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Matthew S. Dahabieh, Stefanie Bröring, Elicia Maine

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Authors: Matthew S Dahabieh[a,b,d], Stefanie Bröring[c,e], Elicia Maine[a,f,*]

Affiliations:

[a] Beedie School of Business, Simon Fraser University, Vancouver, Canada
[b] Renaissance BioScience Corp., Vancouver, Canada
[c] Institute for Food and Resource Economics, University of Bonn, Bonn, Germany
[d] matthew_dahabieh@sfu.ca
[e] s.broering@ilr.uni-bonn.de
[f] emaine@sfu.ca
[*] Corresponding author

Abstract

The food and agriculture biotechnology (FAB) sector is poised to respond to some of society's most pressing challenges, including food security, climate change, population growth, and resource limitation. However, to realize this promise, substantial barriers to innovation must be overcome. Here, we draw upon industry experience and innovation management literature to analyze FAB innovation challenges, as well relevant frameworks for their resolution. In doing so, we identify two major FAB innovation challenges: specialized adoption uncertainty, and complex product-market fit across convergent value chains. We propose that these innovation challenges may be overcome by 1) prioritizing the establishment of organizational and social technology legitimacy, and 2) leveraging technology-market matching methods and open innovation practices.

Keywords

Food and agricultural biotechnology; innovation management; adoption barriers; uncertainty analysis; technology-market matching; convergence-driven value chains; open innovation; product-market fit

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Background

Food and Agricultural Biotechnology (FAB) encompasses technology innovation designed to improve plants, animals, and microorganisms, as well as their cultivation, processing and use, so as to increase their economic, social, and health-related value. As such, the sector is comprised of a broad collection of innovation areas encompassing technologies that respond to changing consumer preferences in food production and consumption, opportunities in nutritional supplementation and preventative healthcare for humans and animals, issues of food security and environmental sustainability, the transition towards a 'bio-based' economy and green chemistry alternatives to synthetics, and enabling novel material use such as bio-plastics and/or specialty ingredients (**Table 1**).

Although still emerging as a standalone innovation area, the FAB sector has seen immense growth over the past five years, and has attracted significant investment activity from angel investors, private equity, incubators and accelerators, as well as venture capital (VC) firms (both broad biotechnology funds and FAB-specific corporate VCs). In 2016 alone, there were a reported 580 FAB sector financing deals globally—worth approximately $3.2 billion USD—made with over 650 unique investors, including 14 dedicated VC FAB funds worth nearly $850 million USD[1]. Moreover, since 2014 over $10 billion USD has been invested into the FAB sector, compared with only $2.3 billion USD invested in total between 2010 and 2013[1]. While these figures highlight the substantial growth of the FAB sector, the industry as a whole is still in its infancy. For example, the broader biotechnology/biopharmaceutical (healthcare) sector in the US attracted over $11 billion USD investment in 2016 alone, out of the total $58.6 billion USD invested in the US that year and the approximately $100 USD invested globally[2]. Importantly, 57% of 2016 FAB sector investments were at the

[1] AgFunder—https://agfunder.com/research/agtech-investing-report-2016
[2] https://www.pwc.com/us/en/moneytree-report/assets/PwC & CB Insights MoneyTree Report - Q4'16_Final V1.pdf

Seed stage[1], which further highlights the nascent nature of the FAB sector, but also signals its substantial promise for innovation at the intersection of existing industries.

Undoubtedly, one of the driving forces for investment and growth in the FAB sector is the need for, and promise of, technological solutions to important food and agricultural issues. Food quality and security are fundamental to the health and well-being of societies worldwide, yet today unprecedented population growth, resource limitation, and climate change are beginning to challenge our ability to feed ourselves in never-before-seen ways (Boehlje & Bröring, 2011; Boehlje, Roucan-Kane, & Bröring, 2011; Raiten & Aimone, 2017). The successful development and deployment of innovative technologies by focused, agile, and opportunistic FAB ventures can help overcome these challenges. However, in order to be successful in technology commercialization, FAB ventures must be cognizant of the barriers to innovation they may face and, more importantly, develop proactive strategies to cope with the aforementioned challenges. Indeed, the evolution of novel technologies, such as synthetic biology, robotics, and applied data science, as well as the emergence of the bio-economy, highlights the substantial need for an innovation management lens to be applied to the food and agricultural biotechnology sector.

In response, we draw upon technology and innovation management literature to analyze the FAB sector, thereby positioning it within the broader context of science-based ventures (SBVs) and the technology sector as a whole. Moreover, we utilize our collective academic and industrial experience in science & technology entrepreneurship, commercialization strategy, and diffusion of technology in converging industries (especially food and beverage), to identify and examine innovation challenges particularly pertinent to the FAB sector. This examination contextualizes each challenge within a specific innovation management framework in order to highlight 1) why the challenge is particularly relevant to the FAB sector, and 2) how the challenge may be addressed through applied innovation management frameworks. To the best of our knowledge, this commentary is one of the first examinations of barriers to innovation in the emergent FAB sector, with the aim of increasing awareness of innovation management approaches that may be useful in promoting successful FAB technology development and deployment.

Positioning of the FAB sector—Innovation challenges shared with other SBVs

Technological innovation can be broadly divided into two basic categories—one in which technology uncertainty is low, i.e. existing and/or near-term technologies are applied to yet-unresolved engineering problems; and, another in which technology uncertainty is high, i.e. solution engineering requires novel research yielding advances in fundamental scientific knowledge in order to be successful (Bröring, Leker, & Ruhmer, 2006a; Garcia & Calantone, 2002; O'Connor, 1998).

