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The Evolution of Ecosystems for Complex Biotechnologies: Barriers for Technology Exploration and Exploitation

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Abstract

We study the case of a promising biotechnology to understand the interaction between technology commercialization challenges and the barriers for a new ecosystem development.
Prior research on innovation ecosystems highlights the importance of actors' interactions, collaborations, and engagement in generating an innovation value chain. Despite the attention in the recent years, less is known on the early-stages of ecosystems and how the technology commercialization challenges impact on the further emergence of the ecosystem.
We combine data from publications, patents and interviews to build a case on a biomarine (algae-extract) that has been receiving increasing attention in the last years. The case focuses on a multi-country network of actors that have taken the first steps to generate an incipient ecosystem that aims to push forward the commercialization of the biotechnology.
Our findings introduce additional factors to the ecosystem's emergence theory, suggesting that an initial technology application case is not enough to drive an ecosystem and that the categorization of the biotechnology can have substantial effects on the further development of the overall technology and the innovation ecosystem.

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Introduction

Biotechnologies offer an unprecedented market potential as they are driven by new promising research on health, agriculture and industrial applications, as well as an increasing demand for sustainable social and environmental sourcing (Auerswald and Dani 2017). Despite promising application opportunities, as suggested by extensive research activities, the commercialization of bio products is often rather challenging (Haeussler 2011). One reason is the rather heterogeneous transition from laboratory research to a final market solution being complex for biotechnologies, especially due to a high number of multidisciplinary actors (Clarysse et al. 2011). As a technology with origins in multiple research fields, the development of biotechnologies and related applications strongly depend on the successful integration of knowledge, tools and activities from distinct disciplines in accordance with regulative, environmental and social acceptance. Consequently, they require the evolution of innovation ecosystems that involve multidisciplinary, often previously unrelated, actors in collaborative exploration and exploitation processes (Huang-Saad et al. 2016).

At a firm level, previous research on technology commercialization strategy suggests several influencing factors such as human and social capital (Auerswald and Dani 2017), patents and VC funding (Clarysse et al. 2011), market orientation (Baum and Silverman 2004), or legal and economic context (Haeussler 2011). At an inter-organizational level, research suggests that companies and institutions cooperate in knowledge exchange, sharing costs and risks, aiming to shorten time to market, or to generate other synergetic effects (Tödtling et al. 2009). Prior research has focused on the motivations of single organizations and their own benefits, especially profit maximization, as a core driver of development.

Nevertheless, innovation ecosystems literature has taken a broader approach to these challenges, studying not only the successful cases but also how they emerge and mature (Jacobides et al. 2018). Yet, very little is known on the specific especially early steps during the evolvement of an innovation ecosystem such as the nature of the concrete value co-creation and the knowledge transfer or the loose connection between research and application fields in the actual collaboration process during the emergence of a technology (Hoenen et al. 2014). Therefore, little is known on the necessary steps or events that help to address the innovation barriers in such complex contexts. We argue that we need a better understanding of the barriers so that policy interventions can be more effective to stimulate to the commercialization of technology and emergence of new ecosystems (Autio et al. 2018).

To address this research gap, we engage in an inductive, multi-method, research inquiry using the case of a promising bio marine extract that, despite the existing hype and expectations, has failed to generate the expected social and economic impact. We engaged with the actors involved in a cross-disciplinary effort to bridge the lab findings and the market applications. Using data from publication and patent activity, but mostly from interviews, we identify and describe a nuanced view of the different barriers' dimensions and their impact on the future development of a supportive ecosystem for technology commercialization.

The present study contributes to the technology commercialization and innovation management literature in the field of marine biotechnologies and gives practical implications for the acceleration of new ecosystems around promising technologies. We posit that a well-connected and coordinated ecosystem may help to accelerate the technology development and commercialization of final products, even in distant biotech applications areas.

The article is structured as follows: first, we describe the complexity of biotechnologies with a multidisciplinary background and their development and innovation processes in an ecosystem context. Second, we introduce the case of the fucoidan biotechnology, using publications and patent data as well as interviews to identify the key barriers for value creation and collaboration across actors in the emerging ecosystem. Third, we focus on the collaboration dynamics among these actors using expert interviews to decipher the barriers. Finally, we discuss our results in light of current literature on the topic before we conclude our findings outlining the implications for researchers and policy makers.

