Commercializing Covid-19 Diagnostic Technologies: A Review of Challenges, Success Factors, and Insights from the Profiting From Innovation Framework

Abstract

Evidence shows that only a few newly developed diagnostic technologies to control and mitigate the recent health crisis-Covid-19 pandemic, have been successfully commercialized. Building on this, we review systematically the literature on the challenging and success factors of the commercialization of Covid-19 diagnostic technologies. In so doing, we draw on the six components of the Profiting From Innovation (PFI) framework, introduced by Teece (1986, 2006, 2018), including networking, supply chain, competitive manufacturing, services, appropriability regimes, and complementary technology, to provide major insights into technology commercialization challenges for Covid-19 diagnosis technologies. Also, the inductive approach is used to extract other challenges that were not addressed by the PFI framework. Our review makes significant theoretical contributions to innovation management (PFI framework) and crisis management research, and also draws policy implications. We also provide useful directions for future research.

Keywords: Technology commercialization, Profiting from innovation, Covid-19 Diagnostic Technology; Grand Challenges

1. Introduction

The global economy is besieged by environmental, health, political, and social *Grand Challenges* (GCs), which represent pressing *crises* that, if tackled, would help solve an important societal problem with a high degree of global impact through widespread implementation (George et al., 2016); and the extent to which firms create and capture value from innovation remains an enduring matter (Teece, 2018). The development of new technologies is deemed to meet emerging challenges, allowing firms to remain competitive in an increasingly turbulent and competitive environment. The word "crisis" is composed of two characters—one representing opportunity, the other danger. On the one hand, the commercialization of new technologies during a crisis enables firms to adapt to changing market conditions, streamline production, and increase efficiency (Brem et al., 2020). As such, the survival of firms in light of a crisis is based to a large extent on the successful commercialization of technologies (Gibson and Naquin, 2011). On the other hand, developing new technologies in response to crises such as economic turmoil, pandemics, and natural disasters might have negative consequences such as delayed product sales, supply chain and commercialization disruptions, and decreased profit (Lichtenthaler, 2021). A commonly adopted strategy for capturing high value from innovation is commercializing technologies as it permits firms to move a technology or innovative concept from the laboratories to global market acceptance and use (Chen et al., 2011). In the context of GCs, the technology commercialization process is becoming critical as it determines to a large extent failure or success of new products and services offering. In this paper, we rely on the PFI Pframework as to identify the success and failing factors of technology commercialization in the context of GCs, particualrlly Covid-19 pandemic.

In December 2019, humans witnessed a grand challenge in the form of a societal crisis (pandemic) that dramatically changed all aspects of social life. The Covid-19 virus, like its families, Ebola, SARS, and MERS, threatened human life and health with the highest rate of widespread and death (Tang et al., 2020, Parihar et al., 2020, Fabiani et al., 2021, Shen et al., 2021, Montiel et al., 2022, Park et al., 2022). About 4.6 million people have died, and 224 million infected[1]. The virus affects more than 60% of economic activity[2], and psychologists and sociologists are still studying the effects of lockdown on social life (Mucci et al., 2020, Zheng et al., 2020, Prati and Mancini, 2021, Lugo-Marín et al., 2021).

Governments, international health organizations, and medical centres have tried to prevent or reduce the transmission of the virus by developing different strategies such as screening, testing, tracing, quarantining, isolating, and social distancing high-risk people (Park et al., 2022, Böger et al., 2021). To this end, they supported both academic and practical research to ease access to a variety of diagnostic technologies regarding capability and number (Alhalaili et al., 2020, Hui et al., 2020). For example, European Research Council allocated 48.5 million Euro to 14 research projects[3]. Also, extensive academic research has been carried out to develop Covid-19 diagnostic technologies (about 221,000 articles were indexed in PubMed, Scopus, and Google Scholar databases). Initially, researchers focused on molecular diagnostic methods and antibodies (Bhalla et al., 2020), and later developed Electrochemical, Optical, Piezoelectric methods (Afzal, 2020, La Marca et al., 2020, Narita et al., 2021, Fabiani et al., 2021), and RNA (Ribonucleic acid), and Information and Communications Technology (ICT) areas (Thompson and Lei, 2020, Lukas et al., 2020, Kontou et al., 2020). Significant research costs, herd immunity failures (Randolph and Barreiro, 2020, Yazdanpanah et al., 2020), and mutations in the virus have emerged as the main Tech Commercialization challenges of Covid-19 diagnostic technologies (Thunstrom et al., 2020). In addition, The Covid-19 pandemic, which follows the Ebola, SARS, and MERS, warns us that it may not be the last pandemic. Indeed, governments, international health organizations, research and medical centres need to learn how to diagnostic technologies for dealing with a similar pandemic in future.

In light of the above, the paper reviews the literature that deals with the commercialization challenges of new technologies during the COVID-19 pandemic as we raise the following questions:

What are the technology commercialization challenges of COVID-19 diagnostic technologies?

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[1] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports
[2] Global Economic Effects of COVID-19: https://sgp.fas.org/crs/row/R46270.pdf
[3] European Research Area Corona Platform: https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/ec_rtd_cv-projects.pdf

To answer this question, we review the literature that deals with how the Covid-19 pandemic has challenged the commercialization of diagnostic technologies. In so doing, we used PFI, introduced by Teece (1986). Tecce (1986, 2006, 2018) introduces the non-profiting of research achievements and technology development in the absence of complementary assets. Due to the ill-positioned in the market, Technology Commercialization (TC) of innovation activities with novel products, processes, or services may be failed even if they provide high value to end users. Although researchers like Colombo et al. (2006), Hallberg and Brattström (2019), Swink and Nair (2007) introduced frameworks for evaluating the success of TC, the TC challenges of Covid-19 diagnostic technologies have been studied upon PFI framework because of i) PFI has been used widely for studying innovation failure in various industries (e.g., Computer, Telecommunications, Nano-electronics, Biosensor industries, see Rothaermel and Hill (2005), Salazar-Elena et al. (2020), Lin and Wang (2005), Boudreau et al. (2022), Yaghmaie et al. (2020), Gambardella et al. (2021), Wang et al. (2022), Nasirov et al. (2022), Helfat and Raubitschek (2018), Petricevic and Teece (2019), Hallberg and Brattström (2019), Capponi et al. (2019), Pitelis et al. (2018)); ii) *Research Policy Journal* published two special issues about the theoretical foundations and applications of PFI framework to study TC challenges in 2006 and 2018; iii) PFI is a holistic framework that shed light on the different components of successful TC requirements like *appropriately regime*, *dominant design*, and *complementary assets*. Indeed, PFI helps to analyze internal and external requirements of TC for a firm like Intellectual Property Rights (IPR) and regime and competitors.

This paper uses a Systematic Literature Review (SLR) approach to identify the TC challenges of Covid-19 diagnostic technologies. Chauhan et al. (2022) and Khan et al. (2021) proposed an SLR approach within three main phases including preparation, selection, and assimilation. The relevant publications will be reviewed to provide a sketch of present developments and logic behind the experienced of TC challenges of Covid-19 diagnostic technologies. Furthermore, in the assimilation phase, deductive and inductive content analysis will be used as an effective method for synthesizing qualitative data (Seuring et al., 2005). First, the deductive approach will be conducted regarding the factors of the PFI framework i.e., *complementary assets*, *complementary technology*, *completive manufacturing*, *supply chain*, *service*, *appropriability regimes*, *financing source*, and *networking*. Second, the inductive approach was used to explore other factors of TC success by analyzing and coding the selected articles independently (Miles and Huberman, 1994). The lessons learned from the TC of Covid-19 diagnostic technologies shed light on future research facing pandemics.

This article offers several contributions to different literature streams. Firstly, it provides insights for research on innovation management, specifically PFI (Pisano, 2006), by providing a conceptual basis for the challenging and success conditions in the commercialization of new technologies during GCs. In so doing, we conduct, organize and synthesizes a systematic review on the success and failing factors in the commercialization of technologies during Covid-19 pandemic. We take the bulk of knowledge relying on the PFI framework and recognize its dominant themes and provide a comprehensive understanding of the relevance of the framework to explain innovation in crises. Secondly, we advance the PFI framework by stressing that the framework does not explain and justify all failure and success factors of the TC during the pandemic, and further stress the need to extend the framework by adding some factors that adapt to specific contexts (e.g. pandemic and medical technologies). We draw on PFI from technology push and market pull perspectives to discuss TC challenges of new technologies in case of Covid 19. The review highlights that there are other challenges that were not addressed in the PFI framework. While PFI frames critical strategic decisions and considers the business environment- proposing new issues such as the appropriability regime and business models (Teece, 2018), it somehow underscores the strategic decisions about choosing, integrating, and moving between technology push and market pull perspectives. Thirdly, in applying the PFI framework, the review contributes to research into crisis management (Kim, 1998, Tanda, 2018) and uncover the success and failure factors within the stage of technology commercialization during crises. We extend research by scrutinizing the most important stage for value creation for firms and to mitigate the risk of crises. In our study, we stress that technology commercialization is a vital stage in business value creation and also in Covid-19 mitigation, through which a slow or delayed commercialization leads to high level of virus spread and death tolls. This implies that identifying and exploring the main stage in a crisis is critical for the effective management and mitigation of such crisis.

2. Background

2.1 Technology Commercialization

Morricone et al. (2017) and Nieto Cubero et al. (2021) studied TC as a group of activities to capture value from an innovation that transformed R&D into a profit-making position in the market. Firms are faced different challenges in TC (O'Connor et al., 2008), like resource allocation, uncertainty, and market structure (Battaglia et al., 2021b, D'Este et al., 2012, Si and Chen, 2020). Some scholars (Chiesa and Frattini, 2011, Rhaiem and Amara, 2021, Cenamor and Frishammar, 2021, Illiashenko et al., 2021) emphasized that TC is known as one of the most critical firms' strategic decisions. A successful TC process requires an understanding of market demand, customers' willingness, and market structure (Shang et al., 2021, Christensen et al., 2018). Regarding the *innovation process* perspective, scholars like (Aarikka-Stenroos and Lehtimäki, 2014, O'Connor et al., 2008, D'Este et al., 2012, Pekovic and Bouziri, 2021) indicated TC as a stage after ideation, technical development, and technology validation phases. They introduced market analysis as a significant step in TC for increasing fitness and sustained competitive advantage (Anokhin et al., 2011, Chiesa and Frattini, 2011). Kaal and Vermeulen (2017), Butenko and Larouche (2015) emphasized that effective TC activities have to change the market structure by focusing on the "newness" of products, services, processes, and business models. Nieto Cubero et al. (2021)

studied how the forward innovation process moved to a circular process in which TC affect even the early phases of innovation, described by exploration, learning and ecosystem creation activities.

This study reviews the TC challenges of Covid-19 diagnostic technologies based on the PFI framework. Teece (1986) present PFI, to address the success of TC at the firm level in terms of the dependence between innovation and *appropriability regime*, *dominant design*, and *complementary assets*. In his framework, the firm's ability to capture the profits generated by an innovation does not depend much on its market share. While other efforts play a key role in profiting including the structure and ownership of the complementary assets, the manager's decision about when to enter the market and the regimes of appropriability in the form of the nature of knowledge (tacit or codified), and the legal mechanism of protection (patents, copyrights, trade secrets, trademarks). Later, Teece (2006) addressed the issue of how to capture value from innovation in an effort by reviewing the analytical foundations of the theory, refining and extending the PFI framework presented in 1986. Teece (2006) argued that PFI falsifiable theory (not just a framework) can predict profit based on the appropriability regime, market timing, and asset ownership. Teece's framework sheds light on dominant design and technology complementary that ring the bells of firms' success. Teece (2018) tried to show the application of PFI in the face of enabling technologies in the digital economy which requires understanding the dynamics of platforms and ecosystems. PFI is a relatively narrow framework, but neither as narrow as ecosystem or industry-level perspectives nor as wide as most neoclassical economics exercises. He opened the aperture a notch that show different forms of complementary assets in such platforms and their different impact on value capturing. The differences are rooted in coordination and market design challenges can be emerged by complementors. In this environment, innovators must have designed a workable business model to overcome the bargaining power of complementors and interact with regulators, especially the incentives for free-riding by potential licensees are considerable. In fact, it is difficult for innovating firms to design a business model to capture more than a profit from R&D efforts and investment in incomplete markets and weak intellectual property. This study will review the PFI components including *Networking, Supply Chain, Competitive Manufacturing, Services, Appropriability regimes, Complementary Technology* to coins out the TC challenges of Covid-19 diagnostic technologies.

2.2 TC of medical technologies

Due to the differences between the nature of the medical and other technologies, scholars have developed different frameworks to describe the obligate activities of TC for medical technologies like the *stage-gate process* (Cooper, 1996, Soenksen and Yazdi, 2017, Pietzsch et al., 2009), the *MedTech Development Process* and *MedTech Innovation* (Durfee and Iaizzo, 2019, Durfee and Iaizzo, 2016), the *early-stage health* frameworks such as Early health technology assessment (EHTA) (IJzerman et al., 2017, Wang et al., 2021a, Smith et al., 2019), the *e-health commercialization process* (Gbadegeshin, 2019, Cho et al., 2008) and the *technology readiness level* based models

(Ates et al., 2021, Basu and Ghosh, 2017). MedTech Development Process models emphasise multiple regulatory controls for TC by including pre-clinical and clinical tests as essential steps (Durfee and Iaizzo, 2016, Durfee and Iaizzo, 2019). EHTA frameworks focus on stakeholders' needs and expectations (e.g. patients, physicians, industry, and policymakers) (Smith et al., 2019, Wang et al., 2021a). Digitalization and its impact (including data gathering, storage, analysis and dissemination) (Gbadegeshin, 2019), risk assessment, technological evolution, and flexibility (Ates et al., 2021) were accomplished in e-health commercialization process and technology readiness level-based models.

TC frameworks in medical technologies have both technical and medical aspects. Reviewing the TC models for medical technologies represent that i) pre-clinical (Bench testing and animal testing) and clinical testing (human testing) are unique stages in their process (Songkajorn and Thawesaengskulthai, 2014, Durfee and Iaizzo, 2019, Gbadegeshin, 2019, Smith et al., 2019, Marešová et al., 2020, Eaves and Clem, 2021); ii) the target market for medical technologies is dedicated and restricted-regulated. For example, in Europe all the medical technologies need to be approved and affix a CE mark[1]; iii) rather than technical specialists, a wide range of medical professionals play critical roles in TC of medical technologies. Although these models provide helpful process insights into the sequence of medical technology innovation activities, they still do not provide an answer to why some innovations have failed for TC of medical device. Therefore, examining this process from PFI is necessary. On the other side, this paper aims to find to what capacity the PFI framework could be used for explaining these features of the medical technologies for successful TC. To the best of our knowledge, this paper for the first time studies the TC challenges of Covid-19 diagnostic technologies based on the PFI framework.

In addition to evaluating the success of TC for medical technologies based on the PFI model, this paper seeks to consider the unique characteristics of the pandemics like issuing emergency licenses to ease the regulations and massive demand during a period of a pandemic. Table 1 summarizes Covid-19 diagnostic techniques including molecular tests (e.g., genetic-based tests or nucleic acid tests), antigen tests, antibodies tests and computer tomography (digital radiographically screening) (Abdelhamid and Badr, 2021, Bhalla et al., 2020, Fabiani et al., 2021). Due to the rapid spread of the virus and the short time to deal with it, the TC processes for these diagnostic technologies are different even from other medical technologies. This study is keen to provide managerial implications and evaluate TC challenges of Covid-19 diagnostic technologies based on the unique characteristics of the GCs, like Covid-19 pandemic.

Table 1. Covid-19 Diagnostic technologies

Covid-19 Diagnostic technique		Products	Reference
Molecular tests	Real-time quantitative reverse transcription-polymerase chain reaction (RT-qPCR), isothermal amplification (e.g., Loop-	Saliva Direct, CRL Rapid Response, Pro-AmpRTSARS-	(Wang et al., 2020a, Shen et al., 2021)

[1] https://www.medtecheurope.org/new-medical-technology-regulations/

Covid-19 Diagnostic technique		Products	Reference
	mediated isothermal amplification (LAMP), nucleic acid sequence-based amplification (NASBA), transcription-mediated amplification (TMA), rolling circle amplification (RCA) and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)	CoV-2 Test and iAMP COVID-19 Detection Kit	
Antigen tests	viral proteins analysis (e.g., colorimetric, field-effect transistor (FET), enzyme-linked immunosorbent assay (ELISA) and mass spectrometry (MS)	antigen kits such as STRONGSTEP, BIOCREDIT and MOLAB	(Abdelhamid and Badr, 2021)(Fabiani et al., 2021)
Antibodies tests	ELISA, electrical (EC) biosensors, localized surface plasmon resonance (LSPR) and surface-enhanced Raman scattering (SERS), the antibodies (Immunoglobulin M (IgM) and Immunoglobulin G (IgG))	Diazyme DZ-LiteSARS-CoV-2 IgMCLIAKit, CareStartCOVID-19IgM/ IgG and Orawell IgM/IgG Rapid Test	(Abdelhamid and Badr, 2021, Santiago, 2020, Chong et al., 2021, Shen et al., 2021)
Computer tomography	Three-dimensional (3D) images with contrast by of the X-rays (e.g. Chest CT scan)		Bhalla et al., 2020

2.3 Covid-19 as a Grand Challenge

The Grand Challenges refer to a significant barrier that, if successfully overcome, would resolve a pressing social issue with a high potential for global impact via broad-scale implementation (George et al., 2016). We provide four reasons why Covid-19 can be described as a grand challenge. Firstly, Covid-19 represents a societal crisis that has a global and multifaceted impact. The pandemic has affected nearly every country worldwide, with over 190 million confirmed cases and over 4 million deaths reported as of July 2021[1]. The rapid spread of Covid 19 across borders and continents highlights the interconnectedness of our world and the need for global cooperation in addressing the pandemic. Also, the pandemic has exposed the vulnerabilities of our healthcare systems, supply chains, and governance structures, requiring coordinated efforts to mitigate the impact of the pandemic (Campos-Ferreira et al., 2021, Benda et al., 2021, Montiel et al., 2022, Park et al., 2022, Böger et al., 2021).

