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The three pointers of research and development (R&D) for growth-boosting sustainable innovation system

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ABSTRACT

Research and development (R&D) is frequently touted and labelled as the fundamental engine for creating sustainable innovations and achieving climate transitions. Yet, recent R&D efforts have struggled to live up to the widespread life-altering results they delivered in the 1960s when the term R&D was coined. In our attempt to address this concern, we propose a sustainability pathway model to achieving an economically viable innovation system that is anchored in three important pointers of R&D which have long been viewed as mutually distinct components in R&D budgets—*investment, talent,* and *learning institutions*. Directing attention to the pervasive need to align R&D investments with talents and learning institutions, we delineate how these pointers of R&D coming together to constitute a trivalent force may drive a growth-boosting sustainable innovation system. While there is no simple recipe which suggests an optimal combination of new scientific understanding, technologies, and process that could help produce the much-needed innovations and technological change, we present a set of propositions that highlights opportunities for reflection on existing R&D investment strategies and serves as a bridge to connect the emergent scholarship on sustainability with the intellectual traditions of R&D in innovation management.

1. Introduction

Sustainability has come to dominate scholarly commentaries on socio-economic renewal, and has become a focal point of science, technology, and innovation policies. In weaving the tenor of sustainability into the existing socio-technical systems, the extant literature accords a central role to intensive research and development (R&D) efforts and innovation (Shao et al., 2021; Wang and Zhang, 2020; Fischer and Newell 2008). However, there are lingering concerns about the weak and delayed impact or pay-offs from R&D investments over time leading to a continuous shrinkage in expenditure outlay (Bhattacharya and Packalen, 2020; Becker, 2015; Kammen and Nemet, 2005). As a result, some scholars contend that there is little expectation that the era of great innovation, that is, the period between 1870 and 1970, when important inventions such as the internal combustion engine and electrification transformed the way life globally, will be repeated (Gordon, 2000, 2016). Also, some emerging conjectural debates suggest that the *publish or perish* culture taking hold in the scientific community further stirs up concerns about the ability to bridge the gap between basic research and societal need (The Economist, 2021d; Bhattacharya and Packalen, 2020). As such, it has been argued that investments in R&D would only produce more research papers and provide incremental improvement in technology-in-use but would not yield the radical and growth-boosting innovations needed to improve the material condition of society (D'Agostino and Malpas, 2021). To the extent that these arguments are valid, they re-emphasize that the world is losing out on the benefits of a dyadic relationship between scientific knowledge and growth-boosting innovation output.

Nonetheless, other scholars have long recognised and advocated that a persistent investment in R&D remains vital for unlocking more sophisticated and sustainable innovations (Holt et al., 2021; Xu et al., 2021; Ganda, 2019). Thus, in pursuit of the potentially positive impact that investing in R&D could have on overall economic growth, there have been several efforts, from both governments and the private sector, to boost investment in R&D and innovation. Some statistical reports suggest an unfolding upturn in global R&D expenditure. A recent report on R&D intensity among OECD countries, for example, indicates a rising trend in R&D investment, recording an expenditure increase from 2.4%

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in 2018 to 2.5% in 2019 (OECD, 2021). A similar trend is recorded in the UNESCO Institute for Statistics (UIS) fact sheet on global investment in R&D, which reported some remarkable growth in resources allocated to R&D globally (UNESCO, 2021), with the non-government sector being the main driver of such growth in expenditure (The Economist, 2021a). It is, however, worth noting that the intense global sense of mission to restrict the temperature rise to less than 2 °C above the pre-industrial levels in order to avert catastrophic threats of climate change remains the underlying motivation for these rising trends in R&D investments (The Economist, 2021c; Umar et al., 2020). A global endeavour to bring to fruition an *industrial revolution* that is socio-ecologically entrenched has seeded a new trajectory in the innovation landscape: a transition from the combustion-engine to electric cars and a new paradigm of *prosociality* among business organisations.