Theoretical background: ecosystems and technology commercialization

We introduce the ecosystem concept as the theoretical lenses that allow us to understand how the context can influence on the evolutionary dynamics of technologies that rely on a multidisciplinary background. Ecosystems currently receive significant attention from scholars and practitioners as the innovation landscape becomes more diverse and complex in times of an exponential growth in data, information, and knowledge transfer (Scaringella and Radziwon 2017). The concept of innovation ecosystems is still not well defined and subjective to heated debates among researchers (Oh et al. 2016). Metaphorically, a definition can be derived from a biological ecosystem and refers to a set of interacting organizations that depend on each other. In ecology, a community of interacting organisms influenced by its outer physical environment builds an homogeneous unit called ecosystem (Hooper et al. 2005). Accordingly, a business ecosystem comprises the network of interdepending suppliers, distributors, outsourcing firms, makers of related products and services, technology providers that share the interest of maintaining extending the network (Iansiti and Levien 2004). Ecosystems are defined as “the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize” (Adner 2017, p. 40).

Therefore, ecosystems are neither clusters nor regional innovation systems (Hofmann and Giones 2019; Scaringella and Radziwon 2017). While regional innovation systems (RIS) are described as triple-helix initiatives to activate collaborations between university, industry and other institutions in a region, ecosystems are market-driven and private actors should have a substantial role in driving its evolution. Similarly, they are also different from clusters.

Ecosystems can have global connections and actors that respond to the market and technological changes (Ritala and Almpanopoulou 2017).

Differences across types of ecosystems

Recent literature reveals that there are numerous different types of ecosystems such as innovation ecosystems (Leten et al. 2016; Li and Garnsey 2014; Nambisan and Baron 2013), entrepreneurial ecosystems (Autio et al. 2014; Spigel 2017), knowledge ecosystems (Borgh et al. 2012; Clarysse et al. 2014), or hub/platform ecosystems (Gawer and Cusumano 2014). These definitions also include research and development institutions as core partners including their activities influenced by external stakeholders. In accordance to other scholars we find parallels and overlapping characteristics in these definitions. We follow to Adner's (2017) definition of innovation ecosystems adding aspects related to the diversity of disciplines of the participants in the ecosystem, using the following working definition of an innovation ecosystem as a structured network of multidisciplinary organizations along the value chain tied by multilateral interactions to generate economic value.

The dynamics of an ecosystem

A functioning ecosystem is characterized by its multidisciplinary institutions as well as its direct multilateral relationships that cannot be decomposed into bilateral interactions. Thus, the process of technology development and application cannot be subdivided along the supply chain and relies on the simultaneous collaboration of multiple actors. These actors comprise all organizations along the value chain that take part in the value creating process including all institutions involved in fundamental research, sourcing, processing and refining of the product and development and commercialization activities as well as adjacent external stakeholders that may influence the inner network. Diverging aims, or disputes, resulting from different individual organization objectives or prioritization must be revealed to ensure the well-being of the innovation ecosystem (Jacobides et al. 2018). Finding the decision- making principles and behavioral chains that affect the growth and decline of the ecosystem is vital to understand and adjust the processes within the innovation ecosystem (Scaringella and Radziwon 2017).

New technologies and the emergence of ecosystems

The dynamic nature of ecosystems opens the question of what makes them emerge and decline, on the enablers and barriers for ecosystem development (Autio et al. 2018). For instance, what type of actors or actions can contribute in the early-stages of a new ecosystem? Recent research has suggested the potential positive contribution of new entrants such as entrepreneurs (Spigel and Harrison 2017), spin-offs from established players that have an interest in the technology (Giones and Brem 2017), or institutional actors such as specialized research centers (Hofmann and Giones 2019).

It is also suggested that the ability to attract new entrants at a global scale might be a critical aspect for the new ecosystem (Autio et al. 2018), but we know little on how the global connections of the technology, the markets, and the actors in an emerging ecosystem influence its future development. Similarly, we know little on how regional proximity aspects play a role on such early-stages of an ecosystem (Boschma 2005). Overall, we are left with an intriguing question on what type of barriers block further development of a promising ecosystem around a new technology, and how are those perceived by the actors that could potentially contribute to overcome them.

Research Setting

In order to develop a holistic framework of the interplay between technology commercialization and the development of an innovation ecosystem, we perform an explorative study on a case of a promising marine biotechnology. We use the case of fucoidan, a brown-algae extract with a highly promising outlook (Fitton et al. 2015). We study how the origin of the biotechnology, its actors and their characteristics, and their interactions influence on the technology and ecosystem development.