Secondly, Covid-19 is a multifaceted challenge. The pandemic has affected various aspects of daily life, including healthcare systems, economies, social interactions, and mental health. The pandemic has strained healthcare systems, with shortages of medical supplies and personnel leading to increased mortality rates (Azmi et al., 2021). The pandemic has also caused significant economic disruptions, with many businesses forced to close due to lockdowns and social distancing measures (Du et al., 2023). Furthermore, the pandemic has increased social isolation and mental health challenges, particularly among vulnerable populations such as the elderly and those with pre-existing mental health conditions(Pierce et al., 2020). Thirdly, Covid-19 requires collaboration across various fields. Addressing the pandemic requires expertise from multiple disciplines, including medicine, public health, economics, and technology (Parupudi et al., 2020, Wang et al., 2021b). Medical professionals have played a critical role in treating patients and developing vaccines and treatments for Covid-19. Public health experts have guided social distancing measures and vaccination campaigns. Economists have analyzed the impact of the

[1] https://www.who.int/publications/m/item/weekly-epidemiological-update-on-covid-19---20-july-2021

pandemic on global markets and proposed policies to mitigate economic disruptions (for instance: Padhan and Prabheesh (2021), Barua (2021)). Finally, technology has played a critical role in facilitating remote work, learning, and enabling contact tracing and device distribution.

Finally, Covid-19 has highlighted existing inequalities and disparities (Chowkwanyun and Reed, 2020). The pandemic has disproportionately affected marginalized communities, including low-income households, racial and ethnic minorities, and those with pre-existing health conditions (Misa et al., 2021). These disparities have been exacerbated by existing inequalities in healthcare access and outcomes, with marginalized communities experiencing higher infection and mortality rates. Addressing these disparities requires targeted interventions that address the root causes of inequality, including poverty, discrimination, and lack of access to healthcare services. In summary, Covid-19 can be described as a grand challenge due to its global impact, multifaceted nature, need for collaboration across various fields, and highlighting of existing inequalities and disparities. According to George et al. (2016), this Explanation helps to understand how PFI can be used to solve GCs, and how GCs impact firms' commercialization and PFI. In the first line, we examine PFI to explain the failures in commercializing Covid-19 detection technologies. While the framework provides a helpful explanation of network effects, it may need to fully account for the rapid network formation and impact changes due to the short timeline from research and development to commercialization for Covid-19 technologies. Social priorities and public health concerns may also challenge the framework's purpose in describing the supply chain to create specialized assets for a firm. In the second line, we investigate the explanatory power of this framework in light of the increased demand for Covid -19 detection technologies and government investment. We question how effective institutional changes are in commercializing these technologies with the emergence of new players as market innovators. This line of inquiry may highlight the role of multiple stakeholders in commercialization (Leonidou et al., 2020) and regulation economics theories (Stigler, 1974, Becker, 1985).

3. Methodology

This survey uses a Systematic Literature Review approach to identify the TC challenges of Covid-19 diagnostic technologies. A SLR approach by evaluating the state of the literature upon the research objective (Siddaway et al., 2019, Burgers et al., 2019), seeks to identify relevant primary papers, extract the required data, analyze and synthesize the results to provide a broader insight into a field of research (van Dinter et al., 2021, Kraus et al., 2020). This paper uses the SLR approach proposed by Chauhan et al. (2022) and Khan et al. (2021) in three main phases including *preparation*, *selection*, and *assimilation* as shown in Figure 1.

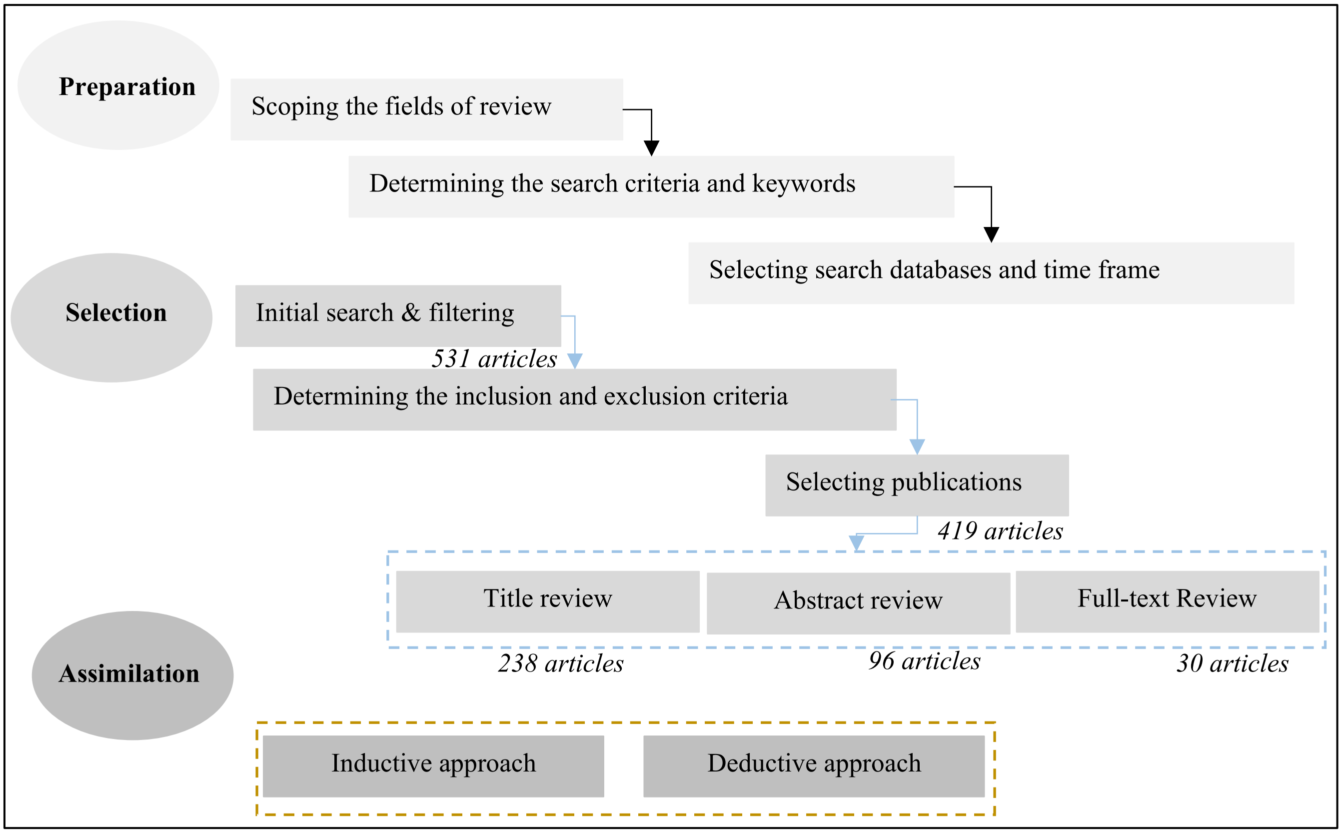

Figure 1. SLR methodology partially adapted from Chauhan et al. (2022) and Khan et al. (2021)

3.1 Preparation

The preparation phase consists of two important steps i.e. scoping the review fields and determining the search criteria and databases (Khan et al., 2021). This survey aims to explore the factors that impact the success of TC for COVID-19 diagnostic technologies. As shown in Figure 2, this review survey TC of COVID-19 diagnostic technologies filed according to the TC frameworks, particularly PFI. Starting with the PFI framework in COVID-19 diagnostic technologies, we analyze the effect of PFI's factors on the success of innovation and R&D activities for developing COVID-19 diagnostic technologies. Also, other TC factors (rather than PFI's factor) would be reviewed to explore the holistic TC framework for pandemic diagnostic technologies.

According to the scope of this review, first trial and error with different keywords were carried out to select the final keywords including "*commercialization*" and "*medical device*" and "*diagnostic*" and "*COVID*" and "(*profiting from innovation* or *complementary assets* or *complementary technology* or *completive manufacturing* or *distribution* or *service* or *appropriability regimes* or *financing source* or *networking*)". Considering the relevance of the research area to medical and management sciences, we searched for relevant publications in online databases including web of science, Scopus, PubMed, and PubMed Central and found 9241 sources. Since the COVID-19 pandemic started in 2019, the returned result was filtered from 2019 to February 2022.

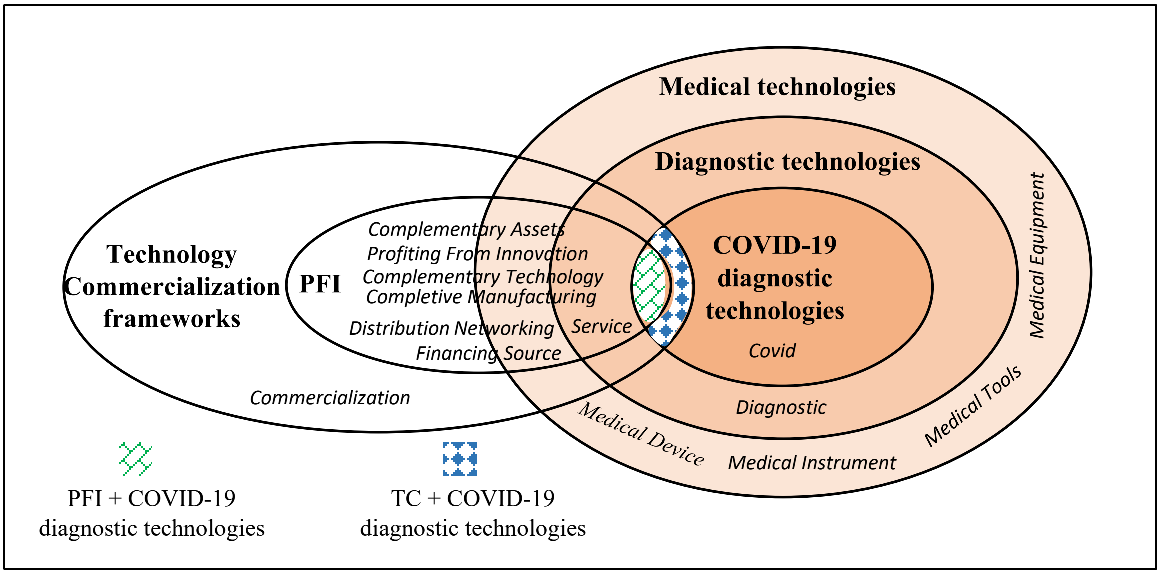

Figure 2. The proposed classification scheme and scope of the analysis

3.2 Selection

This phase involves selecting the appropriate articles for analysis in three steps i) initial database search; ii) determining the inclusion and exclusion criteria; iii) selecting the relevant articles. After filtering the document type to journal articles in the English language and discarding duplicate articles, 531 articles were selected. In this step, the inclusion and exclusion criteria were defined to select relevant studies. Inclusion criteria were defined as follows a) Challenges of TC for COVID-19 diagnostic technologies; b) complementary assets for commercialization of COVID-19 diagnostic technologies; c) the development of new COVID-19 diagnostic technologies during the pandemic. On the other side, two exclusion criteria were defined to exclude irrelevant articles i) Cite Score less than 1.0 (according to the web of science to ensure the quality of the articles); ii) articles that were only focused on the technical aspects of COVID-19 diagnostic technologies (see (Rai et al., 2021)). To select the final articles according to inclusion and exclusion criteria, the screening process was performed in 3 stages: reviewing the title, reviewing the abstract, and reviewing the full text of the articles. Consequently, 29 articles were selected to explore the main challenges and success factors of TC of COVID-19 diagnostic technologies.

3.3 Assimilation

The last step involves extracting, analyzing and synthesizing data and reporting the findings (Xiao and Watson, 2019). The components of the PFI framework have been underpinned to provide major insights into the TC challenges of Covid-19 diagnosis technologies. Deductive and inductive content analysis are used as effective methods for synthesizing qualitative data (Krippendorff, 2004, Seuring et al., 2005). The data extraction process generally involves coding based on a deductive or inductive approach (Suri and Clarke, 2009) First deductive approach is conducted regarding the components of the PFI framework. Second, the inductive approach is used to explore other factors of TC success. To this end, the authors independently analyzed and coded the selected articles and followed an iterative approach, moved backwards and forward between the data and the emerging conceptions and simultaneously compared the codes (Miles and Huberman, 1994). When there was a difference of opinion, we discussed the reasons and followed the discussion until a consensus was achieved (Siddaway et al., 2019)

4. Research profiling

For a profile of the selected articles, we have tallied the publications' output over time, journals, geographical location of the Authors' affiliations, research methods, and research objective and findings. Profiling the researches represent the current status of the TC challenges of COVID-19 diagnosis technologies. Figure 3 represents the number of articles by publication years. Raising the number of articles on medical technologies and diagnostic technologies over time reflects the importance and challenges of TC in this area. However, only 29 articles focused on TC challenges of COVID-19 diagnosis technologies. The small number of articles in this still shows that significant efforts are still needed to develop new technologies and that not much attention has been paid to why commercialization has failed[1].

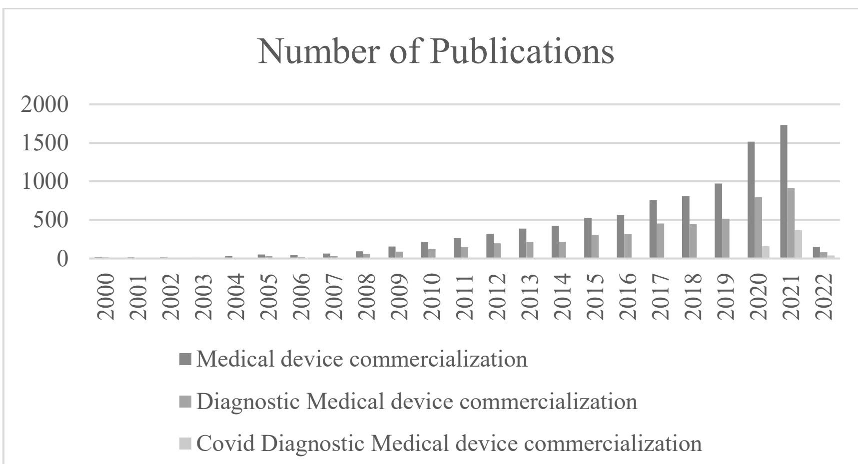

Figure 3. Distribution of articles by publication year

The selected articles were published in 21 different journals (see Table 2). As shown in Figure 4, most of the articles were published by journals in the field of Medical (39%) and Sciences (23%). Only 7% of the article were published in Management journals. According to the scope of the journals (Figure 5), Medicine (16%) and Immunology and Microbiology (11%) have the highest publications while business, management, and accounting only have 7%. Thus, more attention needs to be paid based on the management science perspectives to explore

[1] World Health Organization (WHO) also confirmed the needs for developing ore research in this field. https://cdn.who.int/media/docs/default-source/documents/r-d-blueprint-meetings/r-d-achievements-report_v42.pdf?sfvrsn=c4728b39_5&download=true

and analyse the TC challenges for diagnostic technologies of pandemics. *Nature Reviews Microbiology* has the highest impact factor (IF=78.3 in 2021). With 3 articles the *ACS Sensors* and *Sensors* are at the top of contributing journals. This supports the premise that COVID-19 diagnostic technologies need the development of sensors and equipment research. The second place is for *ACS Nano*, *Analytical and Bioanalytical Chemistry*, *Diagnostics*, and *Micromachines* journals with two articles. We also show the selected articles as a proportion of the journal's total publications to represent the importance of the TC for COVID-19 diagnostic technologies rather than other topics in each journal. Results show the journals Trends in Analytical Chemistry and Biosensors with a ratio of 0.05 ranking top and followed by Diagnostics and ACS Sensors (A ratio of 0.04). This information relating to the scope of review reflects the focuses and interests of journals and also guild researchers to choose a journal for their submission.