Yet, within this evolutionary trajectory of investment in R&D of cutting-edge eco-innovations lies the enduring concern about how to ensure that these sustainability efforts are able to improve life and generate economic activities in the process. Although the socio-economic benefits of R&D investments in sustainable innovation have been well imagined in the literature (Hung and Chou, 2013; Yeh et al., 2010; DeSanctis et al., 2002), we are still challenged with finding widespread evidence of growth-boosting results (Kolmakov et al., 2015). Despite the increasing openness of scientific knowledge and the prevalence of social and climate pledges (Liu et al., 2021; Min et al., 2020; Agreement, 2015), concerns about geographical dominance in innovation output leading to biases in socio-economic welfare and the tendency to decouple ecological concerns from growth (Wang and Zhang, 2020) seem to maintain their momentum. Thus, while the existing literature has led commitments to highlight the centrality of R&D investments, talents, and learning institutions in fostering innovation and growth (Boeing et al., 2022; Jiang et al., 2020; Etzkowitz and Viale, 2010), we reanimate these existing ideas by capturing them as a triad of interdependent and mutually enabling elements which should not be treated as distinct components in R&D budgets. A renewed attention to these elements is timely and important, as we contend that investments in R&D that aim at creating and deepening knowledge to develop new capabilities and to innovate (Li et al., 2020; Sahaym et al., 2010) cannot be achieved without talented scientific cadres with the skills, expertise, and curiosity to explore new fields. Neither can the novel scientific lore be exploited to provide breakthrough sustainable innovations without well-developed talents. Furthermore, we posit that investments in modern scientific and technological infrastructure are needed to accelerate the rate of initiating and developing research output to yield widespread economic benefits, and as learning institutions in recent times are driven towards a more entrepreneurial approach (Datta et al., 2019; Etzkowitz and Viale, 2010), their intellectual resources and training are required to nurture entrepreneurial scientists who are oriented towards infusing basic research with socio-ecological concerns and economic impacts. Thus, in our effort to recalibrate the extant discussions on R&D, we propose a close-link between these elements and present them as the key *pointers* of R&D, which constitute a trivalent force needed to propel growth in the innovation machinery. We therefore aim to suggest a sustainability pathway towards achieving higher returns on the R&D investments.

Specifically, we argue that R&D investments directed to providing scientific infrastructure ought to align with talents and learning institutions to produce sustainable innovations that can yield widespread life-altering results. We add that using educational models that prioritise experimental research and nurture entrepreneurial value is a precondition for enriching the absorptive capacity needed to capture innovative ideas and to commercialise innovation output for a sustained socio-economic impact. In this vein, the paper complements the ongoing efforts to pull sustainability into the mainstream discourse on innovation management in several ways. First, by arguing that R&D investments should not be taken as a given but must be pursued as an *en bloc* component which constitutes the capability and capacity of R&D personnel and learning institutions, we both enrich and extend existing knowledge about the direct relationship between R&D and innovation. We draw attention to how the taken-for-granted assumptions about R&D driving innovation seem to steer classical innovation toward a dead-end within the rising tensions of ecological, social, and economic concerns. The paper thus highlights how the performance of each of the *three pointers of R&D* align and entwine to establish a comprehensive and economically viable sustainable innovation machinery. Second, we develop a conceptual framework and a model, and provide detailed propositions based on insights from our arguments. The ultimate purpose is to fashion a more conceptually sound appreciation of the seamless relationship between R&D, sustainable innovation, and economic growth. Third, our arguments on the mutually reinforcing pointers of R&D provide the impetus to invigorate future empirical research and encourage policymakers to initiate systematic and well-structured reforms that can foreground sustainability in the discourse and practice of innovation management.