Accordingly, technology innovators that comprise the latter category—often referred to as Science Based Ventures (SBVs) and defined as those who attempt to “not only use existing science but also to advance scientific knowledge and capture the value of the knowledge it creates” (Pisano, 2006)—face significant barriers to successful technology development and deployment. These challenges have been broadly documented in the past, particularly in the context of advanced materials and nanotechnology ventures (Maine & Seegopaul, 2016), and may include the following: 1) large capital requirements for research and development (> $5-10M), 2) extended technology readiness timeframes (> 5-10 years), 3) the need for co-innovation to ensure technology adoption (ventures are typically upstream in value chain and business-to-business (B2B)-focused), 4) highly interdisciplinary knowledge requirements for research and development (R&D), 5) high technology uncertainty (especially for biological based technologies), and 6) high market and adoption uncertainty (especially for platform technologies, radical or disruptive innovations, or technologies that are highly visible yet unfamiliar to the public) (Hall, Bachor, & Matos, 2014; Maine & Garnsey, 2006; Maine & Seegopaul, 2016; Pisano, 2010). Of note, these challenges stand in contrast to those facing other non-SBV technology-driven industries such as the information and communication technology (ICT) sector, which is characterized by low technology and market uncertainty, relatively low capital requirements, and short timeframes for commercialization (Cusumano, MacCormack, & Kemerer, 2009; MacCormack & Verganti, 2003) (Figure 1).

Notwithstanding ICT-type food and agriculture technologies, FAB ventures are more closely aligned to SBVs than other technology innovation sectors (Figure 1). Indeed, many of the most promising FAB innovation categories, namely agricultural biotechnology, bioenergy and biomaterials, and innovative food, all face high technology uncertainty and must perform fundamental interdisciplinary research in diverse areas such as microbiology, genetics, human and animal nutrition, immunology, polymer and enzyme chemistry, bioengineering, synthetic biology, etc. As such, it is clear that the FAB sector must address the same broad set of barriers to innovation that affect other SBVs.

However, given that the sector seeks to bring radical innovation to otherwise low technology intensive industries with relatively low R&D spending and a culture of incremental, process-driven innovation (Trott & Simms, 2017), it is clear that the FAB ventures must also overcome a set of sector-specific innovation challenges.

Positioning of the FAB Sector—Sector-specific innovation challenges

In addition to the broad innovation challenges facing SBVs, FAB ventures face a number of sector-specific barriers to innovation that arise from the application of biotechnology into a complex food and agriculture sector with substantial specialized technology and market adoption drivers, most notably vested consumer interest in an otherwise business-to-business sector (Figure 1 and Table 2). Of note, while these challenges are not necessarily exclusive to the FAB sector, they are likely to be particularly relevant to radically innovative FAB ventures seeking to make major changes to the technological status quo of the food and agriculture industries.

In the next section, we examine two specific, yet strongly interconnected, FAB-sector challenges—specialized adoption uncertainty, and product-market fit across industry convergence-affected value chains—within the context of relevant innovation management frameworks. Indeed, we find that the FAB sector is subject to several convergence processes at the technology (e.g. genomics, biotechnology) and market (e.g. hybrid products such as preventative foods or personalized nutrition) levels. This both creates and reinforces specialized adoption uncertainty at the technological, commercial, organizational, and societal levels, which perpetuates the already complex challenge of finding the right product-market combination in hybrid convergent value chains and industries.

Innovation Challenge 1: Obtaining Sociopolitical Legitimacy to Mitigate Adoption Uncertainty in Highly Visible FAB Markets

Uncertainty is an inherent component of innovation and, much like the more general category of SBVs, FAB ventures face a high degree of both technology and market uncertainty. However, given the positioning of the FAB sector at the confluence of food, agriculture, and biotechnology, FAB ventures also encounter unique uncertainties stemming from food's inextricable link to our identity as individuals, cultures, and societies (Hall et al., 2014) (**Table 2**). This creates complex adoption uncertainties at the organizational and societal levels.

For example, growing consumer demands for transparency and traceability within the ingredient and food supply chain (Duarte Canever, Van Trijp, & Beers, 2008; Pant, Prakash, & Farooquie, 2015; Trienekens, Wognum, Beulens, & van der Vorst, 2012; Wognum, Bremmers, Trienekens, van der Vorst, & Bloemhof, 2011) highlights the changing nature of organizational uncertainty in the FAB sector, where conventional food technology appropriability regimes, i.e. trade secrets and proprietary knowledge of process and formulation innovation (Alfranca, Rama, & Tunzelmann, 2002; Arundel, 2001; Leiponen & Byma, 2009), may no longer be suitable for value creation and capture. Likewise, the ongoing debate between the scientific community and the consuming public (Leshner, 2015) over foods derived from genetically modified organisms (GMOs) highlights the power of societal uncertainty, and especially issues of risk perception, emotionality, tradition, and public opinion, on the adoption of FAB derived products.

How then do FAB ventures successfully develop and deploy innovations in a highly uncertain ecosystem where organizational and societal pressures have significant consequences on technology adoption? One approach may be to prioritize a structured and holistic analysis of technology, commercial, organizational and societal (TCOS) uncertainties, so as to facilitate the establishment of overall technology 'legitimacy' in two key areas—cognitive and socio-political (Hall et al., 2014) (**Table 3**).

Within such a framework, cognitive legitimacy is defined as the "knowledge about the new activity and what is needed to succeed in an industry" (Hall et al., 2014). More specifically, this type of legitimacy refers to overcoming both technological and commercial uncertainty. Technological uncertainty relates to barriers on the scientific research, development, and engineering of a technology. Key forms of technological uncertainty include design and utility challenges, technology functionality, scale-up issues, etc. Importantly, although technological uncertainty in FAB ventures—as well as SBVs as a whole—is often very high, it is the form of uncertainty that is most well understood and directly controlled by a venture. On the other hand, commercial uncertainty is concerned with a technology's value proposition and competitive advantage in the marketplace. Key questions in this area are how and where a technology fits into the value chain, whether or not it can compete with less expensive or more effective alternatives, and if co-innovations are necessary to drive market adoption. These forms of uncertainty are also generally well understood and can be mitigated by careful analysis of the competitive landscape, as well as the entire system into which a technology is embedded.