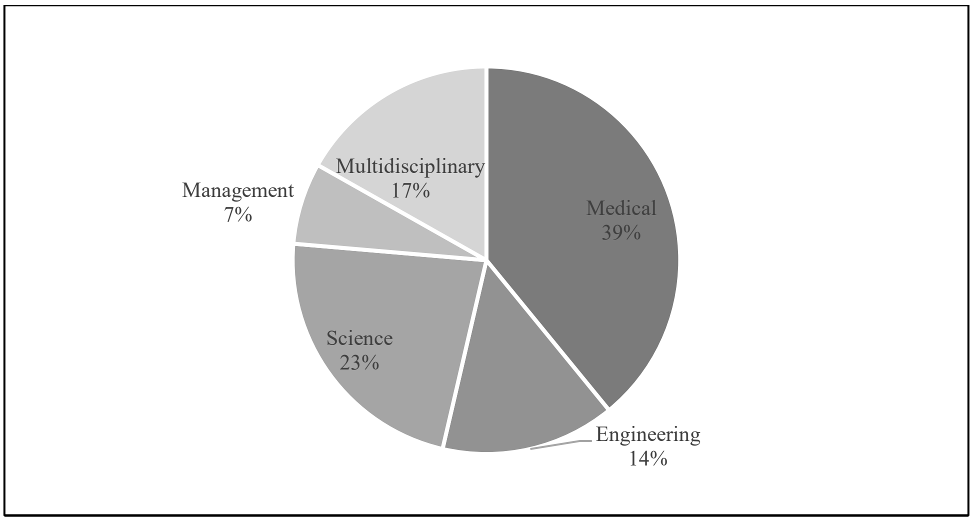

Figure 4. Journals' field

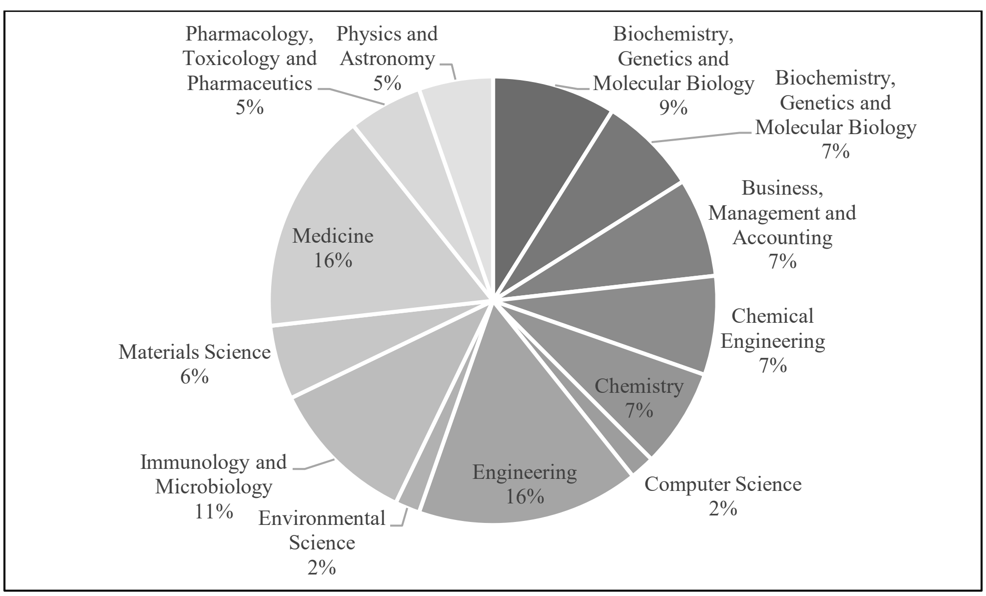

Figure 5. Journals' scope

Table 2. Distribution of articles by contributing journals

Journal	Indexed Year	Journal's IF	Cite Score 2022	Number of articles in 2021 and 2022	Number of relevant articles to COVID-19	Reviewed articles
Nature Reviews Microbiology	2003	60.63	42.2	345	4	Vandenberg et al. (2021)
ACS Nano	2007	15.88	20.3	3373	39	Bhalla et al. (2020), (Lukas et al., 2020)
Trends in Analytical Chemistry	1981	12.296	20.2	583	33	Ozer and Henry (2021)
Journal of Advanced Research	2010	10.479	15.2	341	4	Afzal (2020)
Journal of Controlled Release	1984	9.776	13.2	1177	16	Kamat et al. (2021)
ACS Sensors	2016	7.711	11.7	949	45	Hosseini et al. (2020) Leichle et al. (2020) Mattioli et al. (2020)
Eurosurveillance	2001	6.307	24.3	555	11	Carroll and McNamara (2021)
ACS Applied Nano Materials	2018	5.97	6.6	2708	10	Wu et al. (2020)
Biosensors	2011	5.519	4.3	739	41	Fabiani et al. (2021)
Frontiers in cellular and infection microbiology	2011	5.293	4.9	2268	35	Azmi et al. (2021)
Applied Microbiology and Biotechnology	1984	4.813	7.3	1481	16	Gupta et al. (2021)
R&D Management	1970	4.272	6.9	91	1	Battaglia et al. (2021a)
Analytical and Bioanalytical Chemistry	1996	4.142	5.8	1662	11	Giri et al. (2021) Rasmi et al. (2021)
Biochemical Engineering Journal	1998	3.978	5.6	609	1	Campos-Ferreira et al. (2021)
Frontiers in Medicine	2014	3.9	2.6	3866	99	Liang et al. (2021)
Diagnostics	2011	3.706	2.7	3513	175	Rezaei et al. (2020) Yu et al. (2021)
Sensors	2001	3.576	5.2	16011	124	Benda et al. (2021) Ibrahim et al. (2021) Wang et al. (2021b)
ACS Applied Bio Materials	2018	3.25	5.4	1675	12	Parihar et al. (2020)
Micromachines	2010	2.891	3.9	2719	24	Escobar et al. (2021) Shaffaf et al. (2021)
Biotechniques	1984	1.993	3.1	234	5	Parupudi et al. (2020)
Acta Virologica	1957	1.162	1.6	108	1	Priyanka et al. (2020)

We analyse the authors' contributions according to the number of authors, location, and disciplines. Azmi et al. (2021), Fabiani et al. (2021), and Gupta et al. (2021) with 13, 12, and 9 authors rank first, while (Afzal, 2020) published one author. On average, the number of authors was about 5 in each reviewed article which represents the importance of group working in this field. Figure 6 shows the distribution of articles by author countries. The researchers from India (33), the United States (23), Italy (15) and Canada (15) have the highest contribution.

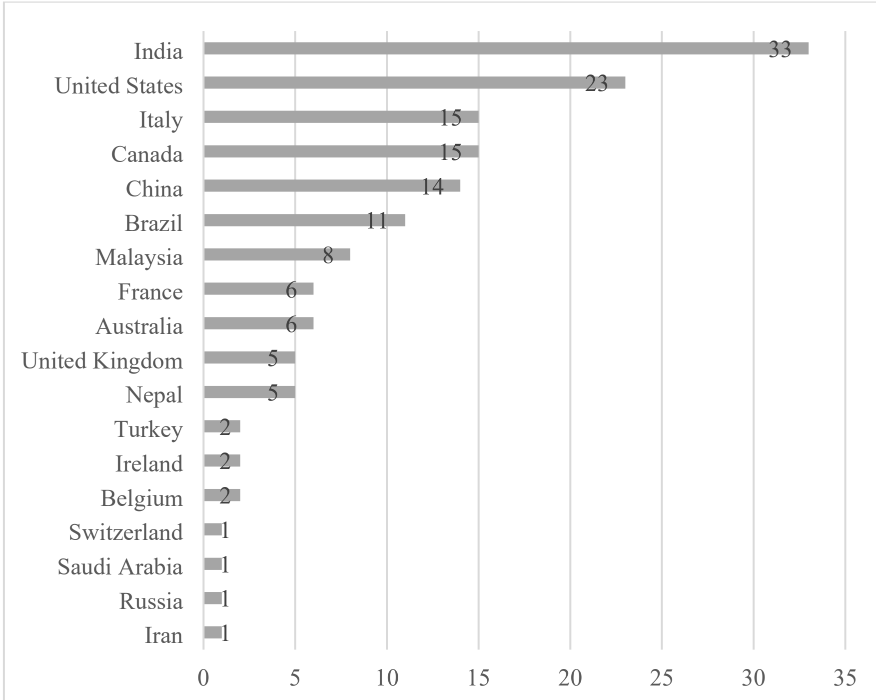

Figure 6. Geographical affiliations of the Authors

We classified research methods articles into three general categories including case study, survey and multi-case study strategy (Denzen and Lincoln, 2005). The first category is case studies that have attempted to present the benefits and TC challenges of the COVID-19 diagnostic technologies. For example, Battaglia et al. (2021a) have tried to explain how to commercialize COVID-19 diagnostic technologies by creating academic spinoffs. Escobar et al. (2021) also show how effective and viable on-site microfluidic diagnostic platforms are developed for several notable pathogens, including SARS-CoV-2. The second category has selected the survey strategy. Scholars have tried to measure the sensitivity and specificity of COVID-19 diagnostic technologies by collecting and analyzing the primary data such as Biosensors and Nanoscale Analytical Tools (Bhalla et al., 2020), Telemedicine Tools (Lukas et al., 2020), Magnetic-Nanosensor-Based Virus and Pathogen Detection (Wu et al., 2020), CASSPIT (Cas13 Assisted Saliva-based & Smartphone Integrated Testing) (Azmi et al., 2021), electrochemical biosensing platforms (Campos-Ferreira et al., 2021), Diagnosis of Based on Graph Convolutional Network (Liang et al., 2021), the crucial role of diagnostic tests during the first global wave of COVID-19 (Vandenberg et al., 2021), and real-time-PCR assays (Carroll and McNamara, 2021).

Finally, the third category of articles has tried to show the advantages, features and applications of various diagnostic methods by comparing diagnostic methods based on a multi-case study strategy. For example, Yu et al. (2021) summarize and compare the principles, technologies, protocols and performance characteristics of amplification- and sequencing-based tests that have become alternatives to the CDC 2019-nCoV Real-Time RT-PCR Diagnostic Panel. Parupudi et al. (2020) show that Mobile platforms are effective for remote and small-scale deployment. Whereas facility-based platforms in hospital and laboratory settings offer higher throughput by reviewing the role of evidence-based point-of-care technologies. Gupta et al. (2021) have extensively reviewed the present CRISPR-based approaches, challenges, and prospects in the light of diagnostics and therapeutics against SARS-CoV-2. Shaffaf et al. (2021) suggested an overview of the complementary metal-oxide-semiconductor (CMOS) biosensors, which are potentially useful for implementing Point-of-Care (PoC) platforms based on such assays. The reviewed articles present a new method or compare new diagnostic equipment, methods, and strategies. Furthermore, showing the advantages of new methods, they have tried to address the challenges of TC. However, only nine articles (Afzal, 2020, Battaglia et al., 2021a, Bhalla et al., 2020, Campos-Ferreira et al., 2021, Mattioli et al., 2020, Parihar et al., 2020, Priyanka et al., 2020, Rasmi et al., 2021, Vandenberg et al., 2021) have explicitly focused on TC challenges of Covid-19 diagnostic technologies. Table 1 in Appendix I summarizes the research objectives and findings of the Covid-19 diagnostic technologies.

5. Thematic foci

The contents of the publications were assimilated through deductive and inductive approaches to provide crucial insights into the TC challenges of Covid-19 diagnostic technologies. Six components of PFI have been used to conduct the deductive approach. Also, the inductive approach was performed to explore other factors of TC success by analyzing and coding the publications independently (Miles and Huberman, 1994). The hybrid process helps to extract the factors that have an impact on TC challenges of Covid-19 diagnostic technologies. Through the hybrid approach we can find the answer to the main research question i.e., "what are the technology commercialization challenges of COVID-19 diagnostic technologies?" and indicate what doesn't PFI explain.

5.1. Deductive Thematic Analyzing

Hsieh and Shannon (2005) recommended the deductive approach when a solid theory or framework is attainable to select and define the categories clearly. This study conducted the deductive approach according to six components of the PFI framework introduced by Teece's (1986, 2006, 2018).

5.1.1. Networking

Teece (1986, 2006, 2018) indicated the importance of networking in successful innovation in terms of dynamic networks and network effects. Dynamic networks characterized by vertical disintegration and contracting may not reflect innovative organizational forms initially, the firms' capacity reduction, time urgency, and complicated innovation activities have become a typical form of companies today (Teece, 1986). Network effects create a lock-in market and dependent activities that consolidate the standards, and dominant design, and increase return on investment effectively (Teece, 2006, Teece, 2018). Afzal (2020) confirmed that TC of COVID-19 diagnostic technologies needs vast organizations' efforts to collect diagnostic tests and samples from both medical manufacturers and hospitals. Indeed, strengthening networking between them ensures the needs of physicians and hospital systems to face COVID-19 (Parupudi et al., 2020, Wang et al., 2021b). Campos-Ferreira et al. (2021) show that collaborative data support between academia and industry is necessary for the rapid development of diagnostic technologies, mainly by emerging new variants of SARS-CoV-2. In addition, they needed significant resources and volunteers to conduct large-scale clinical trials (Benda et al., 2021). Complicated R&D activities, needs for specific instruments, and huge procedures for molecular analysis led to forming the formal and informal networks. The formal network includes multidisciplinary researchers i.e., physicians, engineers, and, immunologists (Leichle et al., 2020). Also, the informal networks for the data access (Vandenberg et al., 2021), government support (Kamat et al., 2021), and certifications (Battaglia et al., 2021a) are noteworthy.

Networking reflection: *While the PFI framework emphasizes the importance of networking for the success of commercialization, especially in the context of grand challenges, networking should be formed in the R&D stage. Also, the special conditions of Grand Challenges including variety of actors, intervention intensity of actors, and time pressure, indicate the need for more research for networking. Table 3 and 5 represents the needs of networking and relevant research questions for developing networking factor in Grand Challenges.*

5.1.2. Supply Chain

Teece (2006) presented two reasons why firms need to pay attention to the supply chain for TC a) specialization increased transaction costs if reliance was made externally; b) buying complementary assets enhances the appropriability situation for imitators to serve the market than the innovator itself (Teece, 1986). Hence, PFI implied that TC decisions should be made regarding transaction costs, capability, and asset pricing criteria. Montiel et al. (2022), Benda et al. (2021), Escobar et al. (2021), Shaffaf et al. (2021), and Vandenberg et al. (2021) emphasize the importance of supply chain challenges for TC of Covid-19 diagnostic technologies. Benda et al. (2021) believed that building a sustainable supply chain is essential to increase test size in low- and middle-income countries. Escobar et al. (2021) showed that while strong communication within the supply chain network on the upstream side reduces lead time, the efficient configuration on the downstream reduces transportation, warehouse and operational risk and cost. Also, high cooperation with suppliers could reduce packaging and distribution costs (Shaffaf et al., 2021). Vandenberg et al. (2021) confirmed that the supply chain responded to the challenges of logistics, supplying the materials and equipment, and distribution. Furthermore Battaglia et al. (2021a) show that partners and resources outside the firm's boundaries must be accessed to coordinate and speed-up the manufacturing, certification, and commercialization stages.

Supply Chain reflection: *While the PFI framework emphasizes the development of the supply chain based on the two factors including cost reduction and difficulty to imitation, in the conditions of grand challenges, other factors are more important such as the capacity of production units, production rate, geographical dispersion to reduce the time and cost of production and transportation, and access to resources. In addition, the agile or leagile strategy is more suitable than the lean strategy for the supply chain in grand challenges. Table 3 and 5 represents the needs of supply chain and relevant research questions for developing supply chain factor in Grand Challenges.*

5.1.3. Competitive Manufacturing

Competitive Manufacturing refers to critical operations capabilities in terms of cost, quality, delivery, flexibility, service, innovation, and environment (Sansone et al., 2017). The pandemic, short lead-time with a large volume, needs a mass-production line to meet a huge demand quickly (Vandenberg et al., 2021). Wang et al. (2021b) show that the lack of competitive manufacturing was the main TC challenge of "Plasmon meta-surfaces instant detection equipment" to respond to the large demand for Plasmon Chips urgently. Also, Bhalla et al. (2020), Mattioli et al. (2020), and Carroll and McNamara (2021) TC Covid 19 diagnostic technologies have been attributed to the manufacturing possibility of biosensors and advanced instruments, Geno-sensing devices, and infrastructure for high-throughput RNA extraction respectively.

Competitive Manufacturing reflection: *PFI framework emphasized on the importance of competitive manufacturing as a complementary asset for success of TC. In condition of the grand challenge, the Competitive Manufacturing is essential for the success of commercialization. In other words, TC success cannot be achieved without the cooperation of incumbents with advantages of competitive manufacturing. While the PFI framework emphasizes the importance of competitive manufacturing due to the increase in the difficulty of imitation, in Grand Challenges other limitations forces innovators to chase competitive manufacturing such as short production time, high production volume, high quality and acceptable service level. Table 3 and 5 represents the needs of Competitive Manufacturing and relevant research questions for developing Competitive Manufacturing factor in Grand Challenges.*

5.1.4. Services

The success of TC needs to know-how in question to be utilized in conjunction with other capabilities or assets. Services such as marketing and after-sales support are almost always needed and often obtained from complementary assets. The services it provides are likely to face competition, which will hold down the returns on the assets (Teece, 1986). Our thematic analysis showed that services are considered from four aspects: First, training of human resources (Technicians, Nurse, Doctors, Immunologists, and public health policymakers) directly active in sampling and analysis of results (Yu et al., 2021, Vandenberg et al., 2021). Second, large-size sampling requires the supply, distribution, and delivery of equipment and consumables (Shaffaf et al., 2021, Randolph and Barreiro, 2020). Third, the provision of calibration services is essential with the emergence of new strains (Priyanka et al., 2020, Parihar et al., 2020, Ozer and Henry, 2021) Finally, information technology services enable the collection, aggregation, and online analysis of information (Ozer and Henry, 2021, Mattioli et al., 2020, Lukas et al., 2020).

Service reflection: *In line with the PFI framework, the service is inevitable for the success of TC in Grand Challenges from two perspectives including the activities and sources of service. Innovators must be able to serve essential services such as after-sales services, maintenance scheduling, equipment and spare parts on time. In addition, they must be able to provide the necessary sources such as experts, facilities, transportation. Table 3 and 5 represents the needs of service and relevant research questions for developing service factor in Grand Challenges.*

5.1.5. Appropriability regimes

A regime of appropriability is related to environmental factors rather than the firm and market structure, that govern an innovator's ability to capture the profits created by innovation (Teece, 1986). The most critical dimensions of the regime are the nature of the technology and its efficacy. The legal protection mechanism is not limited to severe patent protection frameworks. It depends on the type of industry and the type of knowledge (Pisano, 2006, Hanel, 2006). For instance, Trade secrets are critical in industries where innovation is embedded in their process and products. Also, in cases where tacit knowledge is in the innovation process, the involved complex knowledge is self-enhancing appropriability and will be an incentive for further innovation. The PFI framework clarifies that the firm's intellectual property portfolio is dependent on its business strategy and that business strategy demands an appreciation of intellectual property issues (Teece, 2006). In other words, the absolute imperative for PFI is that unless the inventor/innovator pushes an improvement path and enjoys strong natural protection against imitation and/or has strong intellectual property protection, then potential future streams of income are at risk. Thus, the related appropriability regime is critical to forming possible profits (Teece, 2018). Leichle et al. (2020) show that trustworthy drivers for the importance of developing Method PCR and ELISA are the lack of a technological regime and a well-established market, which could be an excellent opportunity to turn this method into a gold standard in the market. This finding shows that establishing a gold standard is the best incentive for the innovator to benefit from the market structure. Battaglia et al. (2021a) also said that the reasons for the success of spinoff companies from research centres are the existence of a strict legal regime that protects their intellectual properties, such as patents. They believe that such companies cannot protect themselves against competitors and will quickly take market share from imitators. It is why some companies were not profited from diffusing their research achievements during the pandemic (Vandenberg et al., 2021).