In the following sections, we present our three pointers of R&D by first highlighting recent trends in global R&D investments and the importance of R&D expenditure to produce sustainable innovations. We then present a conceptual framework that emphasises the need to give priority to aligning R&D investments with talents and learning institutions. We next explore the role of talents and absorptive capacity, the significance of investing and building innovation capacity through the provision of modern scientific and technological infrastructure, as well as the role of learning institutions and entrepreneurial universities, to produce and commercialise cutting-edge sustainable innovations. We then add further discussions to our arguments by presenting a unifying model that provides an integrative logic to arrive at a fine-grained explication of the relationship between our three pointers of R&D. Finally, we consider the implications of our arguments for future research and conclude by suggesting directions for further empirical studies.

2. The three pointers of R&D

It is widely reflected in the literature that R&D is germane to the process of building sustainable and robust innovation machinery. Specifically, current R&D efforts create a knowledge pool for appropriability and increase the potential for future research to exploit technological opportunities (Miroshnychenko and De Massis, 2020; Cohen and Levinthal, 1989). Therefore, R&D enables the accumulation of knowledge needed to build a rich absorptive capacity that serves as the substrate on which new technological insights are conceived (Lewin et al., 2011; Miller et al., 2007). In this respect, it follows that learning performance and productivity is sensitive to the prior or existing knowledge stock (Garvin et al., 2008; Lewis et al., 2005). This cumulative nature of knowledge acquisition creates the impetus for intensive R&D initiatives in order to be prepared to capitalise on innovative opportunities that may emerge from the external environment (Lewin et al., 2011). Intensive R&D is also significant in enhancing cooperation among firms and in facilitating collaboration with external institutions such as universities (Melnychuk et al., 2021; Lewin et al., 2020; Ahuja, 2000). Such cooperation in the research effort enables the sharing and development of ideas about new areas of scientific knowledge for eco-innovation development and the value extraction thereof (Tumelero et al., 2019; Sarpong et al., 2017). In turn, the knowledge-sharing mechanism facilitates the development of novel technologies and transcends the innovative capacity to the frontiers of technological preadaptation and the predictability of potential trajectories of the innovation landscape (Vrontis et al., 2017; Cattani, 2006). R&D thus provides the necessary means to effectively assimilate and apply knowledge in novel ways to improve the performance of the existing scientific infrastructure and to provide new and sustainable product development models and processes (Furman et al., 2002; Lane et al., 2006).

A look into the recent dynamics of the R&D investment landscape

among leading countries reveals a competitive arena where nations who seek to control the commanding heights of the scientific knowledge production and technological innovation battle for hegemony (Kondo, 2013; Wang 2010). The United States (US), for instance, takes up its position as a global leader in scientific research and knowledge production with $550 bn annual expenditure on R&D (The Economist, 2021a). A steep rise in the expenditure on R&D by China, from $135 bn in 2008 to $439 bn in 2018, has also propelled the country to take on the front rank of scientific research, thereby dominating in 23 out of the 30 mostly popular research domains and accounting for 24.5 percent of the 21 percent increase in scientific publications between 2015 and 2019 (The Economist, 2021a; 2021d). This has inspired many other countries to dedicate more resources to R&D in the race to gain global dominance in science and technology (The Economist, 2021a). This competitive playing field, characterised by a rising expenditure for R&D, is, however, motivated by the quest to achieve sustainable green innovations that would yield huge socio-economic benefits (Wang and Zhang, 2020; Ganda, 2019). The UK government's strategic plan to invest in sustainable innovation and become a world-leading hydrogen economy (The Economist, 2021b; UK Gov, 2021) is the quintessence of such strong nudges by governments to address systemic climate challenges (Mazzucato, 2018). Also, the private sector is not excluded from this global endeavour to catalyse and navigate the sustainability transition as they account for 85% of investment, as reported in the European Union's research and innovation in low carbon technologies (European Commission, 2017, 2021). A new crop of investors adopting what has come to be known as *sustainable investing,* which seeks to embed sustainability into the global financial system (Umar et al., 2021; Eccles and Klimenko, 2019), illustrates that the current innovation system has found a new paradigm, one which is characterised by the notion of eco-economic decoupling (Vadén et al., 2020).