On the other hand, socio-political legitimacy is defined as the "the value placed on an activity by cultural norms and political influences" (Hall et al., 2014), and is concerned with overcoming both organizational and societal uncertainty. Organizational uncertainty relates to the strength of an organization's appropriability regime with respect to a given technology. That is, how well is an organization able to create and capture value from the technological innovation that it creates (Teece, 1986). Key questions include how a venture invests its resources with respect to being either control or execution focused within a value chain, as well as how a venture orients itself with respect to collaborating or competing into a value chain — each of these factors influences a venture's choice of business model. Meanwhile, societal uncertainty is concerned with the social and political impacts of the technology and how diverse sets of stakeholders may respond and influence an innovation's success. Key questions include which groups will be invested in a technology's implementation, what power and influence do stakeholders have in determining a technology's legitimacy in the marketplace, and how can stakeholder reactions be predicted and, if negative, mitigated.

Given the close cultural and social links to food and agriculture, FAB ventures should be particularly concerned with establishing sociopolitical legitimacy so as to avoid costly organizational and societal adoption barriers. With respect to organizational uncertainty, a key issue for FAB ventures to consider is the nature of the appropriability regime used to create and capture value from innovation and, more specifically, how such regimes may impact—and be impacted by—consumer viewpoints. Indeed, increasing consumer demands for transparency, labeling, education, and, ultimately, choice over novel foods, food ingredients and other biotechnology-enabled foods (BEFs) necessitates that FAB ventures critically evaluate the utility of conventional food and beverage sector appropriability regimes (Duarte Canever et al., 2008; Pant et al., 2015; Trienekens et al., 2012; Wognum et al., 2011). Moreover, the ubiquity and accessibility of social media has enabled active consumer engagement with companies, as well as discussion amongst consumers (Rutsaert et al., 2013), thereby accelerating demands for transparency in knowledge and potentially compounding consequences of poor strategic decision making.

Historically, new product and technology development in the food and beverage sector has occurred through incremental process and formulation innovation (Boehlje et al., 2011; Boehlje & Bröring, 2009; Lefebvre, De Steur, & Gellynck, 2015; Trott & Simms, 2017)—these types of innovation generally lend themselves to appropriation through trade secrets, proprietary information, and other ‘closed’ forms of knowledge control (Arundel, 2001; Leiponen & Byma, 2009; Lemper, 2012; Thomä & Bizer, 2013). However, in a new marketplace with educated consumers demanding transparency, such appropriability regimes may, at best, delay technology adoption or, at worst, foster active distrust and advocacy against a given technology. Indeed, knowledge, perception, and attitude are among key intrinsic factors thought to drive food and agricultural technology adoption, as evidenced by evaluation of GMO seed and crop technology adoption in developing countries (Meijer, Catacutan, Ajayi, Sileshi, & Nieuwenhuis, 2014).

As an alternative to ‘closed’ appropriability regimes, FAB ventures may seek to utilize patents and/or other intellectual property rights as a means to protecting and monetizing their intellectual property. Such approaches are arguably more transparent than the use of trade secrets; however, a patent-driven strategy may also be problematic for a number of reasons. Firstly, the acquisition and maintenance of patents can be prohibitively expensive, especially for resource-limited ventures. Secondly, the enforceability and/or protection of patents may be difficult in certain jurisdictions, especially developing countries with limited patent laws (Hall et al., 2014). Thirdly, strong patent regimes requiring control by a select group of stakeholders may be prohibitive to collaborative R&D and open innovation practices (Laursen & Salter, 2014), which are thought to be crucial for innovation in the FAB sector (Pellegrini, Lazzarotti, & Manzini, 2014; Saguy & Sirotinskaya, 2014; Sarkar & Costa, 2008). Lastly, even though strong, patent-enabled appropriability regimes are more transparent than trade secret-based regimes, consumers may still take exception to the level of authority and restriction exerted by patent holders seeking to enforce their patents—indeed, such a response has been seen previously towards multiple seed and crop technologies owned by multinational agribusinesses (Hall et al., 2014).

With respect to societal uncertainty, public concerns surrounding GMOs and BEFs create an extremely high degree of specialized adoption uncertainty for ventures. This is perpetuated by the fact that many FAB ventures create technologies with high consumer visibility and impact (i.e. affecting food production, manufacturing, and nutrition), despite the fact that the sector as a whole occupies an upstream position in the value chain and thus is business-to-business oriented (i.e. process innovation for agriculture, novel ingredients, etc.). Moreover, this upstream positioning in the value chain presents challenges for FAB ventures trying to communicate with end-customers, gather social and market intelligence, and interface with downstream users of their technology, especially if co-innovation and/or education is needed to drive adoption (Maine & Seegopaul, 2016). In this way, novel ingredients and functional food ventures may face particularly acute adoption uncertainty in the form of consumer reticence towards BEFs. For example, Golden Rice—a genetically modified rice varietal engineered for Vitamin A enrichment—was never successfully commercialized due to anti-GMO sentiment, despite being technologically sound

(Hall et al., 2014). Moreover, it is possible that even if FAB firms do not employ GMO technology—or are outside of the life sciences for that matter, e.g. agricultural data science or food processing technologies—consumer perceptions of “unnatural” foods, so called “food neophobia” (Schnettler et al., 2013), may create significant barriers to adoption.