Fucoidan has shown consistent promise in research since the mid-1980s but has had a limited market impact, in particular in the high value-added medical field (Fitton et al. 2015). Due to its vast array of beneficial bioactivities a broad scope of possible application fields is expected. Fucoidan summarizes a class of inhomogeneous sulfated polysaccharides with a high fucose content. Scientists of different research fields revealed numerous characteristics of these polysaccharides or single fractions such as anti-inflammatory, anti-viral, anti-bacterial, VEGF-inhibitive abilities or even anti-cancerogenic (Atashrazm et al. 2015). Nowadays, fucoidan is mainly part of algae-based additives in food supplements or in cosmetic products. Despite therapeutic possibilities like tissue engineering, immune modulation, cancer inhibition, or pathogen inhibition there are no (to the authors best knowledge) approved cases for the use of fucoidan fractions in biomedical applications.

Therefore, this research setting offers a unique context to explore the mismatch between the technology promise, the ecosystem potential, and the existing barriers to block a further development.

Data and Methods

The complex dynamics within biotechnology development suggest that it is crucial to identify the actors and their perceptions across the whole spectrum of the potential ecosystem (Auerswald and Dani 2017). Therefore, we follow a mixed-method research design, starting with a descriptive publication and patent content analysis and continue with an inductive field-work.

We use the Web of Science platform to identify relevant research publications and the database of Orbit Questel to show existing application fields from patent data and reveal active actors in the fucoidan biotechnology trajectory. This data contributed to identify the dominant trends and application fields related to the technology under study, as well as to have the necessary references (at a local and global scale) to understand the perceptions and motivations of the emerging ecosystem actors.

The qualitative data came from an inductive field-work with a large multi-disciplinary group of fucoidan researchers and users is conducted to reveal their connections and interactions and make sense of the key themes that impact on the research and commercialization dynamics of the biotechnology case. Consistent with this inductive research approach, a total of 17 in-depth interviews were conducted with either research and commercial institutions engaged in the fucoidan technology or a strong interest in its development (see Table 1). The interviewee selection started with the group of network partners in an Interreg Project (EU) called FucoSan. Using a snow-balling technique new actor were invited into the data collection until the different type of possible ecosystem actors were captured.

Table 1. Description of the interviews sample

Institution Type / Role	Position	Interview year	Country
Algae Producer	Researcher	2017	Germany
University	Pharmacology Researcher	2017	Germany
University Hospital	Ophthalmology Researcher	2017	Germany
University Hospital	Traumatology / Bone regeneration Researcher	2018	Denmark
Large chemical company	R&D Director	2018	Norway
Research Institute	Researcher	2017	Germany

Pharma Company	Director	2017	Germany
Pharma Company	Head of Research	2018	Germany
Regional Institution	Food Regulator	2018	Germany
Fucoidan extract producer	CEO	2018	Ireland
Cosmetics Company	Director	2017	Germany
University	Animal Feed Researcher	2018	Norway
University Hospital	Researcher	2017	Germany
University	Biochemistry Researcher	2017	Denmark
University	Biochemistry Researcher	2017	Denmark
Algae Association	CEO	2017	Denmark
Life Sciences Cluster	Director	2018	Denmark

The transcripts coding has been done by the first author, the second and third challenged and cross-validated the coding themes and interpretation. In a first step, key themes were identified, in a second step, using axial coding, the open codes were matched in abstract theoretical categories. Using inductive and deductive techniques these theoretical categories were then reassessed and clustered in more precise subgroups. The resulting themes and contributing concepts are discussed in the results section.

Results

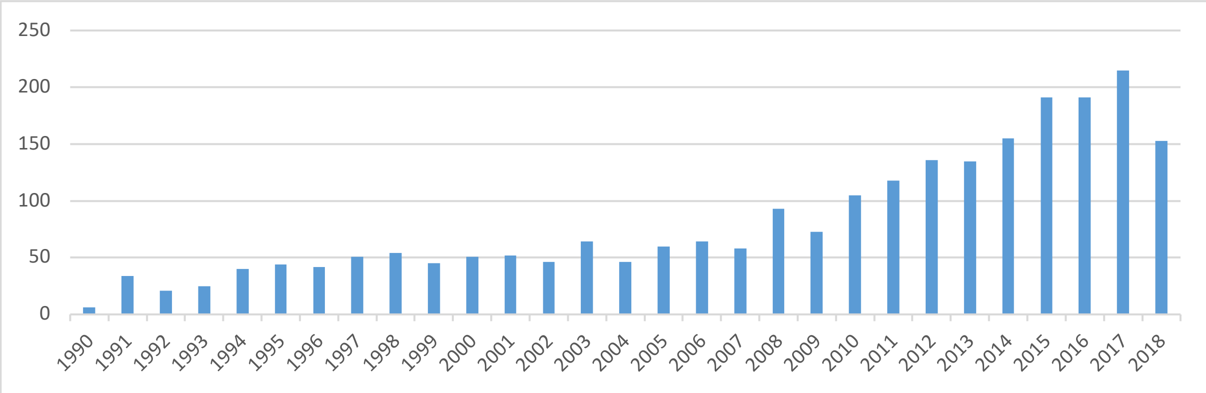
The results section is structured as follows, we first present the results from the publication and patent analysis, then we describe in detail the results of the qualitative data analysis.