However, our re-reading of these commitments to providing financial investment for R&D prompted us to wonder why there has been little evidence of growth to underscore these efforts. In response, we argue that the many benefits of R&D would only yield significant and sustainable benefits if investments were aligned with the development of R&D personnel talents and learning institutions. More importantly, in an era when issues of sustainability have gained much traction and support, efforts to speed up new and sustainable business models call for a reimagination of the traditional conception of R&D in order to establish a clear path towards resolving the human-induced climate challenges (Janzwood, 2021; Shao et al., 2021). As depicted in the framework in Fig. 1, aligning investments in R&D with talented cadres and learning institutions is significant for enriching the absorptive capacity needed to build the knowledge pool to assimilate and exploit new technological ideas. This stock of knowledge, we argue, is what is needed to create a modern scientific infrastructure, such as artificial intelligence and data analytic tools, which are needed to trigger a rapid response to the calls for sustainable innovation. Our framework also highlights the role of entrepreneurial universities as critical to nurturing entrepreneurial scientists, who would pursue basic research in the shadow of addressing socio-ecological and economic concerns, to produce the ground-breaking innovations needed to propel the research on climate change and provide widespread economic impact. Against this backdrop, we now provide brief discussions on each of these three key pointers in our framework to reinforce our position that they command a central role in strengthening efforts to infix growth gear in the sustainable innovation system.

2.1. *Investing in talent: absorptive capacity*

The ability to exploit novel ideas to deliver economically viable innovation is dependent on the strength and availability of scientific cadres and talents (Belderbos et al., 2015; Salter and Martin, 2001). Enhancing the competence and skill of talent therefore plays a distinctive role in the ability to produce and make widespread use of eco-friendly innovations. Amankwah-Amoah and Sarpong (2016) in their work on the historical pathways to a green economy argued that the ability to avoid resource misallocation in the scaling-up of green technologies for economic growth is anchored in well-developed talents and skilled personnel. Also, Pan et al. (2021) in their empirical analyses of the effect of technology infrastructure on innovation capability found that R&D personnel input has a significant impact on the development and coordination of innovation capacity. Expanding the available talent pool and strengthening scientific cadres is critically important in the process of generating scientific knowledge, as it creates diversity in the knowledge and competence needed to produce sustainable innovation. More importantly, these talented cadres are capable of building powerful scientific infrastructures, such as recombinant DNA technologies, artificial intelligence, and data analytic systems, to speed up the innovation at rates that otherwise could not be achievable (Bag et al., 2021). Thus, investing in the training and development of skilled talents and R&D personnel who have the virtue of curiosity to investigate new ideas serves as a valuable seed to conceive distinctive and sophisticated technological knowledge.

Furthermore, as globalisation is facilitating what has come to be known as open innovation (Huizingh, 2011; Zhao et al., 2016), it would be pragmatic to capitalise on and make use of the proliferation of such complex knowledge. This, we contend, is contingent upon the ability to recognize, assimilate, and understand knowledge from the external