Although a decade ago the negative public perceptions of GMOs and other BEFs were primarily attributed to a lack of education (Brossard, Shanahan, & Nesbitt, 2007; Cuite, Aquino, & Hallman, 2005), it is now well recognized that the factors shaping public opinion are complex, multifaceted contextual factors (Butkowski, Pakseresht, Lagerkvist, & Bröring, 2017), centering around subjective risk perception (Slovic, 1987). For instance, a recent study revealed that consumer risk perception associated with plant biotechnology differs depending on the application area (food vs. bioenergy) and is lower for applications in bioenergy (Butkowski et al., 2017). Recent studies have revealed that people tend to interpret information about BEFs in personally relevant ways, depending on their specific level of involvement; therefore, conversations about BEFs must take the form of more than just education (Blancke, Grunewald, & De Jaeger, 2017). Indeed, for both scientifically educated people and the general public alike, past experience, values, social norms, and technology application area all contribute to the contextualization of risk perception and decision-making (Bray & Ankeny, 2017; Christoph, Bruhn, & Roosen, 2008; Frewer et al., 2011; Knight, 2006). Critically however, additional education is likely to be useful in increasing the sophistication of public knowledge about BEFs so as to enable people to differentiate and evaluate BEFs objectively on function and application, rather than viewing all products in broad categories and/or through the same lens. This in turn helps promote case-by-case decision-making rather than, potentially uninformed, catchall judgments (Christoph et al., 2008; Knight, 2006), which are problematic since genetic engineering and biotechnology is simply a set of tools that may be used for any purpose, regardless of the objective and/or subjective value of the target. Moreover, as the debate surrounding GMOs and other BEFs involves many complex non-scientific topics, scientists, science communicators, policy makers, and industry—including FAB ventures—should embrace proactive and transparent communication about their research and technologies (Lewandowsky, Mann, Brown, & Friedman, 2016), especially focusing on understanding consumer viewpoints so as to debate on common ground (Blancke et al., 2017).

Innovation Challenge 2: Determining Product-Market Fit in Interconnected and Convergent FAB Markets

Determining product-market fit—often defined as "being in a good market with a product that can satisfy that market" (Blank, 2005)—, is often one of the most critical aspects of successful innovation, both for aligning required product performance characteristics with customer needs (Nobel, 2011), as well as for enabling customer creation/growth and the scaling of a venture (Blank, 2005).

Although a challenge in many sectors, establishing product-market fit can be even more complex in the FAB sector due to the prevalence of innovations that span highly interconnected and convergent markets (**Table 2**). Indeed, many of the innovation opportunities in the FAB sector are driven by industry convergence of existing value chains to either create complementary value chains enabling new industries (e.g. nutraceuticals, functional foods, probiotics), or else substitutive value chains driving alternative, technology augmented industries (e.g. food e-commerce, drones/robotics, bioenergy, 'green' chemistry). As such, convergence-driven, alternative value chains present FAB ventures with specialized challenges in absorptive capacity—i.e. the ability to acquire and internalize different technological and market-related knowledge required to compete effectively in convergent industries (Cohen & Levinthal, 1990)—which can be costly for firms, especially early-stage ventures that are resource-limited (Bröring & Leker, 2007).

The product-market fit challenge is further compounded in the case of platform technologies—those which "will yield benefits for a wide range of sectors of the economy and/or society" (Keenan, 2003)—spanning convergent industries. Examples of such technologies in the FAB sector are platform farm management and food supply chain technologies that are broadly applicable; however, differences in crop type, geography, and supply chain structure necessitate differential implementation of the technology in each market (Fuglie & Kascak, 2001). Similarly, innovative food technologies, such as alternative proteins, bio-based ingredients, and recombinant enzyme production all utilize common technology tool sets (i.e. synthetic biology and microbial fermentation) for their development; however, differences in target technology application and, more importantly, market considerations require careful evaluation of each instance of the platform technology. For example, the use of synthetic biology and genetic engineering in medical/pharmaceutical applications has paradoxically been well tolerated by consumers (Marris, 2001); yet, the same platform technology is minimally tolerated in agricultural and food applications, thereby necessitating case-by-case analysis of adoption barriers and investment of specific resources to overcome application-specific technological and market uncertainty.

It is clear that the convergence of once-disparate industries driving the emergence of novel value chains (Bröring, 2010) can create new space for successful innovation in new markets, but it also places extra demands on firms who wish, or are forced, to access the convergence-driven value chains. Firms are forced to simultaneously manage the research, development, and application requirements of the convergent technologies, as well as the complexities of distinct consumer markets, new competitive landscapes, emerging regulatory frameworks, innovation cycles and adoption timeframes, etc. Because of this convergence, the required knowledge for success is often outside a firm's core competencies, thus leaving firms with a substantial gap in absorptive capacity.

Industry convergence is primarily driven by two main factors—input-side technology-driven convergence, and output-side market-driven convergence (Bröring, Martin Cloutier, & Leker, 2006b). In the former, the use of similar technologies across different industries, design solutions, or the re-application of existing knowledge can all promote convergence—this is especially true in the FAB sector where many of the venture categories apply externally developed technologies (i.e. genomics, nanotechnologies, nutritional and medical biology, Artificial Intelligence, robotics, etc.) in new applications, such as microbial engineering for food and flavor production, Internet-of-Things and robotics enhancement of agriculture, etc. (Saguy & Sirotinskaya, 2014). On the output-side, market-driven social and political trends, as well as consumer behavior shifts, can also promote convergence by blurring the demand structures of formerly distinct industries. Indeed, this is also particularly relevant to the FAB sector as changing consumer preferences around food are driving developments in sustainable agricultural practices, nutritional enhancement, preventative/functional properties, improved food safety and quality, etc. (McCluskey, Kalaitzandonakes, & Swinnen, 2016).

Further promoting industrial convergence is the fact that as industries and technologies mature, dominant designs tend to emerge that drive the sector to switch from technical product innovation to process-based innovation (Abernathy & Utterback, 1978). While this can offer firms a competitive price advantage, it has the consequences of limiting new, potentially more innovative, entrants and technologies into the market and may even lead to commoditization of technology within a sector as price becomes the predominant product differentiator (Abernathy & Utterback, 1978; Maine, Thomas, & Utterback, 2014). This is also particularly relevant to the FAB sector as the food and agriculture markets tend be to highly mature, slow-to-adopt, and price-sensitive industries in which the pace of innovation has been significantly slower than other industries, i.e. information technology (Boehlje & Bröring, 2009).