Appropriability regimes reflection: *PFI explains that the appropriability regime is based on the structure of the market and how the protection of intellectual property rights has been evolved over years. However, in Grand Challenges, regimes are emerged from multiple stakeholders' current and future forces. Therefore, understanding of stakeholders in the present and future are necessary for appropriability regimes. Table 3 and 5 represents the needs of appropriability regimes and relevant research questions for developing appropriability regimes factor in Grand Challenges.*

5.1.6. Complementary Technology: Specialized, Co-specialized, and Enabling Technologies

PFI explains that complementary assets and technologies form firms' strategies going forward, sometimes positively and sometimes negatively (Teece, 2006). Teece (1986) categorized complementary assets in three lines i) Generic assets do not must be adopted to the innovation inquiry. ii) Specialized assets are those that have unilateral dependence on innovation. iii) Co-specialized assets are those for which there is a bilateral dependence. How to access these complementary assets is a prominent role that managers must play. They sometimes obtain complementary assets within internalized activities based on transaction costs and strategic effects, and sometimes they provide from beyond the firm boundaries. Teece (2018) showed that Enabling technologies are more considerable than General purpose technologies. Because in addition to being widely used in the industry and supporting to improve the firms' technological performance, they will change the game and cause widespread evolutions in the structure of competition. The reviewed articles considered all three categories of complementary technologies to convey the product to market and benefit from these innovations. For instance, Ibrahim et al. (2021), who have introduced Electrochemical DNA biosensors, due to features such as fast response time, user-friendliness, high specificity, and high sensitivity, as a piece of suitable diagnostic equipment for this purpose, have considered the access and development of two technology categories Nanoparticles-Based Biosensors and Nano-based Sensors as Co-specialized and enabling technologies respectively. Liang et al. (2021) also identify 3D convolutional neural network (3D-CNN) and Deep Learning as Co-specialized and enabling technologies essential for the commercialization of Chest computed tomography (CT) to Covid 19 diagnostic. Because the former will be developed in a complicated network of multi-knowledge collaborations with partners, the latter will be available to many suppliers despite outstanding applications. A considerable note is that the 17 studies (58%) (Azmi et al., 2021, Campos-Ferreira et al., 2021, Escobar et al., 2021, Fabiani et al., 2021, Giri et al., 2021, Gupta et al., 2021, Hosseini et al., 2020, Kamat et al., 2021, Lukas et al., 2020, Mattioli et al., 2020, Ozer and Henry, 2021, Parupudi et al., 2020, Priyanka et al., 2020, Rasmi et al., 2021, Rezaei et al., 2020, Shaffaf et al., 2021, Vandenberg et al., 2021) highlighted similar information technologies such as artificial intelligence, mobile applications, IoT, and machine learning for collection, storage, and analysis, so these articles refer to these as enabling technology.

Complementary Technology reflection: *Covid-19 has highlighted the importance of enabling technologies as an essential part of interdisciplinary solutions. However, for an innovative response to Grand Challenges, firms should expand their concept of complementary technological assets and create a complementary technological ecosystem around themselves to enhance the success of TC. Table 3 and 5 represents the needs of complementary Technology and relevant research questions for developing complementary Technology factor in Grand Challenges.*

The deductive analysis shows how companies can benefit from innovation with respect to the six components of the PFI framework. Each component of the PFI framework is analysed based on previous research, and a reflection is presented to demonstrate the impact of grand challenges on each of them. The experiences gained from the Covid-19 pandemic highlight the critical role of the notion of ***time*** in the successful (or unsuccessful) commercialization of innovation during GCs. The impact of time (*huge demand in a short period of time*) can be positive or negative for firms and research centres. GCs have a positive impact on those firms and research centres that are in a *profit-making position* regarding the six components of the PFI framework, and they create a ***window of opportunity***. Such firms can respond to market needs as quickly as possible by leveraging their capabilities. On the other hand, an *ill position* with respect to the six components increases the time spent in the innovation cycle. Windows of opportunity will be closed for this group of firms and research centres during grand challenges by competitors or changes in the market environment and demand side.

Teece (1986) introduced two crucial concepts for innovating firms: ill and profit-making positions. The author emphasized that only firms in a profit-making position, characterized by the optimal alignment of all six components of PFI, can successfully generate profits through innovation. It is imperative to clarify these terminologies in the context of addressing GCs, where opportunities exist for only a limited window of opportunity, and competitors (or imitators) are present. The critical question to address is which firms occupy a profit-making position during GCs. To shed light on this question, we present a reflection for each component of the PFI framework as a strategy to navigate GCs effectively. However, it is yet essential for researchers to dive deeper into assessing the proficiency levels of each component of PFI to confront GCs adequately. Furthermore, firms must be attentive to the transient market demands that arise during GCs. Experience has shown that making substantial investments to enhance capabilities may not always yield satisfactory returns for firms. Therefore, firms must seek ways to attain a profit-making position through strategic contracts, such as vertical and horizontal integrations, partnerships, and alliances. These collaborations enable them to leverage and share their available resources effectively. Results of the deductive approach have been summarized in Table 3.

Table 3. Deductive Thematic Analyzing based on the components of the PFI framework

Thematic foci		Illustrative coding
Networking		TC of COVID-19 diagnostic devices needs 1) various efforts to help collect diagnostic tests and samples from medical manufacturers and hospitals worldwide (Afzal, 2020); 2) collaboration between researchers and manufacturers (Parupudi et al., 2020, Wang et al., 2021b); 3) informal networks for the data access (Vandenberg et al., 2021), government support (Kamat et al., 2021), and certifications (Battaglia et al., 2021a).
Supply Chain		Emphasize the importance and need for a supply chain (Escobar et al., 2021, Shaffaf et al., 2021, Vandenberg et al., 2021); Sustainable supply chain is essential to ramp up population-scale testing (Benda et al., 2021); Players outside of firms must be accessed to coordinate and speed up the manufacturing, certification, and commercialization stages (Battaglia et al., 2021a).
Competitive Manufacturing		TC Covid-19 Technologies needs complicated manufacturing capabilities (Bhalla et al., 2020, Mattioli et al., 2020, Carroll and McNamara, 2021) and accumulated competencies to run manufacturing processes (Battaglia et al., 2021a).
Services		TC Covid 19 Technologies needs to 1) Training of human resources (Yu et al., 2021, Vandenberg et al., 2021); 2) Large-size sampling (Shaffaf et al., 2021, Randolph and Barreiro, 2020); 3) The provision of calibration services with the emergence of new strains (Priyanka et al., 2020, Parihar et al., 2020, Ozer and Henry, 2021); 4) IT services to collect, aggregate, and analysis of information (Ozer and Henry, 2021, Mattioli et al., 2020, Lukas et al., 2020).
Appropriability regimes		Drivers for the importance of developing Method PCR and ELISA are the lack of a technological regime and a well-established market (Leichle et al., 2020); (Battaglia et al., 2021a); The successful reasons for spinoff companies are a strict intellectual properties regime.
Complementary Technology	**Specialized**	Electrochemical DNA biosensors (Ibrahim et al., 2021)
	Co-specialized	3D convolutional neural network (3D-CNN) (Liang et al., 2021)
	Enabling Technologies	Artificial intelligence, mobile applications, IoT, and machine learning for collection, storage, and analysis (Azmi et al., 2021, Campos-Ferreira et al., 2021, Escobar et al., 2021, Fabiani et al., 2021, Giri et al., 2021, Gupta et al., 2021, Hosseini et al., 2020, Kamat et al., 2021, Lukas et al., 2020, Mattioli et al., 2020, Ozer and Henry, 2021, Parupudi et al., 2020, Priyanka et al., 2020, Rasmi et al., 2021, Rezaei et al., 2020, Shaffaf et al., 2021, Vandenberg et al., 2021)

5.2. Inductive Thematic Analyzing: which TC Challenges of diagnosis Covid 19 aren't explained by PFI

To explore the thematic foci of the existing literature, articles were analyzed and coded independently (Miles and Huberman, 1994). Rasmi et al. (2021) proposed an iterative approach, moved forward and backwards between the data and the emerging conceptions and simultaneously compared the codes. The Inductive thematic analysis reflects a wide range of issues for TC Challenges of diagnosis Covid 19, which PFI doesn't explain. Two main themes were extracted including Technology-*Push vs. Demand-Pull Strategy* and *Regulation of Innovation vs. Regulation for Innovation*. Our study has revealed that Covid-19 as one of the most recent pressing GCs presents a unique opportunity to commercialize diagnostic devices. The process of creating this opportunity and how firms can capture it is explained in detail in the section 5.1. However, firms need to pay more attentions to Technology-Push vs. Demand-Pull and regulatory approaches to achieve the profit-making position during GCS. To this end, we examine the shift in commercialization strategies of firms under the pressure of Covid-19 demand, highlighting the need for firms to make different strategic decisions (section 5.2.1). Furthermore, changes in regulatory approaches have been illustrated in section 5.2.2 to show how changes in interest groups and market structures in the context of grand challenges have resulted in the imposition of specific regulatory requirements.

5.2.1 Technology-Push vs. Demand-Pull

The *technology-push* perspective denotes the crucial role of the technological innovation that internal or external development of the science and technology force the firms move towards commercialising a technology (Di Stefano et al., 2012). In contrast, based on the *market-pull* perspective, market circumstances and demand are the main factors forcing firms to first develop science and technology and then follow the TC activities of the developed technology. From a *market-pull* perspective, the characteristics of the market and the economy affect innovation's performance (Chidamber and Kon, 1994, Brem and Voigt, 2009). *Technology-Push* and *Market-Pull* perspectives evoke two types of *Creation* (Schumpeterian) and *Discover* (Kirznerian) entrepreneurial opportunities (Lubik et al., 2013). Schumpeter presented entrepreneurship as "the carrying out of what is already available", while Kirzner suggests that “opportunities are enacted by the entrepreneur (Dutta and Crossan, 2005). These perspectives differentiate the components of the TC regarding infrastructure needs, R&D expenses, R&D timing, nature of uncertainties, competencies, business models, marketing strategy, and barriers to market entry (Maine and Garnsey, 2006, Brem and Voigt, 2009, Rogers Everett, 1995, Guo et al., 2020a, Choi, 2018).

To successful TC, firms have to move from a technology-push to market-pull perspective quickly once a new and sudden market opportunity has emerged. Battaglia et al. (2021a) emphasized that the capability of a firm to approach changes in market demand depends on its “*legacy competencies and practices*”. Hence, the firms must enhance these capabilities to TC of Covid-19 diagnostic technologies during pandemics. For example, there was an urgent and enormous demand for sensors and IT technologies for detecting the fast-spreading Covid-19 accurately and quickly. Furthermore, as new variants of the SARS-CoV-2 arise, there is a pressing need to occasionally follow the samples and assess the clinical and analytical performance that entails achieving significant firms' resources and capabilities (Benda et al., 2021).

The COVID-19 pandemic, as a grand challenge, has created a demand for diagnostic technologies that can quickly and accurately detect the virus. It has required firms commercializing these technologies to move from a technology-push to a market-pull perspective quickly (Bhalla et al., 2020). This means that companies must enhance their capabilities and practices to approach changes in market demand.

In contrast, a technology-push approach focuses on developing technologies based on a company's internal capabilities and resources rather than market demand. This approach may need to be better suited to the fast-paced and rapidly changing demands of the COVID-19 pandemic. As a result, the demand-pull created by the COVID-19 pandemic has required firms to be agile and responsive to changing market demands. Overall, the impact of the COVID-19 pandemic as a GCs on the commercialization of diagnostic technologies has highlighted the importance of a market-pull perspective and the need for firms to enhance their capabilities to commercialize these technologies successfully during pandemics.

5.2.2 Regulation of Innovation vs. Regulation for Innovation

PFI attempts to internalize regulation highlighting IPR as a legal regime and a government solution to protect innovators against imitators (Teece, 1986, Teece, 2006). It is inspired from Schumpeter (1950) that framed competition as, within itself, a driver called invention and innovation. On this basis, the term c*reative destruction* was attributed to it. Arrow (1962) has highlighted the government's role in ensuring property rights as a regulatory tool for promoting innovation by conceptualizing information asymmetry. Although Teece (2018) points out the firms' role in changing the legal regime of the market by creating a standard through appropriability and licensing strategy, firms are still assumed to be passive in the regulatory process. PFI, like its other predecessors, is rooted in the Innovation Economics, which draws an ex-ante relationship between regulations and innovation, and considers regulations as part of the government's incentives or support tools to promote innovation. This paper calls it as a *Regulation of Innovation (ROI).*

Vandenberg et al. (2021) admitted that there is a high technical and knowledge complexity in the development of Covid-19 Diagnostic Technologies, so that there is an information asymmetry between the developer and the consumer. Mazini et al. (2021) also pointed out the importance of patient safety and security and access to a protocol for it. Leichle et al. (2020) and Parupudi et al. (2020) point to it is needs to developing guidelines for data collection in trial stages and even standards for how to use equipment. These cases show aspects of the complexity of commercialization, which, according to the theories of regulation economics and public interest (Peltzman, 1998), require government intervention. But the challenge is not only in understanding the need for new regulations. As Leonidou et al. (2020) showed that the management of innovation and commercialization of products faces a long list of stakeholders, as in the case, it gets more complicated acknowledged by Park et al. (2022), Böger et al. (2021), Parupudi et al. (2020), Wang et al. (2021b). Because innovators have different expertise in the development process (Leichle et al., 2020) and each of them has a different understanding of research and development and the usefulness of products. This is the point that George et al. (2016) refer to as the complexity of providing technological solutions for grand challenges. Also, there is a difference between the users (medical staffs) and the people (end users). As Azmi et al. (2021) indicates that diagnostic equipment is tested on patients, but the end users are the medical staffs. There is a gap between convincing the treatment team that the equipment is useful and vice versa (Vandenberg et al., 2021), which highlights the challenge of the end user's perception of the value created (Slater, 1997). Furthermore, institutional regimes and policy considerations of countries are different. For example, in China, there has been a different view of other diagnostic policies (Gao and Zhang, 2021) or that the governments' policies in the management of Covid-19 have been different from each other (Cascini et al., 2022). In addition to all this, there are traditional actors who try to intervene in the regulatory process. All this means that there are many stakeholders in the regulation for Covid-19, where the possibility of capture is important. Stigler (1971) showed, well established actors try to intervene in the regulatory process in a way that maximizes their benefit. Undoubtedly, the companies present in traditional diagnostics or even the companies producing vaccines are strict competitors for diagnostic equipment. Also, Becker (1983) has shown how these actors create pressure groups to intervene on the regulatory process by identifying common interests. These reveal another relationship between regulation and innovation, which is rooted in regulatory economics, and we call it Regulation for Innovation (RFI). Hence effectively responding to Covid-19 as a GCs through innovation requires a comprehensive understanding of the two-way relationship between regulations and innovation, both ex-ante and ex-post. This understanding is necessary to obtain a more accurate analysis of how multiple stakeholders intervene in establishing regulations and changes in the institutional regime.

The results of the inductive approach have been summarized in Table 4.

Table 4. Results of inductive approach

Thematic foci	Illustrative coding
Technology-Push vs. Demand-Pull Strategy	Moving a firm's development model from a technology-push to a market-pull in a pandemic (Battaglia et al., 2021a)- new variants of the SARS-CoV-2 arise the achieving significant firms' resources and capabilities (Benda et al., 2021)
Regulation of Innovation vs. Regulation for Innovation	The complexity of knowledge in new diagnostic Covid-19 technologies leads to innovators playing a focal role in the regulatory process (Vandenberg et al., 2021); strictly competition among innovators seeks to persuade the government and the market (Giri et al., 2021, Benda et al., 2021, Carroll and McNamara, 2021).

6. Research gaps and potential research areas

This survey used the SLR method to identify factors affecting the success of TC for Covid-19 diagnostic technologies. To this end, the components of PFI were assimilated using the deductive approach. Also, the inductive method was conducted to identify factors in addition to the components of the PFI framework. The following section presents, research gaps and potential research areas for future studies.

6.1 Research design

Based on the research design perspective the gaps in the literature are a) *research method* (most of the articles selected case studies as their research method), the *scope of research* (researchers focused on technology, not a company), *data related* (types and source of data), and *generalization* (generalizability of the results were missing). According to the research method, case studies have tried to analyse various aspects of the developed technologies from their functionality perspective (e.g., (Leichle et al., 2020, Parihar et al., 2020)). The results and implications only were presented about the effectiveness and advantages of technologies. For example, the usefulnesses of the Nano-bio sensors can open new horizons in the detection process (Kamat et al., 2021).

Therefore, both quantitative and qualitative research methods should be applied to finding TC challenges of Covid-19 diagnostic technologies and proposing solutions to tackle them and ensuring the success of TC for Covid-19 diagnostic technologies. Regarding the scope of research, most researchers studied the effectiveness of the technologies to diagnose Covid-19. To the best of our knowledge, no research has been conducted to study the role and circumstances of firms (both research centres and commercial firms) in the success of developing and commercializing Covid-19 diagnostic technologies. In fact, the firms have been ignored as a unit of analysis. The analysis unit in scientific studies helps to examine the research problem from a suitable perspective and find applicable results. Focusing on the firms as the economic actor that seeks to gain benefits in interaction with society help researchers explain business challenges for TC (Nieto Cubero et al., 2021). Furthermore, the TC of the pandemic is a very complex process for firms. Firms have to commercialise research findings quickly and face high and unpredictable demand for a while. Therefore, this area has been presented as a future research stream. More research must shed light on the commercialisation solution for the firms through how the firms can ensure the success of TC by providing appropriate policy and managerial solutions.