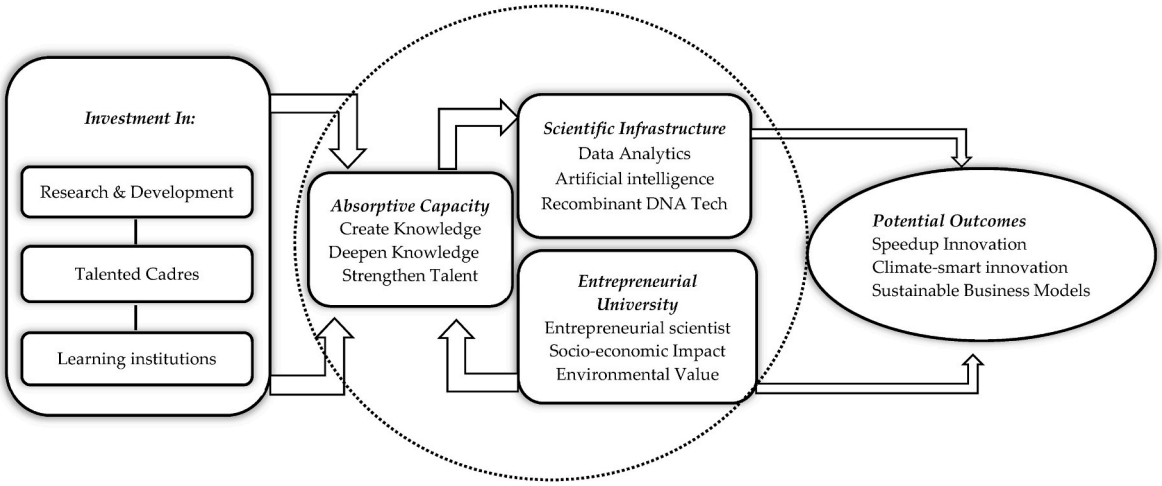

Fig. 1. The three pointers of R&D Investment.

environment (Melnychuk et al., 2021; Zahra and George, 2002). In this regard, strengthening the absorptive capacity increases the productivity of R&D, as the existing stock of technological insight becomes the foundational knowledge upon which new ideas are understood, developed, and commercialised (Fischer and Newell, 2008; Porter and Stern, 2001). Striking a distinction between green innovators and non-green innovators, Cainelli et al. (2015) emphasized that high absorptive capacity is the factor distinguishing those firms that are able to produce sustainable innovations from those that are not. Also, Furman et al.'s (2002) framework on national innovation capacity highlighted that the accumulated stock of technological knowledge is an integral element for building a robust capacity to innovate. Similarly, Gil et al. (2012) in their empirical analysis of the potential of technological adoption for innovating large socio-technical systems emphasized that innovation hinges on technological adoption, which is determined by the capacity to absorb new technologies. Thus, an in-depth understanding of the existing versions of technologies or scientific information facilitates the understanding and exploitation of new ones to provide the novel outputs needed for innovation-driven growth (Nylund et al., 2021). Absorptive capacity is therefore an all-important input to expand the innovation capacity and to maintain the sustainability trajectory of the innovation landscape (Apa et al., 2021; Furman et al., 2002). On this basis we propose the following.

Proposition 1a. *Aligning R&D investment with the expansion of the talent pool and scientific cadres will fortify the capacity to develop eco-innovations that are proximate to industry's needs.*

Proposition 1b. *Enriching absorptive capacity enhances the development of eco-innovation concepts that have the potential to establish an equilibrium in the opposing goals of economic growth and climate action.*

2.2. R&D investment: building scientific infrastructure

Scientific research is essential to building the knowledge capital that would increase the propensity for future research to meet the technological needs of the future. Several studies have found that high expenditure on R&D underlies the exploration and exploitation of unknown technological fields for sustainable innovation (Wu et al., 2020). Enriching and expanding R&D budgets is therefore integral to building a robust and sustainable innovation machinery (Markham et al., 2010). Such investments are needed to establish R&D laboratories and provide the resources required to conduct both the basic and the applied research that would stimulate the flow of new technological knowledge to enrich the innovation potential. This knowledge capital would, in turn, provide the important impetus needed to propel efforts to decouple environmental damage from economic growth (Stojčić, 2021). Fernández et al. (2018) in their econometric analysis of the impact of innovation efforts on the fight against climate change emphasized that R&D investment is a key element that not only drives innovation for sustainability but also fuels the engine of growth. Therefore, investing in intensive research into sustainable technological knowledge underlies the strategic mechanism for developing climate-smart innovation. More importantly, green R&D investment serves as the vehicle to transition the long-established socio-technical system, which has less consideration for the environmental impact, to one that establishes the values of social and environmental responsibility (Shao et al., 2021). As Fischer and Newell (2008) argued, the development of research into benign innovation output is indeed the principal means for dealing with climate change. Therefore, huge financial commitments to R&D to provide clean technologies that are able to address challenges in hard-to-decarbonise sectors is ever more important. On this basis, an integration of the modern scientific infrastructure with basic R&D initiatives would help yield outcomes that would serve the needs of today's climate challenges and provide widespread economic impact. Thus, R&D investments should be drawn towards providing a modern scientific research infrastructure and resources (Pan et al., 2021; UKRI, 2021; Laranja, 2009).