Given the duality of opportunity and challenge that convergent industries pose for the FAB sector, how then do FAB ventures successfully identify and obtain product-market fit? One approach may be to utilize technology-market matching methods to prioritize the possible markets for platform or industry-spanning technologies (Maine & Garnsey, 2006). As the name implies, this approach aims to identify and evaluate technology and market barriers to establishing product-market fit (as discussed above). This innovation management capability also analyzes the critical interplay of such factors so as to facilitate finding product-market fit and guide initial commercialization efforts for ventures (**Table 3**).

Product-market fit is a function of technological and market uncertainties involved in innovation development and deployment. Examples of technology uncertainty include the need for complementary or process innovation (e.g. manufacturing innovation to produce technology at scale) and the need for customized design or R&D in order to implement the technology (Maine & Garnsey, 2006). In the context of the FAB sector, such technological uncertainty is likely to be influenced by inherent biological variability in living systems (i.e. crops/animals and raw materials/ingredients to which technologies are applied), geographical variability, and seasonal / climate influence (Boehlje & Bröring, 2009). General examples of market uncertainty include regulatory structures, the incumbent landscape and value chain positioning, a lack of trialability or visibility (e.g. technologies that cannot easily be demonstrated prior to financial commitment), and customer adoption rates (Maine & Garnsey, 2006). In the context of the FAB sector, such market uncertainty includes regulatory hurdles for approvals of novel foods, food ingredients, and food processing methods, veterinary regulations, environmental regulations, as well as a technologically conservative incumbent and customer landscape (Boehlje & Bröring, 2009), and economic constraints on value appropriability due to historically slim food and agriculture sector profit margins and/or commodity pricing structures[3] (Boehlje, 2004; Cahoon, 2007).

[3] https://assets.kpmg.com/content/dam/kpmg/pdf/2015/09/gvi-profitability.pdf

Other specialized technological and market factors may offset technological and market uncertainties by positively facilitating the technology-market fit. Examples of such factors may include favourable incumbent alliance partners with key complementary assets, the presence of beachhead markets with champion early adopters (Rogers, 2004), markets with specialized incentives to adopt technology (e.g. legislation, subsidy or tax credits), or markets with specialized technology readiness (e.g. reduced need for complementary innovation and/or regulatory barriers) (Maine & Garnsey, 2006). Moreover, prioritizing markets with near-term potential in this way can not only provide ventures with technical visibility and credibility, but can also provide an important source of early revenue that can be applied to accessing longer-term and/or larger future markets (Maine, Lubik, & Garnsey, 2012).

A key determinant of product-market fit in convergent sectors (e.g. nutraceuticals and functional foods) is the availability of open innovation opportunities—i.e. sourcing innovation resources, such as technology, ideas and skills, externally through collaboration and partnerships, rather than developing competencies internally (Bröring, 2010; Chesbrough, 2003; Saguy & Sirotinskaya, 2014; Sarkar & Costa, 2008). Such opportunities mitigate inevitable deficiencies in the crossover of core competencies needed to compete in convergence-driven value chains (Bröring, 2010). In order to bridge such competency gaps quickly and effectively, companies need not only to analyze their existing core competencies, but also to continuously monitor technology and market developments and dynamic opportunities for open innovation (Bröring, 2010). Using such an approach to evaluate technological capability (i.e. R&D needs vs. current expertise) and market capability (required route to commercialization vs. current commercial channels) provides firms with a system to evaluate strategic options for acquiring required technology and market competencies, and thereby maintaining their dynamic capabilities (Teece, Pisano, & Shuen, 1997).

For instance, depending on a firm's current focus, i.e. technology development vs. consumer goods marketing, and the anticipated new market competencies required, the innovation process may benefit from different types and degrees of inter-industry partnerships, from exploratory R&D partnerships to distribution alliances, to joint ventures. Indeed, instead of developing new competencies internally (costly), or relying only on existing competencies (limiting), firms may choose to maximize value creation and capture by broadly integrating themselves into the value chain. This requires that firms address the inevitable competency gap (e.g. a food company that has no previous experience in performing the clinical trials that are needed to empirically validate health claims) by forming strategic partnerships that enable a firm to develop the required competencies in an efficient way, i.e. fast-to-develop and low-cost (Bröring, 2010). In the FAB sector, the utility of open innovation practices to bridge competency gaps has been documented ((Bröring, 2010; Saguy & Sirotinskaya, 2014; Sarkar & Costa, 2008), and is of particular value to the sector since 1) it operates largely within the context of convergent industries; 2) its constituent markets—the food and agribusiness industries—tend to have highly interconnected value chains with a large number of stakeholders servicing a diverse range of interests including intermediate consumers, end-users, regulators, etc. (Sarkar & Costa, 2008); 3) it must continually address changing consumer needs and preferences, dynamic regulatory environments, complex retail landscapes, and a highly competitive time-to-market race (Saguy & Sirotinskaya, 2014). Thus, when establishing product-market fit, alliance opportunities are a critical consideration in the process of technology-market matching.

By critically analyzing the interplay between both positive and negative forces in the marriage of technology and market, FAB ventures can identify priority markets for their technology and expedite the establishment of product-market fit, thereby maximizing the chances of successful innovation. Indeed, this is of critical importance in the FAB sector as high commercialization costs and limited freedom for pivoting means that early choices often have substantial, pathdependent consequences.

Conclusion

By virtue of its role in innovating global food and agriculture, the FAB-sector faces specialized technology and market adoption uncertainty above and beyond that shared with other SBVs (Figure 1). In this commentary, we examined relevant innovation management and FAB sector literature to identify and discuss key barriers to successful FAB innovation, including 1) specialized adoption uncertainty stemming from organizational and social factors leading to consumer reticence towards biotechnology-enabled foods, and 2) challenges in obtaining product-market fit as a result of broad technology applicability and the specialized demands of operating in complex and interconnected value chains created through industry convergence and changing consumer preferences.