While articles collected data from patients to evaluate the effectiveness of technologies (e.g., Azmi et al. (2021) and Afzal (2020)), no research collected data relevant to TC challenges of Covid-19 diagnostic technologies faced by firms. To find the TC challenges of Covid-19 diagnostic technologies, firms need a detailed and accurate understanding and analysis of the market (Battaglia et al., 2021a). To this end, research must be carried out by collecting data from technology users (e.g., clinics and test centres) and technology developers (research centres and commercial firms who are involved in the innovation process) to analyse and extract the main requirements and needs of the market. Hence, the researcher by collecting and analysing data of firms and users of diagnostic technologies can make valuable contributions to the TC of pandemic diagnostic technologies literature like Covid-19. To make meaningful inferences about the generalizability of research results, the target population and scope of study must not be limited to the characteristic of a study alone (Hays and McKibben, 2021). Since most of the selected articles collected data from limited groups of patients in their geographic areas (Kamat et al., 2021), their results couldn't be generalised and used for other cases. To enhance the generality features of future research, this review suggests researchers pay more attention to the diversity of the case study's characteristics (e.g., nature, size, and location of the firms, type of users, and types of technologies). Given the generalizability of the results of research is very important in the field of management sciences, it can be ignored to some extent in the field of medicine. Hence, this research gap is important for management science researchers who seek to analyze challenges and find solutions for TC of Covid-19 diagnostic technologies

6.2 Market mechanism

The success of the TC and making a profit depends on how well firms are interacting with the market and responding to markets' needs (Christensen et al., 2018). A significant research gap in the literature is the lack of research that analyzes the relationship between firms and markets and its effect on TC for Covid-19 diagnostic technologies. This study proposes four streams of future research to cover this gap including a) studying the relationship between TC for Covid-19 diagnostic technologies and market mechanism; b) examining the mediation effects of external factors on firms (who developed Covid-19 diagnostic technologies) and market relationships; c) analysing the impacts of unique characteristics of the market during pandemics like Covid-19 (sudden, unpredictable, and large demand) on the relationship in presence of mediator and moderator factors; d) the impact of regulations as a market factor on TC for Covid-19 diagnostic technologies. For example, the effects of the market actors (like governments, public authorities, health bodies, and market incumbents) on the firms and market relationships and the success of TC for Covid-19 diagnostic technologies. While during the pandemic, governments and health bodies are trying to perform more diagnostic tests quickly, market incumbents aiming to get the highest market share and raising barriers for newcomers. This issue is very important in the case of the market of medical technologies, which is regulated and has several regulatory bodies.

6.3 Research theories

Most of the articles were published in medicine and engineering Journals based on the case study method (see section 4). Researchers in the medical field have tried to evaluate the performance of diagnostic technologies by collecting data from patients and diagnostic test results. Also, articles in the field of engineering have focused on the capabilities of technology and the development of new and effective technologies for Covid-19 diagnosis. This review identified two gaps in literature according to the research theories including a lack of *interdisciplinary research* and *TC theories and frameworks*. In fact, interdisciplinary studies should be developed to achieve not only a better understanding of the TC challenges of Covid-19 diagnostic technologies but also to learn lessons in the face of future pandemics (according to the special circumstances of the market during the pandemics). To this end, future research should move towards interdisciplinary research that simultaneously focuses on different objectives like the technical dimensions of technology (engineering discipline), TC success in innovative processes (management science discipline), and the efficiency and effectiveness of diagnostic test results (medical discipline). The lack of research on using TC theories and frameworks for the innovative process of Covid-19 diagnostic technologies has been identified as one of the most important research gaps in the literature. For example, Colombo et al. (2006), Hallberg and Brattström (2019), Swink and Nair (2007), and (Teece, 1986, Teece, 2006, Teece, 2018) introduced theories and frameworks for evaluating the success of TC in innovative processes. There are several fundamentals like collaborations and networking, transaction cost, locked-in and path dependence, and organizational and firm capabilities that can be used in the analysis of why the TC of covid-19 diagnostic technologies failed. Hence, there are streams for future research to perform interdisciplinary studies by addressing TC theories and frameworks.

6.4 PFI framework

There is a growing opportunity for future research to extend the PFI framework by addressing its components. This review indicated the gaps in the literature according to the six components of the PFI framework including *Networking, Supply Chain, Competitive Manufacturing, Services, Appropriability regimes,* and *Complementary Technology*. We suggest that future research should find the answer to why, how, and what of these five components individually or jointly for the success of TC and the innovative process. For example, a potential research question for future studies could be why networking is important in the success of TC for Covid-19 diagnostic technologies by addressing transaction cost theory (Battaglia et al., 2021b). Also, studying different types of networking models in TC can be analysed in research with multiple case studies. In addition, identifying the actors of the network, understanding the requirements of technology development, and production and marketing of each of them is another category of research that has the possibility of designing new research. A list of research questions for future studies based on six components of the PFI presented is in Table 5.

Table 5. Research questions for future studies

PFI Component	Future research questions
Networking	• Why is networking important in the success of TC for Covid-19 diagnostic technologies? • What factors and forces have highlighted the importance of networking during the pandemic? • What types of cooperation networks have emerged in the TC of Covid-19 diagnostic technologies? • What is the difference between networking requirements for newcomers and market incumbents? • Who are the actors in the TC networks of Covid 19 diagnostic technologies? • What are the conflicts of interest between actors and solutions to tackle them in the TC network for Covid-19 diagnostic technologies?
Supply Chain	• What is the importance of an integrated supply chain (from upstream to downstream side) in the success of TC for Covid-19 diagnostic technologies? • What contractual methods along with the entire supply chain are effective in the success of TC for Covid-19 diagnostic technologies? • What is the difference between the requirements, needs, and expectations of the partners from the upstream to the downstream side of the supply chain? • What supply chain strategies (e.g., lean, agile, or leagile strategies) are effective in the success of the TC for Covid-19 diagnostic technologies? • What are the effective factors of choosing a supply chain strategy to ensure the success of the TC for Covid-19 diagnostic technologies?
Competitive Manufacturing	• What is the impact of competitive manufacturing on the success of TC for Covid-19 diagnostic technologies? • What are the most effective features (e.g., cost, quality, delivery, and flexibility) of competitive manufacturing in the success of TC for Covid-19 diagnostic technologies? • How do companies elaborate the competitive manufacturing capabilities to tackle TC challenges of Covid-19 diagnostic technologies? • What is the impact of outsourcing on the success of TC for Covid-19 diagnostic technologies?
Services	• What is the importance of the after-sales service on the success of TC for covid-19 diagnostic technologies during the pandemic?

PFI Component	Future research questions
	• What is the importance of the after-sales services (e.g., calibration, support, training, and spare parts) on the success of TC for covid-19 diagnostic technologies (particularly by emerging new variants of the virus)? • How firms can evaluate the effectiveness of the after-sale services for Covid-19 diagnostic technologies? • What services are essential for the success of the TC for Covid-19 diagnostic technologies (based on the market perspective)?
Appropriability regimes	• What changes occurred in the market mechanism and its incentives during the pandemic? • What were the features of the supported technologies during the pandemic? • What was the effectiveness of research grants (e.g., supported by governments) on the success of TC for Covid-19 diagnostic technologies? • What is the relationship between the success of TC for Covid-19 diagnostic technologies and national health strategies? • What were the changes in IPR and standards related to medical technologies during the pandemic? and what was its impact on the success of TC for Covid-19 diagnostic technologies?
Complementary Technology	• What is the importance of complementary technologies on the success of TC for Covid-19 diagnostic technologies? • What complementary technologies are essential for the success of TC for the Covid-19 diagnostic technology? • How do firms have to interact and cooperate to access complementary technologies?

6.5 Theme-based literature gaps and future research

Through the inductive method, two themes were extracted as TC challenges of Covid-19 diagnostic technologies. These themes raise the future stream for research on the success of TC for Covid-19 diagnostic technologies. In addition, studying them provides lessons learnt from Covid-19. Firms can use them to tackle TC challenges during the pandemics in future. The first theme was Technology-Push and Demand-Pull perspectives. The firms couldn't respond to the large and unpredictable demand of the market and its needs according to the Technology-Push approach. Indeed, there are successful companies that can quickly react to the new market based on the Demand-Pull perspective. They should be able to effectively meet the quantitative and technical needs of the market in addition to the necessary regulations and standards (Guo et al., 2020b). Therefore, future research could be developed based on the relationship between Demand-Pull perspectives and the success of TC for Covid-19 diagnostic technologies including what are the differences between Technology-Push vs. Demand-Pull perspectives in TC for Covid 19 diagnostic technologies. How and when firms should move from Technology-Push to a Demand-Pull perspective once a pandemic occurred? What behavioural and operational models should be used within firms for moving from Technology-Push to a Demand-Pull perspective?

According to the Regulation of Innovation vs. Regulation for Innovation theme, the main research gap in the literature is the lack of studies focusing on the relationship between firms and other actors in the market like governments and standardizing organisations. While medical-related technologies are subject to strict regulatory and approval processes to enter the market, once the pandemic started, both regulators and government don't have enough time to follow all steps of the approval process (Sachs et al., 2022). Rather than time restrictions, they are facing a lack of knowledge, experts, and large-size test samples to evaluate the usefulness of the developed technologies. This review identified these two major challenges to evaluate the success of TC for Covid-19 diagnostic technologies. Although the government and relevant organisations issued medical device emergency that exemptions a technology from certain regulations and used small size sample tests for tackling these challenges (Gerke et al., 2020), still more effective solutions should be studied in future research. In addition, the impact of these solutions on controlling the pandemic needs to be discussed. Hence, we proposed regulation for Innovation as a stream for future research concerning research questions including What are the emerging regulation conflicts in the TC of Covid 19 diagnostic technologies? What new tools and regulatory frameworks should be developed during the pandemic? What are the efficiency and effectiveness of these tools? How firms should be involved in the regulatory process during a pandemic? How the firms should adapt themselves to the regulatory changes? How do firms rearrange their capabilities in response to the new regulations during a pandemic?

7. Theoretical Contribution

In this systematic review, we offer new insights to innovation management (PFI framework) and crisis management research, and also draw policy implications. Firstly, we provide an important conceptual basis to understand the success and failure factors for new technologies commercialization in Covid-19 pandemic- considered the main societal grand challenge in recent times. To do so, we conduct, organize and synthesise previous recent studies that deal with the success and failing factors in the commercialization of technologies during Covid-19 pandemic. We rely on the six components of PFI framework that include networking, supply chain, competitive manufacturing, services, appropriability regimes, and complementary technology in order to provide a nuanced picture into technology commercialization challenges for Covid-19 diagnosis technologies. This enables understanding the state of technology commercialization during crises and identify the underlying factors that can both create and or damage firms' competitive advantage. Hence, this paper investigates PFI from technology push and market pull perspectives to discuss TC challenges of new MDE in case of Covid 19. Also, we propose a conceptual framework for investigating the commercialization challenges of Covid 19 diagnosis devices.

For decades, scholars debated two Technology-push and Market-pull perspectives. Brem and Voigt (2009) and Choi (2018) discussed that a perspective is not permanent when integrated within corporate technology and innovation management. Timsit et al. (2015) argue that firms must analyze the market structure and resource portfolio to use them optimally to enter the new market. Some scholars such as Lubik et al. (2013) and Sethi et al. (2018) develop a conceptual framework to explore shifts between technology-push and market-pull perspectives to pursue competitive opportunities and sustainable development during the firm's formative years. Furthermore, Guo et al. (2020b) and Aflaki et al. (2021) believe that these perspectives are beneficial to the performance of firms when they will design business models and support the creation and diffusion of innovations, especially in emerging and new businesses. Hötte (2023) finds that demand-pull and technology-push perspectives drives growth, innovation and technological change. We build on this line of research by accreting that market-pull perspective has a stronger effect on the commercialization of Covid-19 diagnostic technologies than technology-full perspective. This implies that, during a pandemic, a successful TC is generated mainly from a market-pull perspective. The Covid-19 pandemic not only changed firms' appropriability but also opened new horizons for the future of TC research. Because the failure or success of the TC for Covid 19 diagnostic technologies had a direct impact on how fast Covid-19 and its variants are spreading and the number of deaths. In addition, once Covid-19 started, research budgets for developing diagnostic technologies have been growing. As result, researchers developed several technologies, some of which failed in the TC stage. The experiences of failures and successes of TC provide opportunities for researchers in the field of management sciences to examine the theories and frameworks of TC. This article reviewed the challenges and success factors of TC for Covid-19 diagnostic technologies based on the PFI framework. Although the PFI framework couldn't justify all the failure or success factors in the case studies, it is a promising framework that needs to be extended based on some factors. For example, more studies should be conducted to develop complementary assets and appropriability regimes components regarding medical technologies, the circumstance of the pandemic, and the role of other actors in medical markets.

To investigate TC challenges of Covid-19 diagnostic technologies, we discuss PFI based on the ROI and RFI perspectives simultaneously. According to the ROI perspective, the strictness of health regulatory bodies reduces the motivations of the firms to invest in innovative technologies and commercialize them (because the regulators affect the market organization). The RFI describes the market factors that increase the failure of TC like information asymmetry and data privacy (Budd et al., 2020, Sharma and Bashir, 2020) and the necessity of new regulations and regulatory frameworks for TC. It can help achieve community health goals, but they have two main issues from a regulatory perspective: the development of these devices creates new failures in the market that the government seeks to mitigate and ensure. Community health security must be regulated. Second, regulation in a market with multi-stakeholders requires the development of new regulatory frameworks. It means government decisions will, directly and indirectly, affect the motivation of innovative efforts and the expected benefits of innovation for innovators.

Secondly, we build on and extend the PFI framework based on the context of new medical technologies in pandemic conditions. PFI is a nascent framework to understand outcomes from investment in innovation, emphasizing the role of strategy and organization in that process (Teece, 2006). The framework directs the appropriate strategies for the innovators and predicts the outcomes to be expected of innovators (Teece, 1986).

Although PFI frames critical strategic decisions and considers the business environment, proposing new issues such as the appropriability regime and business models (Teece, 2006, Teece, 2018), it ignores the strategic decisions about choosing, integrating, and moving between technology push and market pull perspectives. When, in pandemic conditions, some new MDEs fail to commercialize (Afzal, 2020, Shen et al., 2021, Böger et al., 2021) even market demand is fully supporting where many technology-based firms try to innovate. It seems that the framework needs more clarification because both complementary assets for technology-based and market-based strategic decisions are different, and the firms need more dynamic capabilities in the transition to either of these two strategic choices. This implies that PFI framework requires further elucidation when applied in different contexts (e.g. societal crises). We offered an extension of Teece's (1986) original PFI framework to accommodate the important case of emerging technologies during a crisis by considering and discerning the strategic decisions in terms of choosing, integrating, and shifting between technology push and market pull perspectives.

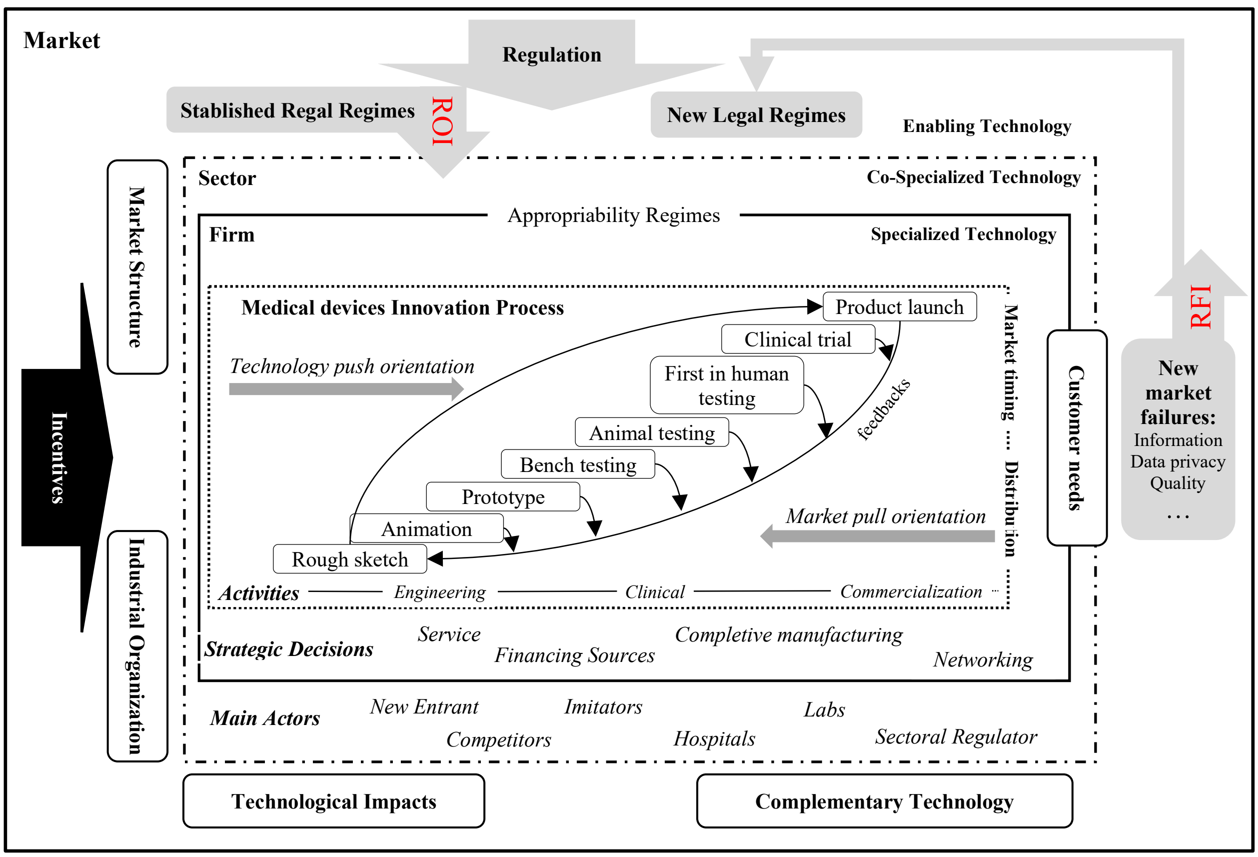

Figure 7. Proposed Framework

The medical device innovation process with its unique features (bench, animal and clinical testing) is at the centre of our proposed conceptual framework, which is shown in Figure 7. For this purpose, we have used the medical device innovation process introduced by Durfee and Iaizzo (2019). The firm will benefit from an innovation based on its complementary assets. In addition to firm-level factors, three external factors: market, technology, and regulation, can also influence the commercialization of Covid 19 diagnosis devices. From a market point of view, market pull in customer needs can be the driver of the innovation process. On the other hand, according to economists, the structure of the market (complete competition and the failure of information) highlights the need for an incentive for starting innovation efforts, and the established legal regime in the form of intellectual property rights responds to this issue. With the rapid growth in the availability and complexity of medical equipment in the 1960s, product experts were recruited to counsel health bodies and develop standards and purchasing specifications (Jefferys, 2001). Regulators play a crucial role in supporting innovation and facilitating new products when increasing the complexity of developing new products (Richards and Hudson, 2016). To assure patient safety and security, regulation agencies continuously modify and strengthen their approaches to regulating medical devices (Mazini et al., 2021). In the current pandemic using new technologies, diagnosis technologies that are easier to be performed produce and provided rapid detection/monitoring of a disease and/or provide sustained/controlled release of a drug molecule or biologics. Diagnostic tests classify as a medical devices, therefore, are many barriers and lengthy regulatory approvals (Lamprou, 2020). The appropriate regulatory pathway is significant during a pandemic since there is pressure to speed up innovation without increasing risk. Regulators should always make such decisions carefully and thoroughly, even in times of crisis (Gerke et al., 2020). On the other hand, the strictness of health regulatory bodies weakens the incentive of companies to invest in innovative efforts and commercialize products because it affects market organization (Oyewole et al., 2021). Science and technology are drivers of innovation (technology push). In addition, complementary technology is another crucial technological factor in commercialization. Despite the impact of market and regulations on the firm's innovation process, a firm is not a passive agent. By carrying out innovative activities, a firm creates new forms of market failure (information asymmetry and data privacy). Hence, creating a new legal regime and an appropriate regulatory framework is another important factor affecting the commercialization of Covid 19 diagnosis technologies.