Exploratory analysis of research publications and patents

We use the Web of Science database to select all peer-reviewed articles of interest. We chose this particular scientific citation indexing platform because it gives access to a variety of different databases referencing high quality cross-disciplinary research journals and articles useful to identify a technology relying on the collaboration an interdisciplinary network. We therefore identity all articles containing the term “fucoidan” or adjacent terms of the word stem and analyze their publication date as well the journal they were published in.

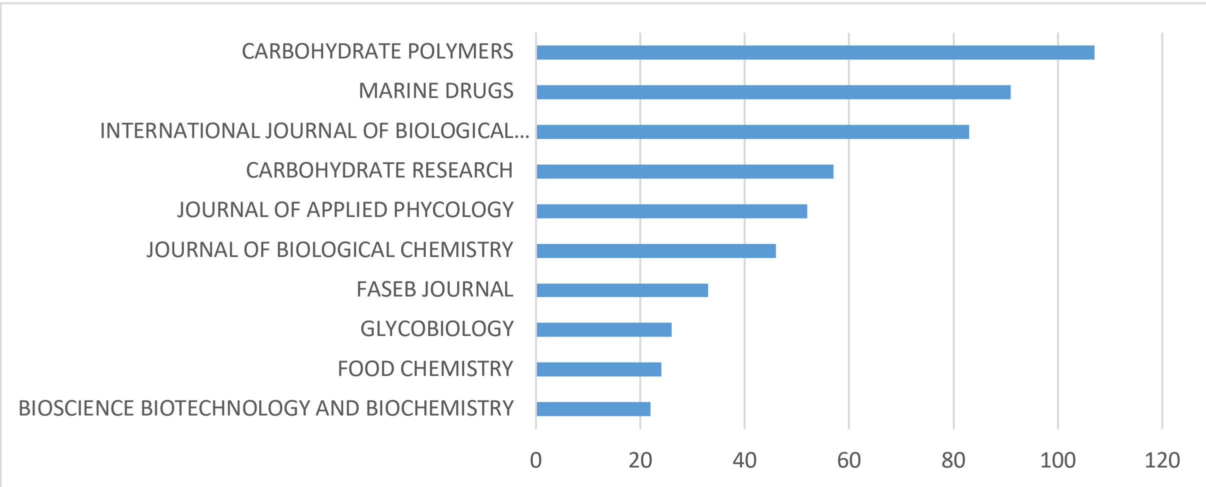
As it can be seen in Figure 1, the research interest on fucoidan has been consistently growing in the last decade.

Figure 1. Number of publications (articles) per year containing the term Fucoidan



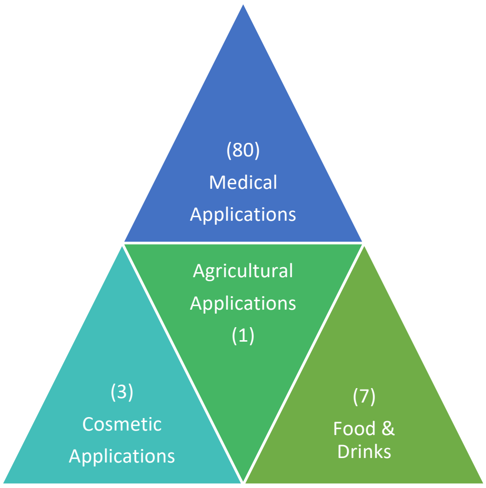
Interestingly, most of the research outputs have been published in chemistry and specialized biology and marine sciences journals (see Figure 2).

Figure 2. Distribution of research publications containing term Fucoidan by journal name



A further analysis of the publications allows us to identify that most of the research publications explore the possible applications of fucoidan in the medical field. Making visible the researcher’s interest in finding potential uses of the extract in this application area.