Based on this analysis, the modern scientific infrastructure serves as a means to delimit the lengths to which scientific research could go in producing ground-breaking sustainable innovations. Thus, providing a modern research infrastructure is important for strengthening the nexus between basic and applied scientific research, which forms the foundation for exploring valuable new technologies (Qiao et al., 2016). In essence, investing in the scientific infrastructure to catalyse experimental research that would provide timely and ground-breaking eco-innovations is a critical point to consider in the sustainability transition agenda (Engwall et al., 2021). Commitment to the development and adoption of a modern technological infrastructure is of vital importance in accelerating innovation performance and in building a robust innovation capacity (Gil et al., 2012; Bygstad and Aanby, 2010). In this regard, we are of the opinion that technological sophistication underlies the capacity to develop viable research into sustainable growth-boosting innovation (Scarrà and Piccaluga, 2020; Furman et al., 2002; Langford and Langford, 2000). Speeding up the green industrial revolution, therefore, requires a modern scientific infrastructure, such as artificial intelligence and data analytic software, which is fundamental to the deployment and subsequent capture of value from the sustainable innovation system. Thus, we propose the following:

Proposition 2a. **:** *The ability to develop groundbreaking eco-innovation with the potential to unleash widespread benefits from R&D investments is predicated on the availability and strength of the scientific infrastructure.*

Proposition 2b. *Integrating scientific knowledge with an innovation target helps to scale-up sustainable technologies that have ubiquitous use.*

2.3. Learning institutions: entrepreneurial universities

Establishing a sustainable and economically viable innovation system, we argue, is largely a function of the absorptive capacity, which, in turn, hinges on both prior knowledge and intensive R&D efforts (Miao et al., 2021). In other words, the ability to harness external knowledge is a function of the intensity of R&D commitment and the existing stock of accumulated knowledge (Lane et al., 2006; Zahra and George, 2002). However, we argue here that this capacity to assimilate new knowledge and the competence to transform and exploit the acquired knowledge to provide innovative output is facilitated by learning institutions. These learning institutions serve as the backbone of both basic and applied research, which is consequential for capturing the technological frontiers of today's sustainable innovation landscape. Particularly, a vibrant university system helps to create and strengthen the talents needed to invent cutting-edge innovations. As Etzkowitz and Viale (2010) argued, universities are crucial to the innovation process and are an increasingly important foundation for the transformation of society. Universities are therefore the key drivers of growth-boosting innovation, as they create a fluid and dynamic nexus between scientific research and social and economic development (Adegbile et al., 2021). Effective collaboration between these universities and industry (UIC) is also important for creating a powerful engine for technological development (Adegbile et al., 2021; De Wit-de Vries et al., 2019; Wirsich et al., 2016). Such collaborations facilitate the convergence between varying scientific domains to produce more radical and sophisticated innovations (Chai and Shih, 2016). In addition, UICs create and deepen the knowledge needed to capture opportunities to spur innovation (Apa et al., 2021; Rajalo and Vadi 2017; Lööf and Broström, 2008) as well as make the most of both basic and applied scientific research in varying aspects of the innovation process. In this regard, learning institutions play a key role in opening frontiers of innovations that are considered to be beyond the operational focus of business organisations thereby increasing the efficiency with which resources are allocated. Investing in these learning institutions would therefore have a significant impact on our efforts to nurture and equip industry personnel with high entrepreneurial skills and the power to speed up and invent more sustainable innovations.

