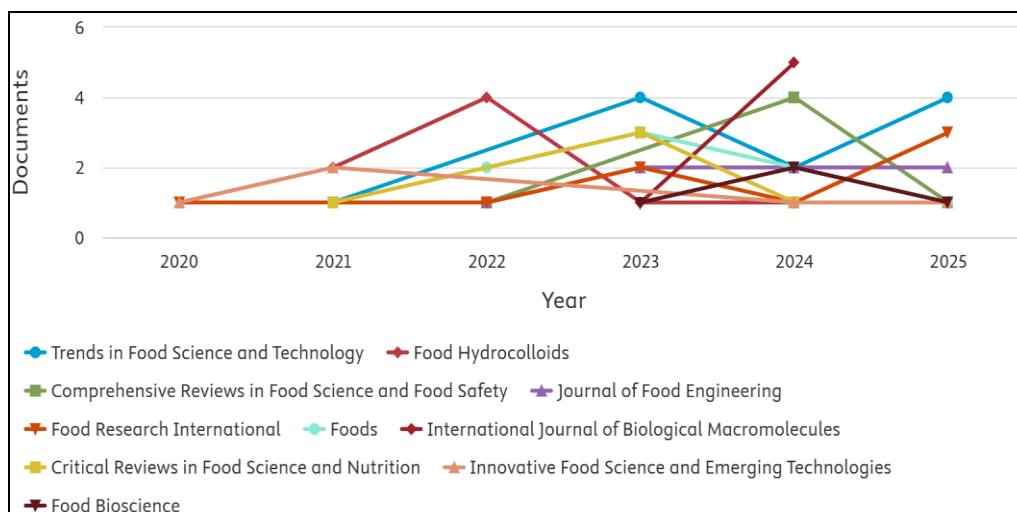
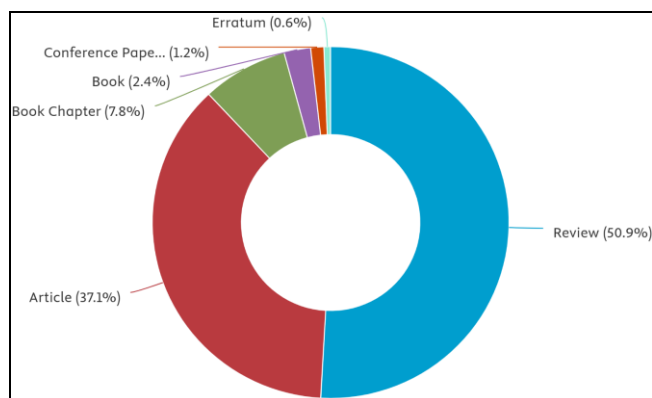


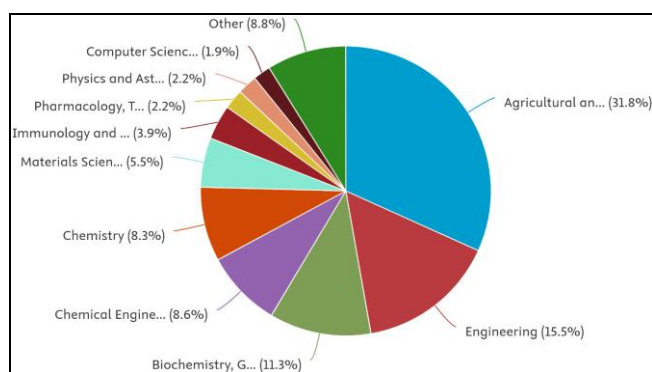
Fig 3: Scientific journals publishing articles on 4D food printing.

Fig 4 shows the distribution of the types of documents published on the topic of 4D food printing. Instead of showing how many articles there are (as in Fig 2) or where they are published (as in Fig 3), this Fig shows what type of publications they are. The most important and revealing piece of information in this Fig is that more than half of all publications are "Review" articles. This is very significant and reinforces what we saw in the previous graphs. When a field of research is very new (such as 4D food printing), it is common to see a high percentage of review articles. Researchers publish reviews to define the new field, summarize existing technologies (such as 3D printing and smart materials), and propose future challenges and opportunities. The fact that there are more reviews (50.9%) than original research articles (37.1%) suggests that the amount of specific experimental work on 4D food printing is still taking off.