Through our examination of innovation management literature, we identified key overarching and complementary frameworks for strategic decision making that we believe to be well suited for addressing such barriers to innovation in the FAB sector. Firstly, FAB ventures may benefit from the utility of specialized uncertainty analysis methods, such as TCOS, as a means to identify and resolve barriers to the establishment of cognitive, and especially, sociopolitical legitimacy. Secondly, structured analysis of product-market fit through technology-market matching may help to prioritize beachhead markets and early adopters for whom sociopolitical legitimacy may be more easily established. Such an analysis should prioritize the evaluation of open innovation possibilities—primarily determined by the availability and utility of 1) industry alliance partners and complementary assets, and 2) responsive consumers to engage with early in the development process—as a means to narrow gaps in absorptive capacity created by the need to establish technology legitimacy in convergent FAB value-chains.

The FAB sector must overcome considerable commercialization challenges the FAB sector must overcome in order to realize its potential. When managed appropriately, risk and uncertainty can bring substantial reward, as the sector is poised to respond to some of society's most pressing challenges, including food security, climate change, population growth, and resource limitation. Through the proactive analysis and management of barriers to innovation, strategic FAB ventures can be successful in maximizing value creation and capture, as well as realizing the power of their innovations to positively change the world.

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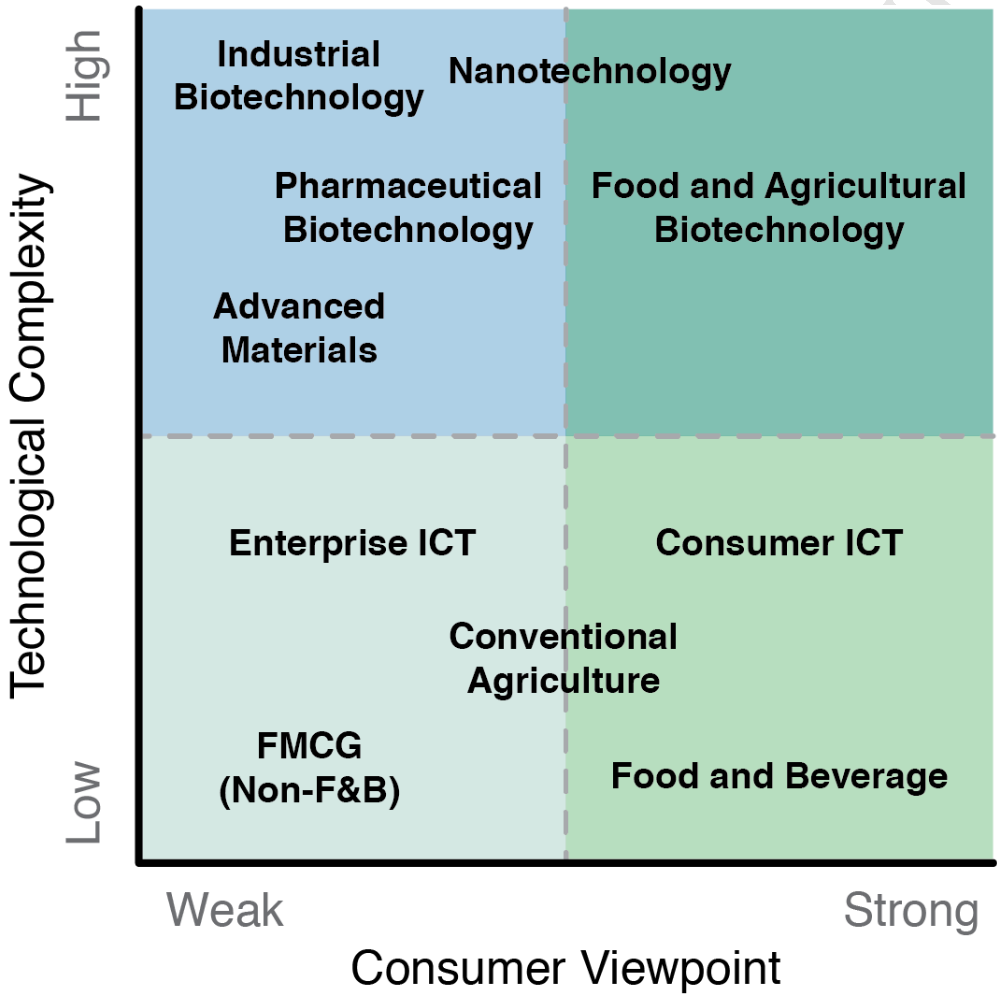
Figure Captions

Figure 1 | Positioning of technology sectors with respect to technological complexity and consumer viewpoint. Technological complexity refers to the magnitude of technical and commercial uncertainty associated with innovation in an industry. Consumer viewpoint refers to both the visibility of an industry to consumers, as well as the strength of vested consumer opinion in that industry. ICT – Information and Communications Technology; FMCG – Fast Moving Consumer Goods; F&B – Food and Beverage.

Figures

Figure 1



Tables

Table 1 | Innovation and technology summary of FAB sector. Adapted from AgFunder[4].

Innovation Category	Technology Description
Agricultural Biotechnology	On-farm inputs for crop & animal ag including genetics, microbiome, breeding
Farm Management Software, Sensing and IoT	Ag data capturing devices, decision support software, big data analytics
Robotics, Mechanization and Equipment	On-farm machinery, automation, drone manufacturers, agricultural equipment
Novel Farming Systems	Indoor farms, insect, algae & microbe production
Supply Chain Technologies	Food safety & traceability tech, logistics & transport, food processing
Bioenergy and Biomaterials	Non-food extraction & processing, feedstock technology
Innovative Food	Alternative proteins, novel ingredients & supplements
Food Marketplace / Ecommerce	Online Farm-2-Consumer, meal kits, specialist consumer food delivery

[4] AgFunder—https://agfunder.com/research/agtech-investing-report-2016

Table 2 | FAB Sector-Specific Barriers to Innovation.