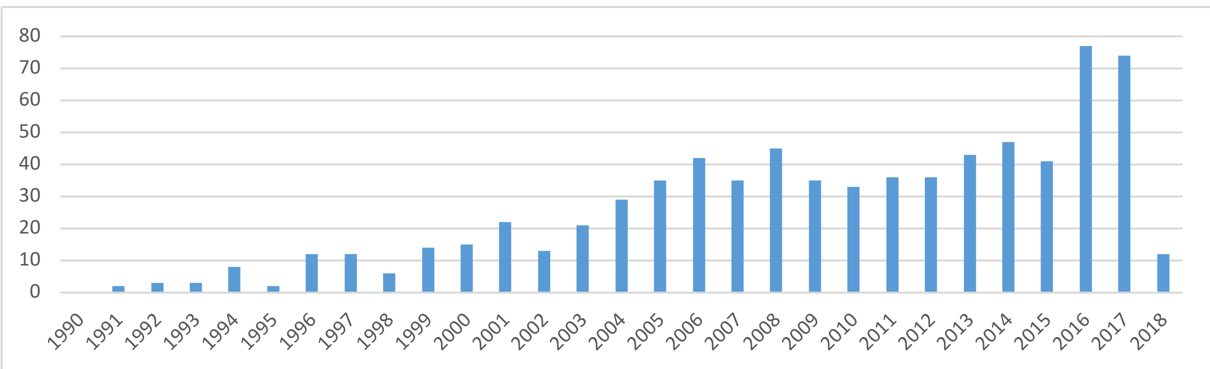
Figure 3. Distribution of research publications by application area



To study the patenting activating on the biotechnology of fucoidan we turn to Orbit Questel as a comprehensive collection of intellectual property databases for each stage of the innovation lifecycle. Compared to the commonly used PATSTAT published by the European Patent Office (EPO) it also contains full text and further legal data of patents. A total of 1530 patents have been identified containing the word stem of fucoidan in the title, abstract, claims, or objectives. Revising the data, our search yields 1283 patents usable for our analysis. We present the development of these patents over time and classify them according to their IPC Class and geographical origin.

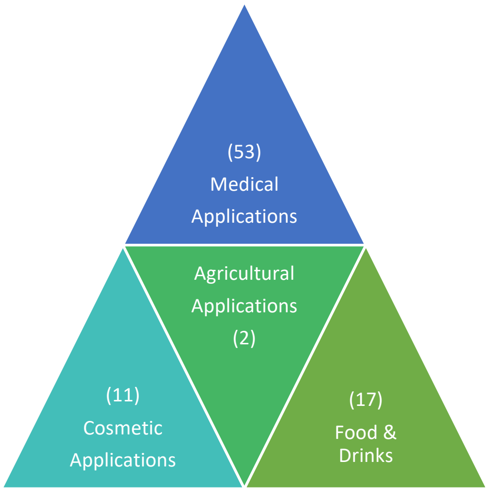
As it can be observed in Figure 4, there has been a sustained activity in patenting fucoidan related applications since early 2000. As we could also observe with the publications, there is a recent peak in the last years (see 2016-2017).

Figure 4: Number of patents by year containing fucoidan



Compared to the research activity, the patenting data shows a more balanced distribution across fields (see Figure 5), but still a strong weight on medical applications. The food and cosmetics application activities suggest that these are areas where there are less barriers towards commercialization of new biotechnologies. In the case of fucoidan, the patents in these two areas are often followed by actual commercial products in the market.

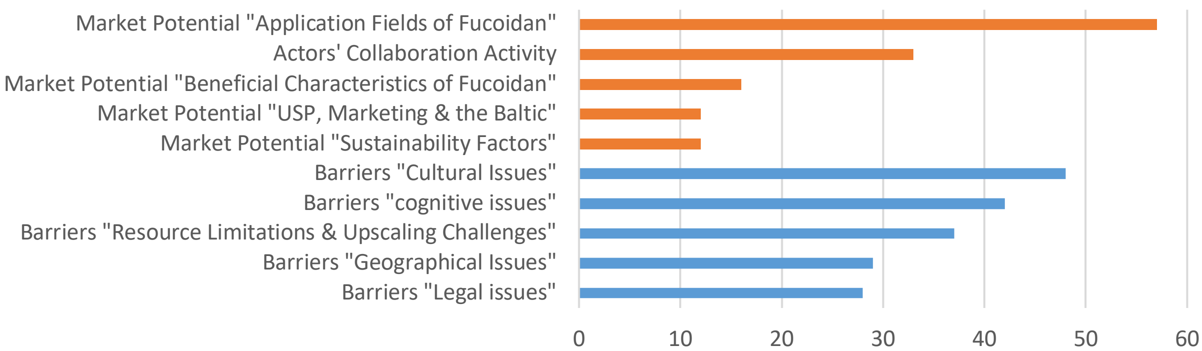
Figure 5: Distribution of patents across key application areas