Thirdly, the review also contribute to the crisis management literature as well as practice (Ngah-Kiing Lim et al., 2009, Tanda, 2018). The extant literature has not explicitly and systematically explained which activities and strategies firms should choose to boost their performance and respond to crises (Naidoo, 2010, Wang et al., 2020b). This study addresses this research gap and explores the main activity, not only to benefit from innovation, but also to mitigate the Covid-19 pandemic. In this respect, we explicate in our study the need for considering the activities and processes that influence business value creation and crisis management. For instance, we emphasise on technology commercialization stage- a highly integrated and interconnected activity, as critical to increase business value, and a successful technology commercialization leads to a better management of crisis (e.g., TC helps to reduce the effect of the Covid-19 pandemic in terms of virus spread and human death). This implies that under specific challenging conditions, there is a need to explore and focus on key activities that are related to the nature of the crisis, as a prerequisite to manage and mitigate it efficiently (Reeves et al., 2020).

8. Conclusion

The discussion about the Commercializing Challenges for Covid-19 Diagnostic Technologies has been hot in recent months. However, the literature provides several commercialization models, which has not been a systematic understanding of the success and challenges of these technologies. In response to this need, this study adopts an SLR approach based on the PFI framework to comprehensively cover these attempts and suggest future research for TC. This study thus proposes six deductive and two inductive thematic categories, the critical gaps in the literature, recalls the research areas for future studies, and supplies many suggestions and research questions to guide further research. Moreover, this study develops an integrated conceptual framework to show that PFI usually emphasizes how the firms' decisions affect the commercialization success and does not explain the active role of innovators in changes in the market structure in post-innovation which can not only be a good framework for the government, regulators, and managers in commercialization success but also to draw future research streams.

References

AARIKKA-STENROOS, L. & LEHTIMÄKI, T. 2014. Commercializing a radical innovation: Probing the way to the market. *Industrial Marketing Management,* 43**,** 1372-1384.

ABDELHAMID, H. N. & BADR, G. 2021. Nanobiotechnology as a platform for the diagnosis of COVID-19: a review. *Nanotechnology for Environmental Engineering,* 6**,** 1-26.

AFLAKI, S., BASHER, S. A. & MASINI, A. 2021. Technology-push, demand-pull and endogenous drivers of innovation in the renewable energy industry. *Clean Technologies and Environmental Policy,* 23**,** 1563-1580.

AFZAL, A. 2020. Molecular diagnostic technologies for COVID-19: Limitations and challenges. *Journal of advanced research,* 26**,** 149-159.

ALHALAILI, B., POPESCU, I. N., KAMOUN, O., ALZUBI, F., ALAWADHIA, S. & VIDU, R. 2020. Nanobiosensors for the detection of novel coronavirus 2019-nCoV and other pandemic/epidemic respiratory viruses: a review. *Sensors,* 20**,** 6591.

ANOKHIN, S., WINCENT, J. & FRISHAMMAR, J. 2011. A conceptual framework for misfit technology commercialization. *Technological Forecasting and Social Change,* 78**,** 1060-1071.

ARROW, K. J. 1962. Economic Welfare and the Allocation of Resources for Invention. *In:* NELSON, R. (ed.) *The Rate and Direction of Inventive Activity.* Princeton, New Jersey: Princeton University Press.

ATES, H. C., BRUNAUER, A., VON STETTEN, F., URBAN, G. A., GÜDER, F., MERKOÇI, A., FRÜH, S. M. & DINCER, C. 2021. Integrated Devices for Non-Invasive Diagnostics. *Advanced Functional Materials,* 31**,** 2010388.

AZMI, I., FAIZAN, I., KUMAR, R., YADAV, S. R., CHAUDHARY, N., SINGH, D. K., BUTOLA, R., GANOTRA, A., GOPAL, D. & IQBAL, J. 2021. A saliva-based RNA extraction-free workflow integrated with Cas13a for SARS-CoV-2 detection. *Frontiers in cellular and infection microbiology,* 11**,** 144.

BARUA, S. 2021. Understanding coronanomics: The economic implications of the COVID-19 pandemic. *J The Journal of Developing Areas,* 55**,** 435-450.

BASU, B. & GHOSH, S. 2017. Assessment of technology and manufacturing readiness levels. *Biomaterials for Musculoskeletal Regeneration.* Springer.

BATTAGLIA, D., PAOLUCCI, E. & UGHETTO, E. 2021a. The fast response of academic spinoffs to unexpected societal and economic challenges. Lessons from the COVID-19 pandemic crisis. *R&D Management,* 51**,** 169-182.

BATTAGLIA, D., PAOLUCCI, E. & UGHETTO, E. 2021b. The role of Proof-of-Concept programs in facilitating the commercialization of research-based inventions. *Research Policy,* 50**,** 104268.

BECKER, G. 1983. A theory of competition among pressure groups for political influence. *The quarterly journal of economics,* 98**,** 371-400.
BECKER, G. 1985. Public policies, pressure groups, and dead weight costs. *Journal of public economics,* 28**,** 329-347.
BENDA, A., ZERAJIC, L., ANKITA, A., CLEARY, E., PARK, Y. & PANDEY, S. 2021. COVID-19 Testing and Diagnostics: A Review of Commercialized Technologies for Cost, Convenience and Quality of Tests. *Sensors,* 21**,** 6581.
BHALLA, N., PAN, Y., YANG, Z. & PAYAM, A. F. 2020. Opportunities and challenges for biosensors and nanoscale analytical tools for pandemics: COVID-19. *ACS nano,* 14**,** 7783-7807.
BÖGER, B., FACHI, M. M., VILHENA, R. O., COBRE, A. F., TONIN, F. S. & PONTAROLO, R. 2021. Systematic review with meta-analysis of the accuracy of diagnostic tests for COVID-19. *American journal of infection control,* 49**,** 21-29.
BOUDREAU, K. J., JEPPESEN, L. B. & MIRIC, M. 2022. Profiting from digital innovation: Patents, copyright and performance. *Research Policy,* 51**,** 104477.
BREM, A., NYLUND, P. & VIARDOT, E. 2020. The impact of the 2008 financial crisis on innovation: A dominant design perspective. *Journal of Business Research*, 110, 360-369.
BREM, A. & VOIGT, K.-I. 2009. Integration of market pull and technology push in the corporate front end and innovation management—Insights from the German software industry. *Technovation,* 29**,** 351-367.
BUDD, J., MILLER, B. S., MANNING, E. M., LAMPOS, V., ZHUANG, M., EDELSTEIN, M., REES, G., EMERY, V. C., STEVENS, M. M., KEEGAN, N., SHORT, M. J., PILLAY, D., MANLEY, E., COX, I. J., HEYMANN, D., JOHNSON, A. M. & MCKENDRY, R. A. 2020. Digital technologies in the public-health response to COVID-19. *Nature Medicine,* 26**,** 1183-1192.
BURGERS, C., BRUGMAN, B. C. & BOEYNAEMS, A. 2019. Systematic literature reviews: Four applications for interdisciplinary research. *Journal of Pragmatics,* 145**,** 102-109.
BUTENKO, A. & LAROUCHE, P. 2015. Regulation for innovativeness or regulation of innovation? *Law, Innovation and Technology,* 7**,** 52-82.
CAMPOS-FERREIRA, D., VISANI, V., CÓRDULA, C., NASCIMENTO, G., MONTENEGRO, L., SCHINDLER, H. & CAVALCANTI, I. 2021. COVID-19 challenges: from SARS-CoV-2 infection to effective point-of-care diagnosis by electrochemical biosensing platforms. *Biochemical Engineering Journal,* 176**,** 108200.
CAPPONI, G., CRISCUOLO, P., MARTINELLI, A. & NUVOLARI, A. 2019. Profiting from innovation: Evidence from a survey of Queen's Awards winners. *Structural Change and Economic Dynamics,* 49**,** 155-169.
CARROLL, A. & MCNAMARA, E. 2021. Comparison and correlation of commercial SARS-CoV-2 real-time-PCR assays, Ireland, June 2020. *Eurosurveillance,* 26**,** 2002079.
CASCINI, F., FAILLA, G., GOBBI, C., PALLINI, E., HUI, J., LUXI, W., VILLANI, L., QUENTIN, W., BOCCIA, S. & RICCIARDI, W. 2022. A cross-country comparison of Covid-19 containment measures and their effects on the epidemic curves. *BMC Public Health,* 22**,** 1765.
CENAMOR, J. & FRISHAMMAR, J. 2021. Openness in platform ecosystems: Innovation strategies for complementary products. *Research Policy,* 50**,** 104148.
CHAUHAN, C., PARIDA, V. & DHIR, A. 2022. Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change,* 177**,** 121508.
CHEN, C.-J., CHANG, C.-C. & HUNG, S.-W. 2011. Influences of Technological Attributes and Environmental Factors on Technology Commercialization. *Journal of Business Ethics,* 104**,** 525-535.
CHIDAMBER, S. R. & KON, H. B. 1994. A research retrospective of innovation inception and success: the technology–push, demand–pull question. *International Journal of Technology Management,* 9**,** 94-112.
CHIESA, V. & FRATTINI, F. 2011. Commercializing Technological Innovation: Learning from Failures in High-Tech Markets*. 28**,** 437-454.
CHO, S., MATHIASSEN, L. & GALLIVAN, M. Crossing the chasm: From adoption to diffusion of a telehealth innovation. IFIP Working Conference on Open IT-Based Innovation: Moving Towards Cooperative IT Transfer and Knowledge Diffusion, 2008. Springer, 361-378.
CHOI, H. 2018. Technology-push and demand-pull factors in emerging sectors: evidence from the electric vehicle market. *Industry and Innovation,* 25**,** 655-674.
CHONG, Y., IKEMATSU, H., TANI, N., ARIMIZU, Y., WATANABE, H., FUKAMACHI, Y., YONEKAWA, A., IWASAKA, S., NISHIDA, R. & ERIGUCHI, Y. 2021. Clinical significance of SARS-CoV-2-specific IgG detection with a rapid antibody kit for COVID-19 patients. *Influenza and Other Respiratory Viruses,* 15**,** 13-18.

CHOWKWANYUN, M. & REED, A. L. 2020. Racial Health Disparities and Covid-19 — Caution and Context. 383, 201-203.

CHRISTENSEN, C. M., MCDONALD, R., ALTMAN, E. J. & PALMER, J. E. 2018. Disruptive Innovation: An Intellectual History and Directions for Future Research. 55, 1043-1078.

COLOMBO, M. G., GRILLI, L. & PIVA, E. 2006. In search of complementary assets: The determinants of alliance formation of high-tech start-ups. *Research policy,* 35, 1166-1199.

COOPER, R. G. 1996. Overhauling the new product process. *Industrial marketing management,* 25, 465-482.

D'ESTE, P., IAMMARINO, S., SAVONA, M. & VON TUNZELMANN, N. 2012. What hampers innovation? Revealed barriers versus deterring barriers. *Research Policy,* 41, 482-488.

DENZEN, N. K. & LINCOLN, Y. S. J. C. S. P. L. 2005. The Sage handbook of qualitative research.

DI STEFANO, G., GAMBARDELLA, A. & VERONA, G. 2012. Technology push and demand pull perspectives in innovation studies: Current findings and future research directions. *Research policy,* 41, 1283-1295.

DU, L., RAZZAQ, A. & WAQAS, M. 2023. The impact of COVID-19 on small- and medium-sized enterprises (SMEs): empirical evidence for green economic implications. *Environ Sci Pollut Res Int,* 30, 1540-1561.

DURFEE, W. & IAIZZO, P. 2016. *Medical device innovation handbook*, Lulu. com.

DURFEE, W. K. & IAIZZO, P. A. 2019. The medical device innovation process. *Engineering in Medicine.* Elsevier.

DUTTA, D. K. & CROSSAN, M. M. 2005. The nature of entrepreneurial opportunities: Understanding the process using the 4I organizational learning framework. *Entrepreneurship Theory and Practice,* 29, 425-449.

EAVES, F. F. & CLEM, M. 2021. Commentary on: The Development and Commercialization of Medical Technologies. *Aesthetic Surgery Journal*.

ESCOBAR, A., CHIU, P., QU, J., ZHANG, Y. & XU, C.-Q. 2021. Integrated microfluidic-based platforms for on-site detection and quantification of infectious pathogens: Towards on-site medical translation of sars-cov-2 diagnostic platforms. *Micromachines,* 12, 1079.

FABIANI, L., CARATELLI, V., FIORE, L., SCOGNAMIGLIO, V., ANTONACCI, A., FILLO, S., DE SANTIS, R., MONTE, A., BORTONE, M. & MOSCONE, D. 2021. State of the Art on the SARS-CoV-2 Toolkit for Antigen Detection: One Year Later. *Biosensors,* 11, 310.

GAMBARDELLA, A., HEATON, S., NOVELLI, E. & TEECE, D. J. 2021. Profiting from Enabling Technologies? *Strategy Science,* 6, 75-90.

GAO, J. & ZHANG, P. 2021. China's Public Health Policies in Response to COVID-19: From an "Authoritarian" Perspective. *Front Public Health,* 9, 756677.

GBADEGESHIN, S. A. 2019. The effect of digitalization on the commercialization process of high-Technology companies in the life sciences industry. *Technology Innovation Management Review,* 9.

GEORGE, G., HOWARD-GRENVILLE, J., JOSHI, A. & TIHANYI, L. 2016. Understanding and Tackling Societal Grand Challenges through Management Research. 59, 1880-1895.

GERKE, S., SHACHAR, C., CHAI, P. R. & COHEN, I. G. 2020. Regulatory, safety, and privacy concerns of home monitoring technologies during COVID-19. *Nature Medicine,* 26, 1176-1182.

GIBSON, D.V. & NAQUIN, H. 2011. Investing in innovation to enable global competitiveness: The case of Portugal. *Technological Forecasting and Social Change*, 78(8), 1299-1309.

GIRI, B., PANDEY, S., SHRESTHA, R., POKHAREL, K., LIGLER, F. S. & NEUPANE, B. B. 2021. Review of analytical performance of COVID-19 detection methods. *Analytical and bioanalytical chemistry,* 413, 35-48.

GUO, H., WANG, C., SU, Z. & WANG, D. 2020a. Technology Push or Market Pull? Strategic Orientation in Business Model Design and Digital Start-up Performance*. 37, 352-372.

GUO, H., WANG, C., SU, Z. & WANG, D. 2020b. Technology Push or Market Pull? Strategic Orientation in Business Model Design and Digital Start-up Performance*. *Journal of Product Innovation Management,* 37, 352-372.

GUPTA, R., KAZI, T. A., DEY, D., GHOSH, A., RAVICHANDIRAN, V., SWARNAKAR, S., ROY, S., BISWAS, S. R. & GHOSH, D. 2021. CRISPR detectives against SARS-CoV-2: a major setback against COVID-19 blowout. *Applied Microbiology and Biotechnology,* 105, 7593-7605.

HALLBERG, N. L. & BRATTSTRÖM, A. 2019. Concealing or revealing? Alternative paths to profiting from innovation. *European Management Journal,* 37, 165-174.

HANEL, P. 2006. Intellectual property rights business management practices: A survey of the literature. *Technovation,* 26, 895-931.

HAYS, D. G. & MCKIBBEN, W. B. 2021. Promoting Rigorous Research: Generalizability and Qualitative Research. 99, 178-188.