FAB Sector-Specific Challenges	Examples	Reference
Specialized adoption uncertainty	High price competition leading to high price sensitivity, especially in B2C food products,	(Bunduchi & Smart, 2010; Trott & Simms, 2017)
	High product failure rates leading to increased costs and reticence towards R&D expenditure, especially in B2C food products	(Fuller, 2016; Trott & Simms, 2017)
	Lack of consumer knowledge and perceived usefulness for biotechnology products	(Boehlje et al., 2011)
	Reticence towards genetically modified or bioengineered food and agriculture products, especially in Europe — need for sociopolitical legitimacy	(Bray & Ankeny, 2017; Gostin, 2016; Hess, Lagerkvist, Redekop, & Pakseresht, 2016)
	Low acceptance rate of novel raw materials and production technologies in food	(Frewer et al., 2011; Golembiewski, Sick, & Bröring, 2015)
	High consumer visibility—even for B2B innovations—due to strong consumer opinion driven by social, cultural, personal, and nutritional associations with food	(Falk et al., 2002; Huesing et al., 2016; Loebnitz & Bröring, 2015; McCluskey et al., 2016)
	Sensitivity to changes in government policy, consumer sentiment, lobbying interests	(Boehlje et al., 2011; Detre, Briggeman, Boehlje, & Gray, 2006)
	Sensitivity to political instabilities, economic and health crises	(Boehlje et al., 2011; Detre et al., 2006)
	Discordance between industry- and consumer- acceptable appropriability regimes—consumer driven trend towards transparency at odds with historical use of trade secrets in industry — need for sociopolitical legitimacy	(Duarte Canever et al., 2008; Pant et al., 2015; Trienekens et al., 2012; Wognum et al., 2011)
Product-market fit - Platform technologies	Difficult product-market fit and business model requirements due to broad implementation of common tool sets and general-purpose technologies, especially in synthetic biology	(Gambardella & McGahan, 2010)
	Requirement for custom application development work to tailor platform technologies to different subsets of FAB sector, especially in broad based agricultural technologies	(Fuglie & Kascak, 2001)
Product-market fit - Industry convergence	High degree of market-driven convergence responding to changing consumer preferences and regulatory landscapes	(Berning & Campbell, 2017; Boehlje et al., 2011; Bornkessel, Bröring, & Omta, 2016; Bröring, 2010; Carocho, Barreiro, Morales, & Ferreira, 2014; McCluskey et al., 2016; Raiten & Aimone, 2017)

FAB Sector-Specific Challenges	**Examples**	**Reference**
	High degree of technical convergence, especially in the areas of synthetic biology for alternative proteins, novel ingredients & supplements, and agricultural biotechnology, including genetics, microbiome & animal and crop breeding	(Boehlje & Bröring, 2011; Bueso & Tangney, 2017; Golembiewski et al., 2015; Lenk, Bröring, Herzog, & Leker, 2007)
	Large number of convergence-driven value chains and new industry segments created, which require cross-functional knowledge and complementary assets	(Bornkessel et al., 2016; Bröring, 2010; Bröring & Leker, 2007; Boehlje:2011vp Cohen & Levinthal, 1990)
Biological variability	Raw material/yield variability affecting transformation/processing using biological materials	(Boehlje et al., 2011)
	Geographical, environmental, and application (e.g. crop type) variability	(Fuglie & Kascak, 2001)
	Long, slow production cycles for biological raw materials	(Boehlje et al., 2011)
Complex knowledge base	Integration and communication between distinct yet complementary scientific disciplines	(Brunswicker & Hutschek, 2010; "Exploring effectiveness of technology transfer in interdisciplinary settings - The case of the bioeconomy," 2017; Golembiewski et al., 2015)
	Management of complex open innovation relationships, especially academic-industry partnerships	(Golembiewski et al., 2015; Pellegrini et al., 2014; Saguy & Sirotinskaya, 2014; Samadi, 2014)
	High degree of innovation enabled from technology convergence, thereby necessitating broad knowledge transfer	(Fitjar & Rodríguez-Pose, 2013; Jensen, Johnson, Lorenz, & Lundvall, 2007; Levidow, Birch, & Papaioannou, 2013)
	High degree of innovation in which technology input for FAB sector is output of other science-based sectors	(Ahn, Hajela, & Akbar, 2012; Brunswicker & Hutschek, 2010; Lane & Lubatkin, 1998; Pavitt, 1984; Tatikonda & Stock, 2003)
	Immature technology base with continual fundamental advancement, especially in biotechnology	(Golembiewski et al., 2015)
Competing innovation goals	Requirement to balance internal environmental, social, and economic (business) sustainability practices with consumer image	(Boehlje et al., 2011; Bröring, 2009; deVoil, Rossing, & Hammer, 2006; McCluskey et al., 2016)
	Increasingly aware customer base demanding sustainable products and businesses	(Boehlje et al., 2011)