**Fig 4:** Distribution of types of documents published on the topic of 4D food printing.

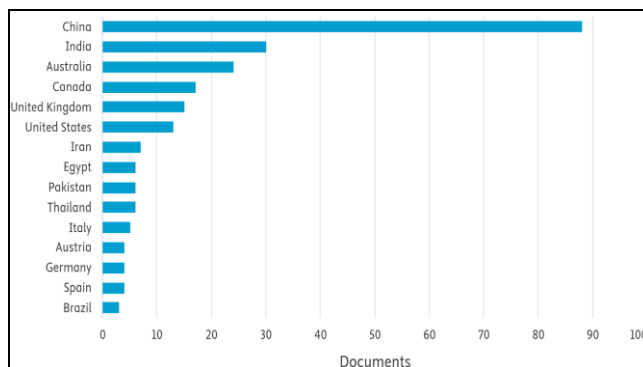
Fig 5 shows the areas of science in which articles on 4D food printing are classified. It tells us which fields of knowledge are contributing most to this new area of research. The Fig shows that the research is highly interdisciplinary, involving many branches of science. However, it is clearly dominated by a few key areas.



**Fig 5:** Areas of science where articles on 4D food printing are classified.

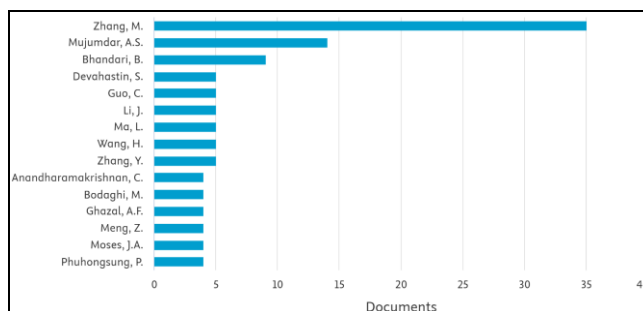
From Fig 6, the most striking observation is China's overwhelming leadership with almost 90 documents. China has published almost three times as many as the second country on the list. Behind China are two countries with notable research activity (India and Australia). A third group of countries, mostly Western, show similar activity to each other, but significantly less than the leaders (Canada, the United Kingdom, and the United States). The rest of the

countries that appear in the graph have more modest contributions, all of them below 10 documents.



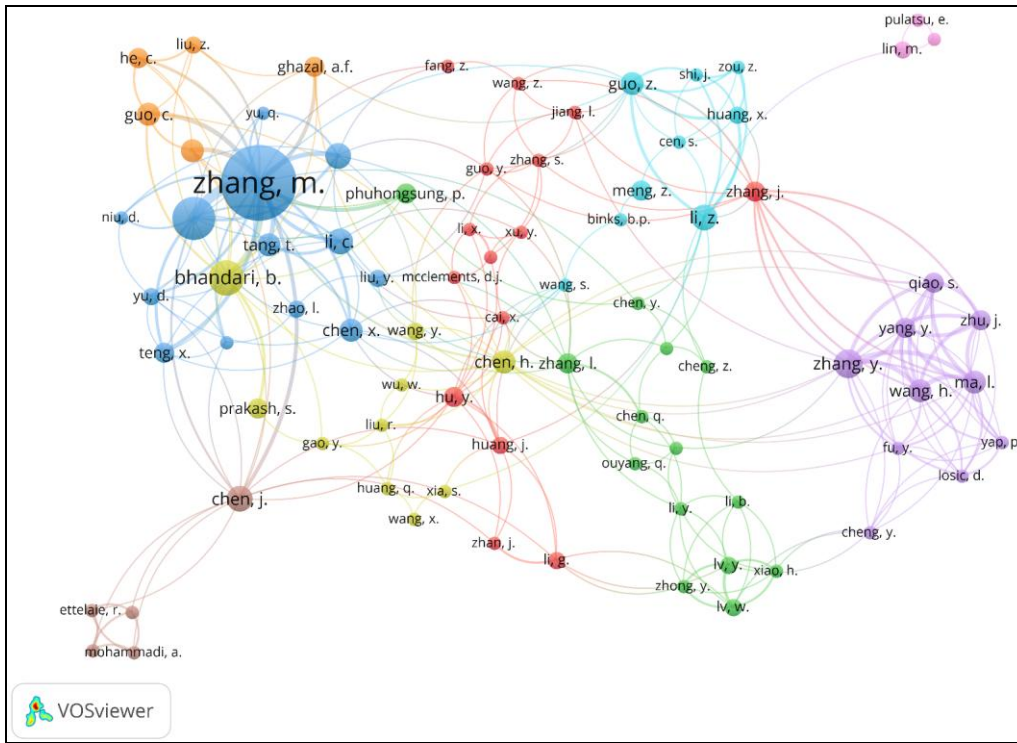
**Fig 6:** Countries according to their scientific productivity in the field of 4D food printing.