Commercialization barriers and new ecosystem challenges

The central element in our results is the data analysis from the interview transcripts. In the first coding exercise we aimed to identify what were the drivers of the market potential of fucoidan as a biotechnology, and what were the main barriers. Just as a descriptive representation, we plotted in Figure 6 the number of occurrences of each of the themes in our data.

Figure 6 Occurrences of the Market Potential and Barriers themes



As it can be seen in Figure 6, the theme that capture the most occurrences is the attractiveness of working with a biotechnology that potential has several possible application fields. Interestingly, the most common occurrence in the barriers themes is the concerns on cultural issues.

The aspects that capture the market potential of the biotechnology are the above mentioned application fields, the existing collaboration activities across researchers in the region, the observed beneficial characteristics of fucoidan as an active component (in vitro), the unique selling proposition of natural sea products from the local region (the Baltic area in this case), and the fact that the use of this natural bio marine product is aligned with a more sustainable use of natural resources for medical and cosmetic applications.

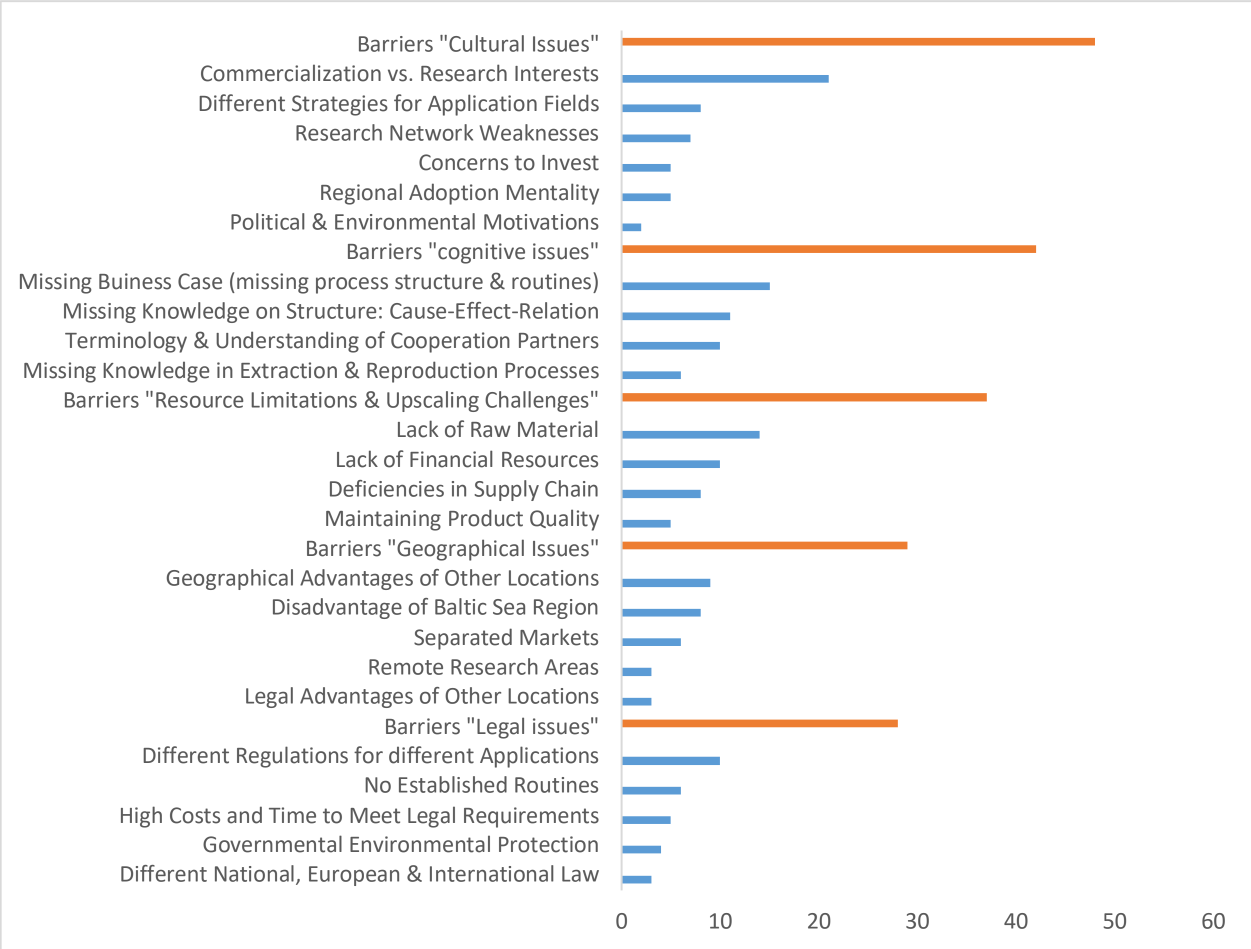
More than focusing on the perceptions behind the potential of the biotechnology, our interests in the data analysis were to decipher the perceived barriers.