HELFAT, C. E. & RAUBITSCHEK, R. S. 2018. Dynamic and integrative capabilities for profiting from innovation in digital platform-based ecosystems. *Research Policy,* 47**,** 1391-1399.
HOSSEINI, A., PANDEY, R., OSMAN, E., VICTORIOUS, A., LI, F., DIDAR, T. & SOLEYMANI, L. 2020. Roadmap to the bioanalytical testing of COVID-19: from sample collection to disease surveillance. *ACS sensors,* 5**,** 3328-3345.
HÖTTE, K. 2023. Demand-pull, technology-push, and the direction of technological change. *Research Policy,* 52**,** 104740.
HSIEH, H.-F. & SHANNON, S. E. 2005. Three approaches to qualitative content analysis. *Qualitative health research,* 15**,** 1277-1288.
HUI, Q., PAN, Y. & YANG, Z. 2020. based devices for rapid diagnostics and testing sewage for early warning of COVID-19 outbreak. *Case Studies in Chemical Environmental Engineering,* 2**,** 100064.
IBRAHIM, N., JAMALUDDIN, N. D., TAN, L. L. & MOHD YUSOF, N. Y. 2021. A Review on the Development of Gold and Silver Nanoparticles-Based Biosensor as a Detection Strategy of Emerging and Pathogenic RNA Virus. *Sensors,* 21**,** 5114.
IJZERMAN, M. J., KOFFIJBERG, H., FENWICK, E. & KRAHN, M. 2017. Emerging use of early health technology assessment in medical product development: a scoping review of the literature. *Pharmacoeconomics,* 35**,** 727-740.
ILLIASHENKO, S., ILLIASHENKO, N., SHYPULINA, Y., RAIKO, D. & BOZHKOVA, V. 2021. Approach to assessment of prerequisites for implementation of strategic directions of innovative development of industrial enterprises. *Eastern-European Journal of Enterprise Technologies,* 3**,** 31-46.
JEFFERYS, D. B. 2001. The regulation of medical devices and the role of the Medical Devices Agency. 52**,** 229-235.
KAAL, W. A. & VERMEULEN, E. P. M. 2017. How to Regulate Disruptive Innovation From Facts To Data. *Jurimetrics,* 57**,** 169-209.
KAMAT, S., KUMARI, M. & JAYABASKARAN, C. 2021. Nano-engineered tools in the diagnosis, therapeutics, prevention, and mitigation of SARS-CoV-2. *Journal of Controlled Release,* 338**,** 813-836.
KHAN, A., KRISHNAN, S. & DHIR, A. 2021. Electronic government and corruption: Systematic literature review, framework, and agenda for future research. *Technological Forecasting and Social Change,* 167**,** 120737.
KIM, L. 1998. Crisis Construction and Organizational Learning: Capability Building in Catching-up at Hyundai Motor. *Organization Science,* 9**,** 506-521.
KONTOU, P. I., BRALIOU, G. G., DIMOU, N. L., NIKOLOPOULOS, G. & BAGOS, P. G. 2020. Antibody tests in detecting SARS-CoV-2 infection: a meta-analysis. *Diagnostics,* 10**,** 319.
KRAUS, S., BREIER, M. & DASÍ-RODRÍGUEZ, S. 2020. The art of crafting a systematic literature review in entrepreneurship research. *International Entrepreneurship and Management Journal,* 16**,** 1023-1042.
KRIPPENDORFF, K. 2004. *Content Analysis: An Introduction to Its Methodology,* Thousand Oaks, SAGE Publications.
LA MARCA, A., CAPUZZO, M., PAGLIA, T., ROLI, L., TRENTI, T. & NELSON, S. M. 2020. Testing for SARS-CoV-2 (COVID-19): a systematic review and clinical guide to molecular and serological in-vitro diagnostic assays. *Reproductive biomedicine online,* 41**,** 483-499.
LAMPROU, D. A. 2020. Emerging technologies for diagnostics and drug delivery in the fight against COVID-19 and other pandemics. *Expert Review of Medical Devices,* 17**,** 1007-1012.
LEICHLE, T., NICU, L. & ALAVA, T. 2020. MEMS biosensors and COVID-19: missed opportunity. *ACS sensors,* 5**,** 3297-3305.
LEONIDOU, E., CHRISTOFI, M., VRONTIS, D. & THRASSOU, A. 2020. An integrative framework of stakeholder engagement for innovation management and entrepreneurship development. *Journal of Business Research,* 119**,** 245-258.
LIANG, X., ZHANG, Y., WANG, J., YE, Q., LIU, Y. & TONG, J. 2021. Diagnosis of COVID-19 pneumonia based on graph convolutional network. *Frontiers in Medicine,* 7**,** 1071.
LICHTENTHALER, U. 2021. Profiting from innovation in the aftermath of an economic crisis. *Journal of Research in Marketing and Entrepreneurship,* 23**,** 282-294.
LIN, C.-T. & WANG, S.-M. 2005. Biosensor commercialization strategy-A theoretical approach. *Frontiers in Bioscience,* 10**,** 99-106.
LUBIK, S., LIM, S., PLATTS, K. & MINSHALL, T. 2013. Market-pull and Technology-push in Manufacturing Start-ups in Emerging Industries. *Journal of Manufacturing Technology Management*.
LUGO-MARÍN, J., GISBERT-GUSTEMPS, L., SETIEN-RAMOS, I., ESPAÑOL-MARTÍN, G., IBAÑEZ-JIMENEZ, P., FORNER-PUNTONET, M., ARTEAGA-HENRÍQUEZ, G., SORIANO-DÍA, A., DUQUE-YEMAIL, J. D. &

RAMOS-QUIROGA, J. A. 2021. COVID-19 pandemic effects in people with Autism Spectrum Disorder and their caregivers: Evaluation of social distancing and lockdown impact on mental health and general status. *Research in Autism Spectrum Disorders,* 83**,** 101757.

LUKAS, H., XU, C., YU, Y. & GAO, W. 2020. Emerging telemedicine tools for remote COVID-19 diagnosis, monitoring, and management. *ACS nano,* 14**,** 16180-16193.

MAINE, E. & GARNSEY, E. 2006. Commercializing generic technology: The case of advanced materials ventures. *Research Policy,* 35**,** 375-393.

MAREŠOVÁ, P., KLÍMOVÁ, B., HONEGR, J., KUČA, K., IBRAHIM, W. N. H. & SELAMAT, A. 2020. Medical Device Development Process, and Associated Risks and Legislative Aspects-Systematic Review. *Frontiers in public health,* 8**,** 308.

MATTIOLI, I. A., HASSAN, A., OLIVEIRA JR, O. N. & CRESPILHO, F. N. 2020. On the challenges for the diagnosis of SARS-CoV-2 based on a review of current methodologies. *ACS sensors,* 5**,** 3655-3677.

MAZINI, L., EZZOUBI, M. & MALKA, G. 2021. Overview of current adipose-derived stem cell (ADSCs) processing involved in therapeutic advancements: flow chart and regulation updates before and after COVID-19. *Stem Cell Research & Therapy,* 12**,** 1-17.

MILES, M. B. & HUBERMAN, A. M. 1994. *Qualitative data analysis: An expanded sourcebook,* Thousand Oaks, CA sage.

MISA, N.-Y., PEREZ, B., BASHAM, K., FISHER-HOBSON, E., BUTLER, B., KING, K., WHITE, D. A. E. & ANDERSON, E. S. 2021. Racial/ethnic disparities in COVID-19 disease burden & mortality among emergency department patients in a safety net health system. *The American Journal of Emergency Medicine,* 45**,** 451-457.

MONTIEL, I., PARK, J., HUSTED, B. W. & VELEZ-CALLE, A. 2022. Tracing the connections between international business and communicable diseases. *Journal of International Business Studies,* 53**,** 1785-1804.

MORRICONE, S., MUNARI, F., ORIANI, R. & DE RASSENFOSSE, G. 2017. Commercialization Strategy and IPO Underpricing. *Research Policy,* 46**,** 1133-1141.

MUCCI, F., MUCCI, N. & DIOLAIUTI, F. 2020. Lockdown and isolation: psychological aspects of COVID-19 pandemic in the general population. *Clinical Neuropsychiatry,* 17**,** 63-64.

NAIDOO, V. 2010. Firm survival through a crisis: The influence of market orientation, marketing innovation and business strategy. *Industrial Marketing Management,* 39**,** 1311-1320.

NARITA, F., WANG, Z., KURITA, H., LI, Z., SHI, Y., JIA, Y. & SOUTIS, C. 2021. A review of piezoelectric and magnetostrictive biosensor materials for detection of COVID-19 and other viruses. *Advanced Materials,* 33**,** 2005448.

NASIROV, S., GOKH, I. & FILIPPAIOS, F. 2022. Technological radicalness, R&D internationalization, and the moderating effect of intellectual property protection. *Journal of Business Research,* 145**,** 215-227.

NGAH-KIING LIM, E., DAS, S. S. & DAS, A. 2009. Diversification strategy, capital structure, and the Asian financial crisis (1997–1998): evidence from Singapore firms. *Strategic Management Journal,* 30**,** 577-594.

NIETO CUBERO, J., GBADEGESHIN, S. A. & CONSOLACIÓN, C. 2021. Commercialization of disruptive innovations: Literature review and proposal for a process framework. *International Journal of Innovation Studies,* 5**,** 127-144.

O'CONNOR, G. C., RAVICHANDRAN, T. & ROBESON, D. 2008. Risk management through learning: Management practices for radical innovation success. *The Journal of High Technology Management Research,* 19**,** 70-82.

OYEWOLE, A. O., BARRASS, L., ROBERTSON, E. G., WOLTMANN, J., O'KEEFE, H., SARPAL, H., DANGOVA, K., RICHMOND, C. & CRAIG, D. 2021. COVID-19 Impact on Diagnostic Innovations: Emerging Trends and Implications. 11**,** 182.

OZER, T. & HENRY, C. S. 2021. based analytical devices for virus detection: Recent strategies for current and future pandemics. *TrAC Trends in Analytical Chemistry,* 144**,** 116424.

PADHAN, R. & PRABHEESH, K. P. 2021. The economics of COVID-19 pandemic: A survey. *Economic Analysis and Policy,* 70**,** 220-237.

PARIHAR, A., RANJAN, P., SANGHI, S. K., SRIVASTAVA, A. K. & KHAN, R. 2020. Point-of-care biosensor-based diagnosis of COVID-19 holds promise to combat current and future pandemics. *ACS Applied Bio Materials,* 3**,** 7326-7343.

PARK, J., MONTIEL, I., HUSTED, B. W. & BALAREZO, R. 2022. The Grand Challenge of Human Health: A Review and an Urgent Call for Business–Health Research. *Business & Society,* 61**,** 1353-1415.

PARUPUDI, T., PANCHAGNULA, N., MUTHUKUMAR, S. & PRASAD, S. 2020. Evidence-based point-of-care technology development during the COVID-19 pandemic. *Biotechniques,* 70**,** 58-67.

PEKOVIC, S. & BOUZIRI, A. 2021. Overcoming obstacles to innovation: can environmental management practices help? *Knowledge Management Research & Practice*, 1-16.
PELTZMAN, S. 1998. The economic theory of regulation after a decade of deregulation. *In:* BALDWIN, R., SCOTT, C. & HOOD, C. (eds.) *A Reader on Regulation (Oxford Readings in Socio-Legal Studies).* UK: Oxford University Press.
PETRICEVIC, O. & TEECE, D. J. 2019. The structural reshaping of globalization: Implications for strategic sectors, profiting from innovation, and the multinational enterprise. *Journal of International Business Studies,* 50**,** 1487-1512.
PIERCE, M., HOPE, H., FORD, T., HATCH, S., HOTOPF, M., JOHN, A., KONTOPANTELIS, E., WEBB, R., WESSELY, S., MCMANUS, S. & ABEL, K. M. 2020. Mental health before and during the COVID-19 pandemic: a longitudinal probability sample survey of the UK population. *The Lancet Psychiatry,* 7**,** 883-892.
PIETZSCH, J. B., SHLUZAS, L. A., PATÉ-CORNELL, M. E., YOCK, P. G. & LINEHAN, J. H. 2009. Stage-gate process for the development of medical devices. *Journal of Medical Devices,* 3.
PISANO, G. 2006. Profiting from innovation and the intellectual property revolution. *Research policy,* 35**,** 1122-1130.
PITELIS, C. N., DESYLLAS, P. & PANAGOPOULOS, A. 2018. Profiting from Innovation through Cross-Border Market co-Creation and co-Opetition: The Case of Global Pharmaceuticals. *European Management Review,* 15**,** 491-504.
PRATI, G. & MANCINI, A. D. 2021. The psychological impact of COVID-19 pandemic lockdowns: a review and meta-analysis of longitudinal studies and natural experiments. *Psychological medicine,* 51**,** 1-11.
PRIYANKA, OP, C. & SINGH, I. 2020. Diagnosis of SARS-CoV-2: a review on the current scenario and future outlook. *Acta virologica,* 64**,** 396-408.
RAI, P., KUMAR, B. K., DEEKSHIT, V. K., KARUNASAGAR, I., KARUNASAGAR, I. J. A. M. & BIOTECHNOLOGY 2021. Detection technologies and recent developments in the diagnosis of COVID-19 infection. 105**,** 441-455.
RANDOLPH, H. E. & BARREIRO, L. B. 2020. Herd immunity: understanding COVID-19. *Immunity,* 52**,** 737-741.
RASMI, Y., LI, X., KHAN, J., OZER, T. & CHOI, J. R. 2021. Emerging point-of-care biosensors for rapid diagnosis of COVID-19: current progress, challenges, and future prospects. *Analytical and bioanalytical chemistry,* 413**,** 4137-4159.
REEVES, M., LANG, N. & CARLSSON-SZLEZAK, P. 2020. Lead your business through the coronavirus crisis. *Harvard Business Review,* 27**,** 2-7.
REZAEI, M., RAZAVI BAZAZ, S., ZHAND, S., SAYYADI, N., JIN, D., STEWART, M. P. & EBRAHIMI WARKIANI, M. 2020. Point of Care Diagnostics in the Age of COVID-19. *Diagnostics,* 11**,** 9.
RHAIEM, K. & AMARA, N. 2021. Learning from innovation failures: a systematic review of the literature and research agenda. *Review of Managerial Science,* 15**,** 189-234.
RICHARDS, N. & HUDSON, I. 2016. UK medicines regulation: responding to current challenges. *British journal of clinical pharmacology,* 82**,** 1471-1476.
ROGERS EVERETT, M. 1995. Diffusion of innovations, vol. 12. *New York*.
ROTHAERMEL, F. T. & HILL, C. W. 2005. Technological discontinuities and complementary assets: A longitudinal study of industry and firm performance. *Organization Science,* 16**,** 52-70.
SACHS, J. D., KARIM, S. S. A., AKNIN, L., ALLEN, J., BROSBØL, K., COLOMBO, F., BARRON, G. C., ESPINOSA, M. F., GASPAR, V., GAVIRIA, A., HAINES, A., HOTEZ, P. J., KOUNDOURI, P., BASCUÑÁN, F. L., LEE, J.-K., PATE, M. A., RAMOS, G., REDDY, K. S., SERAGELDIN, I., THWAITES, J., VIKE-FREIBERGA, V., WANG, C., WERE, M. K., XUE, L., BAHADUR, C., BOTTAZZI, M. E., BULLEN, C., LARYEA-ADJEI, G., AMOR, Y. B., KARADAG, O., LAFORTUNE, G., TORRES, E., BARREDO, L., BARTELS, J. G. E., JOSHI, N., HELLARD, M., HUYNH, U. K., KHANDELWAL, S., LAZARUS, J. V. & MICHIE, S. 2022. The Lancet Commission on lessons for the future from the COVID-19 pandemic. *The Lancet*.
SALAZAR-ELENA, J. C., LÓPEZ, A., GUIMÓN DE ROS, J. & CANCINO, C. A. 2020. Sincerity is a dangerous thing: On how appropriability regimes shape innovation strategies. *Journal of Intelligent & Fuzzy Systems,* 38**,** 5521-5528.
SANSONE, C., HILLETOFTH, P., ERIKSSON, D. J. I. M. & SYSTEMS, D. 2017. Critical operations capabilities for competitive manufacturing: A systematic review.
SANTIAGO, I. 2020. Trends and innovations in biosensors for COVID-19 mass testing. *ChemBioChem,* 21**,** 2880-2889.
SCHUMPETER, J. A. 1950. Capitalism, Socialism and Democracy: (Paperback). Abingdon: Routledge.

SETHI, A., AHUJA, I. & SINGLA, A. 2018. Shifts Between Technology Push and Market Pull Strategies for Sustainable Development in Manufacturing Industries. *In:* CONNELL, J., AGARWAL, R., SUSHIL & DHIR, S. (eds.) *Global Value Chains, Flexibility and Sustainability.* Singapore: Springer.

SEURING, S., MÜLLER, M., WESTHAUS, M. & MORANA, R. 2005. Conducting a literature review—the example of sustainability in supply chains. *In:* KOTZAB, H., SEURING, S., MÜLLER, M. & REINER, G. (eds.) *Research methodologies in supply chain management.* Physica-Verlag HD.

SHAFFAF, T., FOROUHI, S. & GHAFAR-ZADEH, E. 2021. Towards Fully Integrated Portable Sensing Devices for COVID-19 and Future Global Hazards: Recent Advances, Challenges, and Prospects. *Micromachines,* 12**,** 915.

SHANG, T.-T., TIAN, M., TAO, N. & CHEN, Y. 2021. Market-oriented green innovation model: conceptualisation and scale development of disruptive green innovation. *Asian Journal of Technology Innovation***,** 1-17.

SHARMA, T. & BASHIR, M. 2020. Use of apps in the COVID-19 response and the loss of privacy protection. *Nature Medicine,* 26**,** 1165-1167.

SHEN, Y., ANWAR, T. B. & MULCHANDANI, A. 2021. Current status, advances, challenges and perspectives on biosensors for COVID-19 diagnosis in resource-limited settings. *Sensors and Actuators Reports,* 3**,** 100025.

SI, S. & CHEN, H. 2020. A literature review of disruptive innovation: What it is, how it works and where it goes. *Journal of Engineering and Technology Management,* 56**,** 101568.

SIDDAWAY, A. P., WOOD, A. M. & HEDGES, L. V. 2019. How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. *Annu Rev Psychol,* 70**,** 747-770.

SLATER, S. F. 1997. Developing a customer value-based theory of the firm. *Journal of the Academy of Marketing Science,* 25**,** 162-167.

SMITH, V., WARTY, R., NAIR, A., KRISHNAN, S., SURSAS, J. A., DA SILVA COSTA, F., VOLLENHOVEN, B. & WALLACE, E. M. 2019. Defining the clinician's role in early health technology assessment during medical device innovation–a systematic review. *BMC health services research,* 19**,** 1-14.

SOENKSEN, L. R. & YAZDI, Y. 2017. Stage-gate process for life sciences and medical innovation investment. *Technovation,* 62**,** 14-21.

SONGKAJORN, Y. & THAWESAENGSKULTHAI, N. 2014. Medical device innovation development process. *International Journal of Innovation and Technology Management,* 11**,** 1450027.

STIGLER, G. 1971. The theory of economic regulation. *The Bell journal of economics management science,* 2**,** 3-21.

STIGLER, G. 1974. Free riders and collective action: An appendix to theories of economic regulation. *The Bell Journal of Economics Management Science,* 5**,** 359-365.