Fig 7 shows that the field is led, by a wide margin, by one researcher: Zhang, M. There is a very large gap between first and second place. The second most productive researcher is Mujumdar, A.S. After the top two, there is a third prominent researcher, Bhandari, B. Following the top three, there is a large group of researchers who have a very similar number of publications, all in the range of 4 to 6 papers. We saw in Fig 5 that China is by far the most dominant country in this area of research. In Fig 7, we see that Zhang, M. is the dominant researcher. It is very likely that the researcher "Zhang, M." is one of the main contributors (or the leader of a very productive research group) driving China's leadership in this field.



**Fig 7:** Leading authors or researchers (by name) according to their total number of publications on 4D food printing.

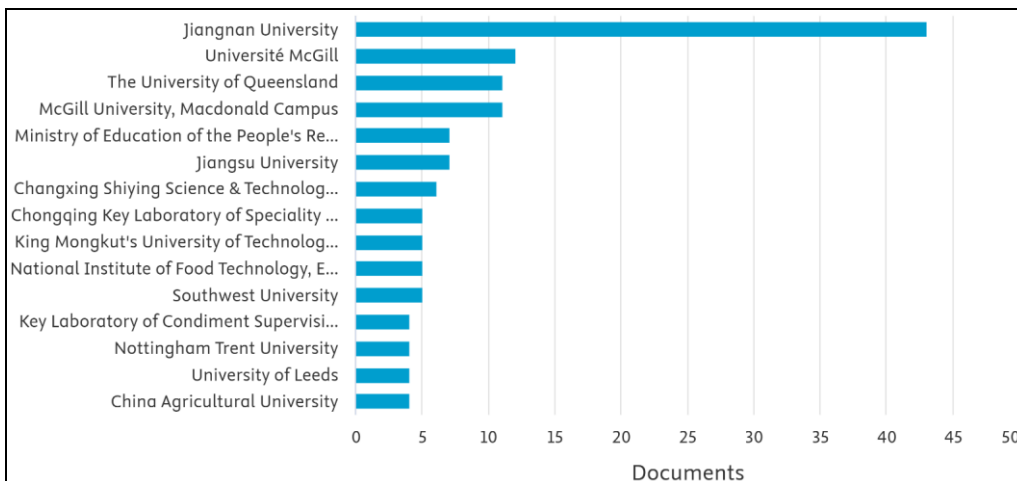
Fig 8 shows the social structure of the field of research into 4D food printing, i.e., who is working with whom. The map is not a single uniform "cloud." It is clearly divided into several colored clusters, indicating that the research is being carried out by different research groups which, although working on the same topic, do not always collaborate with each other. The largest and most influential group is the blue cluster, centered on the dominant author, Zhang, M. Close collaborators in this group include 'Guo, C.', 'Li, C.', 'Phuhongsung, P.', and 'Niu, D.'. This is the "heart" of the network. There is a second large and dense group on the right (authors such as Zhang, Y., Wang, H., Ma, L.). This group collaborates extensively internally but has fewer connections to the main cluster of Zhang, M. The group that includes Bhandari, B. (another prolific author in Fig. 7) acts as a "bridge." It is strongly connected to the blue cluster of Zhang, M., but also forms its own group. This Fig tells us that the field of 4D food printing is being driven by several different research teams.



**Fig 8:** Co-authorship (or scientific collaboration) network map.

Jiangnan University (Fig 9) is, by an extraordinary margin, the most dominant institution in this field. There is a huge gap between first and second place. The second most productive institution is McGill University (less than a third of Jiangnan's output). After Jiangnan, there is a group of institutions that lead the rest of the world, but they are far behind the top spot. It is interesting to note the presence of

the Ministry of Education of the People's Republic of China, which suggests strong government support and funding in this area. China's global leadership in 4D food printing is largely driven by an extremely productive research group at Jiangnan University, most likely led by researcher Zhang, M.



**Fig 9:** Most productive institutions (universities, laboratories, and ministries) in research on 4D food printing, according to their number of publications.