The barriers to technology commercialization and ecosystem development

The more fine-grained analysis of the barriers helps to identify five key themes (see Figure 7), for each of them a more detailed analysis resulted in the characterization of sub-themes or concepts that explain the main theme.

The first barrier that emerged in the data analysis is grouped in the theme of “cultural issues”. These include aspects related to the existing differences across the regions that are part of the emerging ecosystem. Actually, the researchers and actors interviewed highlight how there are substantial cultural differences across the different regions in the world where there are more or less advanced ecosystems around biomarine products. Another concept that appears is the difference between commercialization interests of small cosmetics companies and the researchers aiming to develop medical applications. Some of the tensions described in the interviews were also related to the debate between retaining the intellectual property from the research results, or sharing them publicly by publishing them in a journal (Gans et al. 2017). Such tensions are also related to the different commercialization strategies depending on the application fields. The interviewees suggest that the need for evidence and research to develop cosmetic or food applications are rather different from medical uses. Finally, the theme of “cultural issues” also includes aspects related to the different political and environmental objectives in the different regions, and on the lack of strength of a cross-country network that could make more visible the potential benefits of fucoidan as a biotechnology.

Figure 7: Barriers' theme (in orange) and underlying concepts (in blue) related to Fucoidan commercialization



The second theme that emerged is "cognitive issues". In this theme the key concepts that appeared is the challenge to establish a relationship between the potential benefits of the new biotechnology (the fucoidan) and the assessment of the effect that it has on targeted pathologies or health problems. The absence of clear evidence generates an uncertainty, in both researchers and industry. Such perceptions are also related to the challenges of characterizing the natural compound and to ensure that the extraction processes is standardized and generates an extract with the same bio-active characteristics. Furthermore, the theme of cognitive issues also includes the challenges described by university researchers to engage with other colleagues in different departments, for instance the researchers at pharmacology expect the application areas colleagues (traumatology or ophthalmology) to share the same standards and understanding on aspects such as molecular size, weight or toxicity indicators.

The third theme is labeled as "resource limitations and upscaling challenges". In this theme the barriers related to bringing the industrial case of the biotechnology to the market are described. For instance, one of the pioneering cosmetics companies to use the fucoidan extract mentions that they lack financial resources to scale production and to obtain the necessary production volume of the natural product to cover a larger market. So it is a combination of limited raw material (still in the red-list of natural products in Germany – reducing the possibilities of industrial collection at any scale), and the necessary up-front investments to scale up the production. On the high-value application areas the interviewed researchers estimate a time of about ten years until the first medical products might be available, plus at that point it would be a concern to make sure that the extract has the necessary purity to ensure that the medical product has the expected quality.

The fourth theme is grouped under "geographical issues". The context of the emerging ecosystem is the German-Danish Baltic Sea, despite the advanced research capabilities in the region, there are natural *"disadvantages of the Baltic Sea Region"* as one of the university researchers pointed out in relation to other geographical locations: the topography of the coastline and the water quality affect the further development of production for market applications. In addition, interviewees from research institutions state to be aware of the work of research groups from other research centers (as identified in the publication and patent analysis), for instance in China, Japan or South Korea, but they are not connected to them. These geographical issues are also translated into differences in the legal regulation that impacts the development of the emerging ecosystem.