FAB Sector-Specific Challenges	Examples	Reference
Conservative markets	High degree of process-driven incremental innovation, especially for food manufacturing	(Aylen, 2013; Bunduchi & Smart, 2010; Cohendet, Llerena, & Simon, 2010; Trott & Simms, 2017; Vogel, 2011)
	Historically low R&D spending on innovation initiatives	(Trott & Simms, 2017)
	High number of large, capital-intensive incumbent firms, which drives high switching costs for novel technology (B2B)	(Bunduchi & Smart, 2010; Golembiewski et al., 2015; Trott & Simms, 2017)
	Entrenched brand identity leading to insecurity around customer responses of technology adoption	(Golembiewski et al., 2015)
	Low number of early adopters, especially in commodity markets with slim margins	(Frewer et al., 2011; Golembiewski et al., 2015; Henchion et al., 2013)
Complex supply chains	Competitive, relationship driven sales channels and retail environments (B2C innovation)	(Lambert, 2008; Trott & Simms, 2017; Wynstra, Corswant, & Wetzels, 2010)
	Highly fragmented and uncoordinated supply channels with high degrees of interconnectedness	(Boehlje et al., 2011; Fritz & Schiefer, 2008; Trott & Simms, 2017)
Industry flux	Increasing risk and uncertainty as nascent FAB sector continues to develop and respond to convergence challenges	(Boehlje et al., 2011; Boehlje & Bröring, 2011; Bornkessel et al., 2016; Bröring, 2010; Golembiewski et al., 2015)
	Increased competition for common resources, especially in raw-material inputs for bio-economy segment of FAB sector	(Boehlje & Bröring, 2011; Golembiewski et al., 2015)
	Continually evolving regulatory structures, consumer response, and competitive demands resulting from convergence-driven value chains	(Krimsky & Wrubel, 1996)
Regulatory requirements	Significant regulatory burden of proof for product safety, efficacy and utility	(Bansal & Garg, 2008; Boehlje et al., 2011; Bröring, 2010)
Specialized market economics	Production and market price volatility in commodity markets	(Boehlje et al., 2011)
	Commoditized industries, e.g. food, leading to slim margins and reduced capacity to innovate	(Lindgreen & Wynstra, 2005; Trott & Simms, 2017)
	Inelastic supply and demand pricing	(Boehlje et al., 2011)

Table 3 | Key innovation management approaches relevant to the FAB sector.

	Innovation Management Approach	Primary FAB sector-specific challenges addressed	Description	Reference
1	TCOS Uncertainty Analysis	• Specialized adoption uncertainty • Conservative markets	Evaluation of specific technological, commercialization, organizational, and societal factors driving cognitive and socio-political legitimacy barriers to innovation	(Hall et al., 2014)
1.1	Focused Uncertainty Analysis	• Biological variability • Regulatory requirements	Stage-gate, decision-tree, and/or real options uncertainty analysis	(Boehlje et al., 2011)
1.2	Leveraged Funding	• Complex knowledge base • Biological variability	Leverage specialized funding opportunities, i.e. non-dilutive government funding, domain-specific incubator/accelerator opportunities, and in-kind support (e.g. academic relationships), to facilitate technological R&D	(Beylin, Chrisman, & Weingarten, 2011; Maine & Seegopaul, 2016)
1.3	Strategic Timing	• Industry flux • Specialized adoption uncertainty • Platform technologies	Utilizing strategic timing for high-profile publications and broad blocking patents to attract partners and raise financing	(Maine & Thomas, 2017)
1.4	Supportive Organizational Culture	• Competing innovation goals • Conservative markets • Complex knowledge base	Fostering innovative culture through organizational leadership and management	(Barsh, Capozzi, & Davidson, 2008; Boehlje et al., 2011)
2	Technology-Market Matching	• Platform technologies • Complex knowledge base • Specialized adoption uncertainty	Prioritization of potential markets based on technology and market adoption risk so as to identify product-market fit	(Lubik, Garnsey, & Minshall, 2012; Maine & Garnsey, 2006)
2.1	Alliance Partnerships	• Complex supply chains • Complex knowledge base • Specialized market economics	Forge strong alliance partnerships that provide access to key complementary assets/resources	(Das & Teng, 1998; Eisenhardt & Schoonhoven, 1996; Maine & Garnsey, 2006; Maine & Seegopaul, 2016; Maine & Thomas, 2017)
2.2	Staged Commercialization	• Platform technologies • Specialized market economics • Specialized adoption	Sequential entrance into markets so as to maximize resource utility and mitigate risk and uncertainty in achieving high-impact	(Kalish, Mahajan, & Muller, 1996; Sinfield & Solis, 2016)

		uncertainty	innovation, i.e. 'lily pad' / 'waterfall' commercialization	
2.3	Strategic Appropriability	• Platform technologies • Specialized market economics • Conservative markets	Developing sector/ecosystem and technology-appropriate appropriability regimes and business models to allow for maximal value creation and capture	(Adner, 2006; Gans & Stern, 2003; Lubik & Garnsey, 2015; Teece, 1986; 2010)
3	Convergence-driven Value Chain Management	• Industry flux • Industry convergence • Complex knowledge base	Utilizing specialized strategies to inform management decision making and close competency gaps in convergent industries	(Bröring, 2010)
3.1	Open Innovation	• Industry flux • Industry convergence • Platform technologies	Extensive collaboration and broad networks of expertise with academia, key opinion leaders, and consultants so as to minimize costly knowledge gaps and subsequent internal expertise build out during technology development	(Chesbrough, 2006; Maine et al., 2014; Pellegrini et al., 2014; Sarkar & Costa, 2008)
3.2	Convergence and Value Chain Analysis	• Industry flux • Industry convergence • Complex supply chains	Critical evaluation of drivers for convergence so as to predict and proactively respond to industry convergence	(Boehlje et al., 2011)
3.3	DUI Innovation	• Conservative markets • Competing innovation goals • Specialized market economics	Learning-by-doing, by-using, and by interacting (DUI)' to facilitate innovation in low and medium technology industries	(Fitjar & Rodríguez-Pose, 2013; Jensen et al., 2007; Trott & Simms, 2017)
3.4	Specialized Knowledge Management	• Complex supply chains • Complex knowledge base • Specialized adoption uncertainty	Collaboration and cooperation across the value chain to transfer technical and market knowledge so as to close competency gaps—'in-context' analysis	(T. Brown, 2005; Golembiewski et al., 2015; Nussbaum, 2004)

Highlights

- Food and agricultural biotechnology is an promising emergent and growing sector
- The sector faces innovation challenges common to other science-based sectors
- The sector also faces specialized technology and market barriers to innovation
- These arise from the combination of technology uncertainty and consumer viewpoint
- Sector barriers can be overcome using overarching innovation management approaches