SURI, H. & CLARKE, D. 2009. Advancements in research synthesis methods: From a methodologically inclusive perspective. *Review of Educational Research,* 79**,** 395-430.

SWINK, M. & NAIR, A. 2007. Capturing the competitive advantages of AMT: Design–manufacturing integration as a complementary asset. *Journal of Operations Management,* 25**,** 736-754.

TANDA, A. 2018. The food and beverages stock performance during and after the 2007-2011 crisis. *International Journal of Business Performance Management,* 19**,** 280-288.

TANG, Y.-W., SCHMITZ, J. E., PERSING, D. H. & STRATTON, C. W. 2020. Laboratory diagnosis of COVID-19: current issues and challenges. *Journal of clinical microbiology,* 58**,** 1-9.

TEECE, D. 1986. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research policy,* 15**,** 285-305.

TEECE, D. 2006. Reflections on "profiting from innovation". *Research policy,* 35**,** 1131-1146.

TEECE, D. 2018. Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy,* 47**,** 1367-1387.

THOMPSON, D. & LEI, Y. 2020. Mini review: Recent progress in RT-LAMP enabled COVID-19 detection. *Sensors Actuators Reports,* 2**,** 100017.

THUNSTROM, L., ASHWORTH, M., FINNOFF, D. & NEWBOLD, S. 2020. Hesitancy towards a COVID-19 vaccine and prospects for herd immunity. *Available at SSRN 3593098*.

TIMSIT, J.-P., CASTIAUX, A., TRUONG, Y., ATHAIDE, G. A. & KLINK, R. R. 2015. The effect of market-pull vs. resource-push orientation on performance when entering new markets. *Journal of Business Research,* 68**,** 2005-2014.

VAN DINTER, R., TEKINERDOGAN, B. & CATAL, C. 2021. Automation of systematic literature reviews: A systematic literature review. *Information and Software Technology,* 136**,** 106589.

VANDENBERG, O., MARTINY, D., ROCHAS, O., VAN BELKUM, A. & KOZLAKIDIS, Z. 2021. Considerations for diagnostic COVID-19 tests. *Nature Reviews Microbiology,* 19**,** 171-183.

WANG, M., FU, A., HU, B., TONG, Y., LIU, R., LIU, Z., GU, J., XIANG, B., LIU, J. & JIANG, W. 2020a. Nanopore targeted sequencing for the accurate and comprehensive detection of SARS-CoV-2 and other respiratory viruses. *Small,* 16**,** 2002169.

WANG, X., QIN, Y., XU, Z. & ŠKARE, M. 2022. A look at the focus shift in innovation literature due to Covid-19 pandemic. *Journal of Business Research,* 145**,** 1-20.

WANG, Y., HONG, A., LI, X. & GAO, J. 2020b. Marketing innovations during a global crisis: A study of China firms' response to COVID-19. *Journal of Business Research,* 116**,** 214-220.

WANG, Y., RATTANAVIPAPONG, W. & TEERAWATTANANON, Y. 2021a. Using health technology assessment to set priority, inform target product profiles, and design clinical study for health innovation. *Technological Forecasting and Social Change,* 172**,** 121000.

WANG, Z., CHEN, J., KHAN, S. A., LI, F., SHEN, J., DUAN, Q., LIU, X. & ZHU, J. 2021b. Plasmonic Metasurfaces for Medical Diagnosis Applications: A Review. *Sensors,* 22**,** 133.

WU, K., SAHA, R., SU, D., KRISHNA, V. D., LIU, J., CHEERAN, M. C.-J. & WANG, J.-P. 2020. Magnetic-nanosensor-based virus and pathogen detection strategies before and during COVID-19. *ACS Applied Nano Materials,* 3**,** 9560-9580.

XIAO, Y. & WATSON, M. 2019. Guidance on conducting a systematic literature review. *Journal of Planning Education and Research,* 39**,** 93-112.

YAGHMAIE, P., VANHAVERBEKE, W. & ROIJAKKERS, N. 2020. Value Creation, Value Capturing, and Management Challenges in Innovation Ecosystems: A Qualitative Study of the Nano-Electronics Industry in Belgium and the Netherlands. *Journal of Business Ecosystems (JBE),* 1**,** 20-37.

YAZDANPANAH, F., HAMBLIN, M. R. & REZAEI, N. 2020. The immune system and COVID-19: Friend or foe? *Life sciences,* 256**,** 117900.

YU, C. Y., CHAN, K. G., YEAN, C. Y. & ANG, G. Y. 2021. Nucleic acid-based diagnostic tests for the detection SARS-CoV-2: an update. *Diagnostics,* 11**,** 53.

ZHENG, L., MIAO, M., LIM, J., LI, M., NIE, S. & ZHANG, X. 2020. Is lockdown bad for social anxiety in COVID-19 regions?: A national study in the SOR perspective. *International journal of environmental research public health,* 17**,** 4561.

Appendix I

Research objectives and findings of the Covid-19 diagnostic technologies articles

Author	Research objective	Finding
Afzal (2020)	Reviewing the recent advances in molecular detection technologies for COVID-19 and analysis of their clinical performance.	•The need for independent and accurate evaluation of commercial and approved diagnostic tests to identify diagnostic errors and determine their effectiveness. •Validation of commercial diagnostic tests with limited and insufficient clinical samples due to lack of sufficient time for research and development in pandemic conditions and risk of inaccurate results.
Bhalla et al. (2020)	Investigating the similarities and differences between RNA viral infections from the perspective of COVID-19 and the diagnostic technologies required.	The recent advances in nanotechnology and the creation of a multidisciplinary approach in the future to quickly and timely identify viruses and prevent the spread of infectious diseases in the early stages.
Hosseini et al. (2020)	• Reviewing the emerging point-of-care (POC) diagnostic with usability at any time and place without high cost and skilled laboratory personnel. • Reviewing the role of artificial intelligence in analyzing large volumes of data generated by diagnostic technologies for better pandemic management.	• The need to data combined from multiple technologies for early diagnosis, treatment selection, disease monitoring, epidemiological surveillance, and vaccine and treatment development. • The challenge of implementing AI for immediate COVID-19 analysis due to the limited COVID-19-specific data sets.
Leichle et al. (2020)	Analyzing the cause of less-utilizing mechanical sensors on the front line of diagnosis COVID-19 tests.	Indicating the pitfalls to developing all types of biosensors in the future. To provide tools that can assist medical decision-making criteria of sensitivity must be fulfilled: most importantly, robustness and reproducibility, but also portability, low cost, minimal and generic sample preparation, and a multiplex approach allowing access to precise molecular signatures with integrated reference and calibration. In order to meet these criteria, it is important to design the tools as a whole rather than taking care of the sole sensor and its sensitivity: how to integrate, functionalize, passivate, and store the sensor, how to multiplex the measurement, which sample preparation to use or adapt, and how to standardize the measurement protocols must be the generic set of specifications for future biosensors and, specifically, for MEMS/mechanical biosensors, which so far have not demonstrated any in-the-field capability.
Lukas et al. (2020)	Summarizing current applications of mHealth sensors for COVID-19 and their potential role in better controlling the current pandemic.	Doubts about the inaccuracy of LFA test results compared to RT-PCR and the help of electrochemical sensors to address this challenge by producing accurate and efficient results.
Mattioli et al. (2020)	Identifying the strengths and weakness of the main diagnostic strategies for SARS-CoV-2, including methods to detect genetic material of the virus and immunoassays.	The need for developing low-cost alternatives to the expensive methods by novel uses of nanomaterials.
Parihar et al. (2020)	Discussing biosensor platforms (electrochemical, optical, and microfluidics) for detecting viral infections and summarizing the challenges of their development and commercialization.	• The applicability of Biosensor based point-of-care methods as both home and environmental monitoring diagnostic tools in public places. • The possibility of rapid qualitative estimation of analyze by optical sensors. •The possibility of providing more accurate quantitative results by electrochemical biosensors.
Parupudi et al. (2020)	Reviewing the role of evidence-based point-of-care technologies for early detection and treatment in the field of COVID-19.	•Failure to approve serological tests as a standard test for detecting Covid 19 and creating an extraordinary opportunity for the development of biosensors for serological testing. •The Possibility of increasing the clinical application of serological tests by integrating biosensor platforms with wireless technologies.
Priyanka et al. (2020)	Reviewing existing and developed diagnostic methods of COVID-19 and the need to develop integrated smart devices foe managing the pandemic.	The challenges and low sensitivity of current SARS-CoV-2 diagnostic methods and the need for further research and development and the establishment of integrated intelligent diagnostics to perform accurate and reliable results on a large scale.

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Rezaei et al. (2020)	Reviewing common magnetic Nano sensing techniques and Magnetic point-of-care diagnostic kits to manage the current and future outbreaks.	• The capability of magnetic Nano sensors for antigen, antibody, and nucleic acid detection. • Hindering the magnetic Nano sensor platforms applications due to their dependence of tests on labels for detection and/or separation. •The need to optimization of the magnetic labels, improvement of the magnetic sensitivity, and the development of label-free magnetic biosensors to make magnetic POC platforms more competitive in the market. • The ability of magnetic Nano sensors to reform today's expensive and labor-intensive diagnostics and make cost-effective, user-friendly detection protocols possible with superior/comparable sensitivity in the future.
Wu et al. (2020)	• Overviewing different types of sensors complementary metal-oxide semiconductor (CMOS) biosensors suitable for implementing point-of-care (PoC) platforms. • Studying the protein-based kits developed for COVID-19 detection.	• The ability of a CMOS biosensor incorporated in a microfluidic platform to provide short time workflow, high throughput measurement, low the limit of detection, high resolution, low power consumption, portability, automation, multiplexing, and the parallel detection of a series of parameters. • there is a new avenue for the development of portable low-cost CMOS-based PoC platforms in urgent pandemic situations due to recent advances in CMOS-based biosensors by recent research works.
Azmi et al. (2021)	Explaining two bottlenecks to scaling up COVID-19 testing namely the need for sophisticated instruments and well-trained healthcare professionals, and proposed integrated Saliva-based and smartphone testing	Providing high-sensitive test results of the lateral-flow test strip and integrated the test strip results with a smartphone application for field-deplorability and home testing.
Battaglia et al. (2021a)	Exploring how academic spinoffs to reshape their internal processes and external linkages to survive the disrupting economic impact of the pandemic.	•It outlines how academic spinoffs are able to react to exogenous shocks to reshape their business models and quickly provide solutions aimed at tackling society's needs based on developing 'legacy competences and practices. • It illustrates how COVID-19 as an exogenous 'shock' for spinoffs forcing Spin offs to overcome the dictates imposed by the technology push development. path • It provides some key insights on the societal impact of science commercialization.
Benda et al. (2021)	Comparing the commercialized testing platforms from their analyzing systems, specimen collection protocols, testing methodologies, supply chain logistics, and related attributes.	•Testing platforms are scaled-up and faster screening by different strategies. • The near-term challenges fib in detecting fine infectivity profiles, mapping the transmission dynamics of new variants, lowering the cost for testing, training a large healthcare workforce, and providing test kits for the masses • There is a possibility of universal access to COVID-19 testing and diagnostics shortly while cognizant of the implicit tradeoffs during new testing platforms' development and distribution cycles.
Campos-Ferreira et al. (2021)	Introducing existing paper-based methods for SARS-CoV-2 detection and summarizing their analytical performances, strengths, and weaknesses.	• The great potential of the paper-based detection tools to complement the conventional PCR methods due to their advantages including cost-effective, user friendly, and time-efficient. • The immunoassay tests are the simplest type of the paper-based detection tools, which is ideal for fast decision-making but lacks both sensitivity and specificity. • Integrate CRISPR tests with paper-based platforms is challenging.
Carroll and McNamara (2021)	Evaluating alternative commercially available kits provided sensitivity and accuracy of SARS-CoV-2 genome detection comparable to those used by regional National Healthcare Services (NHS).	• Demonstrating greatly effect of sample treatment on downstream performance of SARS-CoV-2 diagnostic kits. • Showing the reduction time from swab receipt to outcome of test result with new method. • Presenting new protocols to accelerate testing, and reducing cost and environmental impact.
Escobar et al. (2021)	• Presenting criteria for the development of effective and viable on-site microfluidic	• The ability of integrated microfluidic-based diagnostic platforms to screen for and analyze patient samples in a more realistic setting without

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	diagnostic platforms for several notable pathogens, especially SARS-CoV-2. • Evaluating the use of microfluidic integration to improve upon currently, and previously, existing platforms for the detection of infectious pathogens. • Discussing a stage-wise means to translate the findings into a fundamental framework towards the development of more effective on-site SARS-CoV-2 microfluidic-integrated platforms.	sacrificing accuracy or robustness. • The ability of integrated microfluidic-based diagnostic platforms to effectively test for viral DNA/RNA under a wide range of conditions using a self-contained and versatile SIMPLE chip for both qualitative and quantitative analysis. • The possibility to Achieve the WHO's ASSURED criteria, which defines the minimum standards for developing on-site medical diagnostic tests, through micro fluidic integration.
Fabiani et al. (2021)	Reporting the latest diagnostic achievements of SARS-CoV-2 antigens detection using electrochemical and optical biosensors.	•Insufficient sensitivity and specificity of current diagnostic tests for early detection of infection and researchers' efforts to develop more sensitive biosensors using nanotechnology. •Convergence of interdisciplinary technologies and integration of biosensors with technologies such as the Internet of Things to help manage and control pandemics.
Giri et al. (2021)	Comparing the characteristics of recently developed methods for detecting SARS-CoV-2 including the limit of detection, sensitivity, specificity, ease of use, affordability, and availability of accessories.	• The need to establish a quality assurance and regulatory framework due to lack an established reference standard, the use of differing sample collection and preparation methods in available diagnostic methods. • The need to provide rapid, simple, low-cost, portable, temperature-stable assay systems that are appropriate resource-limited settings.
Gupta et al. (2021)	Reviewing the present CRISPR-based approaches for diagnosis of SARS-CoV-2 and their challenges.	• The need to eliminate the most crucial drawback of CRISPR-based methods (assay runtime and complexity of the process) to comply with the WHO guidelines for a suitable point of care diagnostic device. • The ability of the CRISPR-based diagnostics in detecting SARS-CoV-2 and the emerging variants. •The ability of the CRISPR-based diagnostics to providing results within an hour with 100% accuracy, sensitivity, and high specificity as compared to the standard PCR method.
Ibrahim et al. (2021)	Providing an overview on nanoparticles-based biosensors that target pathogenic RNA viruses, toward a robust and effective detection strategy of the existing or newly emerging human viral diseases such as SARS-CoV-2.	•Showing on importance of using noble metals to develop nanoparticles-based. biosensors • Providing broad knowledge about several analytical methods to develop nanoparticles-based biosensors.
Kamat et al. (2021)	Reviewing the role of nanotechnology in the field of diagnosis, treatment and prevention of SARS-CoV-2.	• The ability of Nano sensors to replace existing SARS-CoV-2 diagnostic and therapeutic methods •The need for understanding of nano-biointeractionsand biological responses with nano-tools and SARS-CoV-2.
Liang et al. (2021)	Proposing a three-dimensional (3D) deep learning method with integrating Chest Computed Tomography (CT) and Graph Convolutional Network (GCN) to incorporate multiple datasets	Proposing transfer learning method designing a COVID-19 graph in GCN, and analyzing the feature differences between different equipment types.
Ozer and Henry (2021)	Summarizing the fabrication and detection methods of paper-based devices for virus sensing.	The role of nanotechnology in overcoming diagnostic limitations of the paper-based devices method involves inadequate accuracy and stability.
Rasmi et al. (2021)	Reviewing recent developments in various types of POC biosensors, describing and comparing their benefits.	• The key role of the biosensors in POC testing during the pandemic, because of their simplicity, rapidity, cost-effectiveness, and portability appropriate ability of Antibody tests to detect late-stage or past infections • The effectiveness of nucleic acid tests in identifying the early stage of infection. • The higher sensitivity and specificity, and more lengthy and complicated processes of the current nucleic acid tests in contrast to antibody tests. • The ability of antibody tests to enable fast decision-making and health management in remote settings because of their shorter turnaround time. • The detection of both early and late stages of COVID-19 infection and

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		providing more accurate and reliable results by combination of both IgG/IgM and nucleic acid tests.
Shaffaf et al. (2021)	Describing the principal diagnostic methods developed during the COVID-19 pandemic.	The electrochemical sensing platforms are an ideal point-of-care diagnostic tools for pandemic scenarios due to their high sensitivity and selectivity, easy handling and interpretation (without specialized technicians), and easy execution in the field (without the need for laboratory structure).
Vandenberg et al. (2021)	Summarizing the key role of diagnostic tests and their technical problems during the first wave of COVID-19.	• The necessity for further optimization, more extensive clinical and epidemiological validation, including formal FDA approval for application of current developed tools • lacking of biobanks and the following up of actual patients • The optimality of diagnostic tests depends on the full engagement of the community and the use of protective equipment by individuals.
Wang et al. (2021b)	Enumerate the fundamental mechanism of plasmonic metasurfaces sensing and present their detection in human tumors and COVID-19.	Determining advantages of plasmonic metasurfaces sensing namely rapid sampling, streamlined processes, high sensitivity, and easy accessibility.
Yu et al. (2021)	Summarizing, comparing, and discussing the potential future of latest POC immunoassay, nucleic acid-based and clustered regularly interspaced short palindromic repeats-(CRISPR)-mediated tests for SARSCoV 2.	• Antigen and nucleic acid amplification and detection methods are more suitable than antibody tests for the early and accurate detection of acute infection with SARS-CoV-2. • Commercial kits for viral SARS-CoV-2 antigen detection on POC formats have become widely available in late 2020 and are an appealing solution. • RT-PCR techniques are severely limited in handling pandemic situations, particularly in cities with a fast-growing number of infected patients. • All Isothermal Amplification technologies require more considerable clinical validation to determine their specificity, sensitivity, positive predictive value (PPV), and negative predictive value (NPV), specifically in the detection of asymptomatic infections. • CRISPR-Cas-based detection methods require an amplification and several manual handling steps, thereby complicating them whole process.