Finally, the theme of "legal issues" captures the different aspects that regulate the use and application of fucoidan. The interviewee working in a large chemical company in Norway mentions that they had to move away from other countries looking for areas where they could do an industrial use of algae-based products. The legal regulations not only impact the final application fields but also the wild harvesting or cultivation, this was highlighted by the researcher at the German algae production company. The position of the regulators regarding the legality of the commercial use of biomarine resources can be summarized in this sentence from one of the regional authorities: "*Fucus and seaweeds are multiannual type of plants thus an important habitat for several organisms. Therefore, we see a high ecological potential in its conversation*". As a result, the legal challenges translate into high barriers for organizations and institutions interested in further commercialization of fucoidan-based applications.

Discussion and implications

While prior research studying the case of fucoidan as a promising biotechnology has focused on the barriers from a medical research perspective (Fitton et al. 2015), we have instead used this as a case to study the barriers for technology commercialization from an ecosystems perspective. Our findings suggest that there are two sides to the story, on one side we see the promising potential from lab experiments and tests of a natural product extract, on the other the challenges to transition from the in-vitro context to replicable tests in-vivo that activate the market potential of the bio marine extract.

Interestingly, our findings suggest that the barriers are more nuanced that what could be observable at first sight. There are two distinct challenges, the evolution of the biotechnology (and this is more a bio-chemistry research process), and the connection and coordination of complex research and application areas' actors. Plus, there is an overarching theme regarding regulation that impacts both the evolution of the technology and the emergence of the ecosystem.

From the literature on emerging ecosystems, we extract that it is highly important that the initial entrants in these markets (in our case application areas) find a supportive context where they can start developing initial applications (Spigel and Harrison 2017). In the later stages of the ecosystem, the connections between actors and the further knowledge inflows is expected to contribute to the consolidation process. However, what we can observe in the case of fucoidan is that the degree of connectivity across the actors is highly dependent on the application area. While for cosmetics or food applications there is an active connection between the production, extraction, application and commercialization of algae-based products, such innovation value chain (Adner 2017) is inexistent in medical applications.

This is an important implication for the ecosystem's emergence theory, not all application cases have the same impact on the activation of the ecosystem. Being more specific, the idea that new ecosystems emerge around a new technology (Woolley 2010) suggests that the necessary condition is to identify a first commercialization opportunity for the technology. As it can be observed in the fucoidan case, in complex, multidisciplinary technology research, this might not be a sufficient condition. As our results suggest, it would be the identification of a high-value medical application that would trigger the emergence of a complete value chain that would create an ecosystem around the brown-algae extract.

An additional implication of this research findings is to establish a connection between the literature on ecosystems emergence and category management. As our data suggests, as long as the fucoidan applications remain in the cosmetics and nutrition application areas, it will not be considered as a priority product for human health. As a result, only if the researchers are able to generate evidence on the possible human health applications (in areas like critical ophthalmological pathologies or tissue engineering) the algae-extract will have the opportunity to be placed in a different category in the eyes of the regulators. Following the insights from Ozcan and Gurses (2018) from the dietary supplements case, the selection of the right product category can open the doors to relax the regulation regarding the cultivation or harvesting of the raw product. This would not only favor the activation of medical applications but support the growth and development of the whole ecosystem. A case not so different from the recent changes in regulation regarding cannabis (Coombes 2014).

Limitations and further research

Our research is not absent of limitations. Although we are studying a case of a biomarine product that has been developing during quite a few years, most of our qualitative data comes from a specific point in time. In addition, the potential and barriers perceptions capture the nature of the current situation, with limited insights on how these have evolved in recent years. Given the slow development of biotechnologies, further research should take a longitudinal view to assess how these barriers have an effect on the short- and long-term development of the ecosystem. With our data, we can only hypothesize that if these barriers remain immobile the emerging ecosystem is likely to get weaker and not develop any further. The study of the interplay between technology commercialization challenges and ecosystem development deserves further attention. Our case is a very specific and complex biomarine technology, the evolutionary nature of such type of technology is rather different than the recent group of digital technologies (Cohen et al. 2017). It is plausible, that the complexities and challenges that we are describing only capture part of phenomena, thus generalization of our findings should be done considering the boundaries and intricacies of the specific case we have been studying.

Finally, further research is needed to connect the research and patenting activity with other formal activities such as company formation and ecosystem growth. Given the ongoing interest to extract policy lessons to promote the development of new ecosystems, it would be rather interesting to engage in a further analysis and correspondence between the publications, patents, and firm level activities in new emerging technology areas. Such efforts could render valuable insights for regulators interested in promoting innovative growth in their regions.

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