Instead of showing who works with whom (as in Fig 8), this map (Fig 10) shows which concepts are researched together. It is a map of the "ideas" or "themes" that make up research on 4D food printing. We can see four main clusters that define the field of research. The yellow cluster (center-left) is the central cluster, with the largest words being "4D printing" and "3D printing" (appearing several times). This is logical, since 4D printing is a direct evolution of 3D printing. It is connected to keywords such as "rheological property" and "textures," indicating that the challenge is how the inks flow and what texture they have. The red

cluster (left) is closely connected to the yellow cluster and represents the "4D" aspect, change. It focuses on how food changes: "color changes," "microwave heating," and "colorimetry." It also shows the ingredients used to achieve this: "anthocyanins," "curcumin," "starch," and "gels." The green cluster (bottom right) focuses on advanced materials and techniques. The central words are "three-dimensional printing" (another variant of 3D) and "hydrogel." It is related to high-tech concepts such as "smart material," "bioprinting," "drug delivery system," and "pharmaceutics". This suggests that many 4D food printing techniques are

borrowed from or inspired by the fields of bioengineering and medicine. The blue cluster (above) represents practical application and industrial context. Keywords include "food industries," "nutrition," "food safety," "additives," and "food products." In summary, research on 4D printing (yellow) is

based on 3D printing (yellow). It seeks to create foods that change their properties (such as color) using stimuli (red). To achieve this, it uses smart techniques and materials (green), with the ultimate goal of creating new food products (blue) for industry.

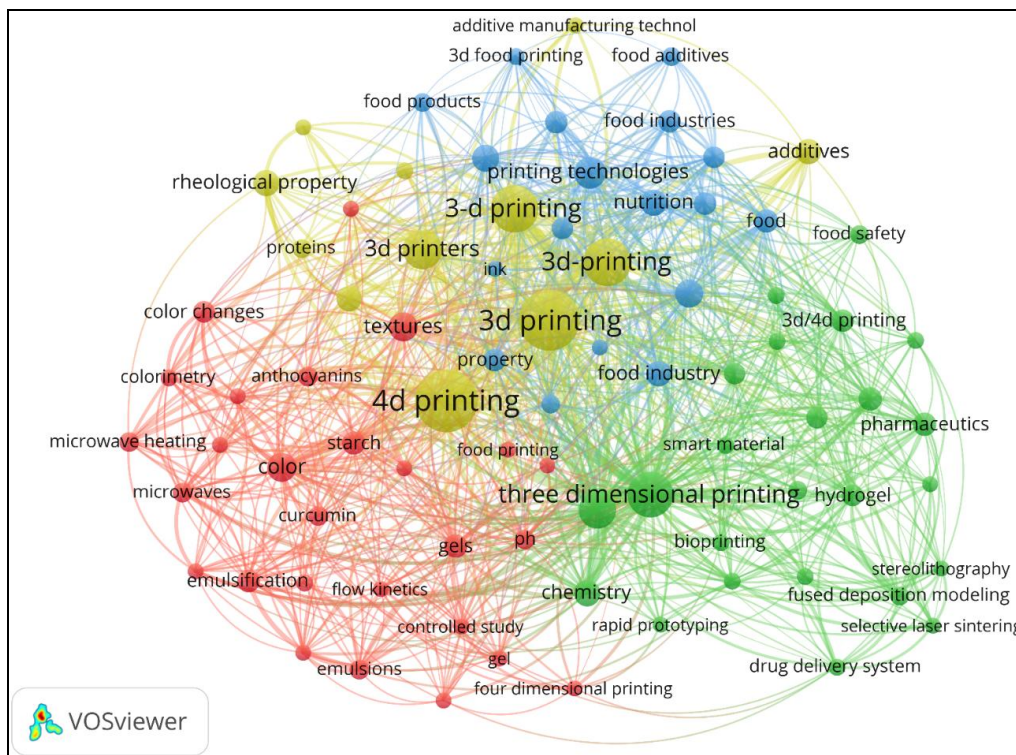


Fig 10: Keyword co-occurrence network map.

## Conclusion

The conclusion is clear: China's global leadership in 4D food printing is largely driven by an extremely productive research group at Jiangnan University, most likely led by researcher Zhang, M. 4D food printing is an emerging field of research that has gained enormous traction and attention from the scientific community in a very short period of time, going from a niche topic in 2018 to an active and rapidly expanding area of research. Although research is growing (as we saw in Fig 2), it is scattered across several high-impact journals rather than concentrated in a single one. The research is volatile and interdisciplinary, attracting the interest of journals focused on materials, engineering, and trend reviews. The topic of 4D food printing is in an early stage of definition and consolidation. The scientific community is actively mapping the terrain through reviews, while original research begins to grow.

## Author contribution statement

José A. Téllez-Morales: Investigation; Writing - original draft; Methodology; Data curation; Conceptualization; Supervision; Writing - review & editing.

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