Against this background, we now draw attention to entrepreneurial

universities (EUs), the third academic revolution (Etzkowitz and Viale, 2010), as institutions that not only provide scientific knowledge but also ensure that R&D efforts yield results that are close to industry needs. By transitioning from an 'ivory tower' to an entrepreneurial system (Etzkowitz et al., 2000), EUs also ensure that basic scientific studies are inter connectable and translatable for practice in order to catalyse industrial innovation and improve economic performance (Chang et al., 2016). These institutions thus extend the traditional objective of the university to include economic development by providing a support structure that facilitates the recombination and exploitation of existing knowledge to enable the creation and commercialisation of novel technologies (Wirsich et al., 2016; Etzkowitz et al., 2000). In this regard, EUs hold the capacity to bridge the "valley of death" innovation by encouraging experimental research, nurturing social and environmental values, and creating stakeholder impact (Sarpong and Maclean, 2012), all of which serve as a strong footing for achieving sustainable innovation-driven growth. This new phase of academic function also serves as a natural incubator that breeds entrepreneurial scientists (Thomas et al., 2020; Jain et al., 2009) who integrate basic knowledge with innovation targets (Etzkowitz and Viale, 2010; Ranga et al., 2003; Etzkowitz et al., 2000). They initiate the formation of new and sustainable business models and manufacturing processes and speed up innovation to create the social and economic impact needed to improve the material condition of society (Adegbile et al., 2021; Thomas et al., 2020). Entrepreneurial universities are therefore the "centre of gravity for economic development" (Etzkowitz and Viale, 2010, p. 596) and must be regarded as a key driver of our sustainable innovation-based growth objectives. These arguments give rise to the following propositions:

Proposition 3a. **:** *A synergy between the R&D investment and the capacity expansion of entrepreneurial universities catalyses impact-oriented and sustainability-driven research.*

Proposition 3b. *Nurturing entrepreneurial scientists would consolidate and accelerate the development of affordable eco-innovation outputs that provide widespread economic growth.*

3. Towards a unifying model

Our discussions so far suggest that the three pointers of R&D are not only complementary but mutually indistinct elements that are vital to infixing economic growth gear in the sustainable innovation machinery. As explicitly stated in our propositions, each pointer offers a unique contribution to the growth-boosting sustainability transition. We re-emphasize that R&D investment provides the resources and scientific infrastructure needed to embark on the exploration of new technological frontiers. Enriching the absorptive capacity to comprehend and exploit new technological ideas also implies that investments in scientific cadres would yield sustainable innovative outputs. The role of EUs in bridging the "valley of death" innovation helps to ensure that laboratory-proven research is transformed into sustainable innovation outputs that are able to yield huge economic benefits. By conceptualising this dynamic interplay between the pointers as an *en bloc* mechanism that requires a holistic investment commitment, we surmise, would yield eco-innovations that provide widespread economic growth.

In the unifying model in Fig. 2, we highlight the dynamic interdependencies between the three pointers to conceptualize three main innovation strategies and signature practices. This is significant for providing a fundamental reconceptualization of ways that would enable the transition of the existing innovation designs, which encourage an irresponsible use of natural resources, to a new technological paradigm that facilitates the combination of climate-smart innovations and economic growth. In this regard, our model indicates that R&D spending on the provision of a modern scientific infrastructure intersects with investment in talented cadres to enrich the absorptive capacity needed to integrate novel ideas with innovation targets. In this sense, deepening the knowledge of and strengthening the talents involved in the R&D initiatives provides the means of extracting the economic value from research outputs. This is, however, grounded in the teaching and learning models provided by EUs which help nurture entrepreneurial scientists. Again, the EUs, we argue, help develop and harness a modern scientific infrastructure to provide experimental research that offers solutions to climate and economic challenges (Guerrero and Urbano, 2012). Engaging in a mild 'predictive fin-de-siècle thinking', we present in Table 1 what we refer to as signature organizing practices and their

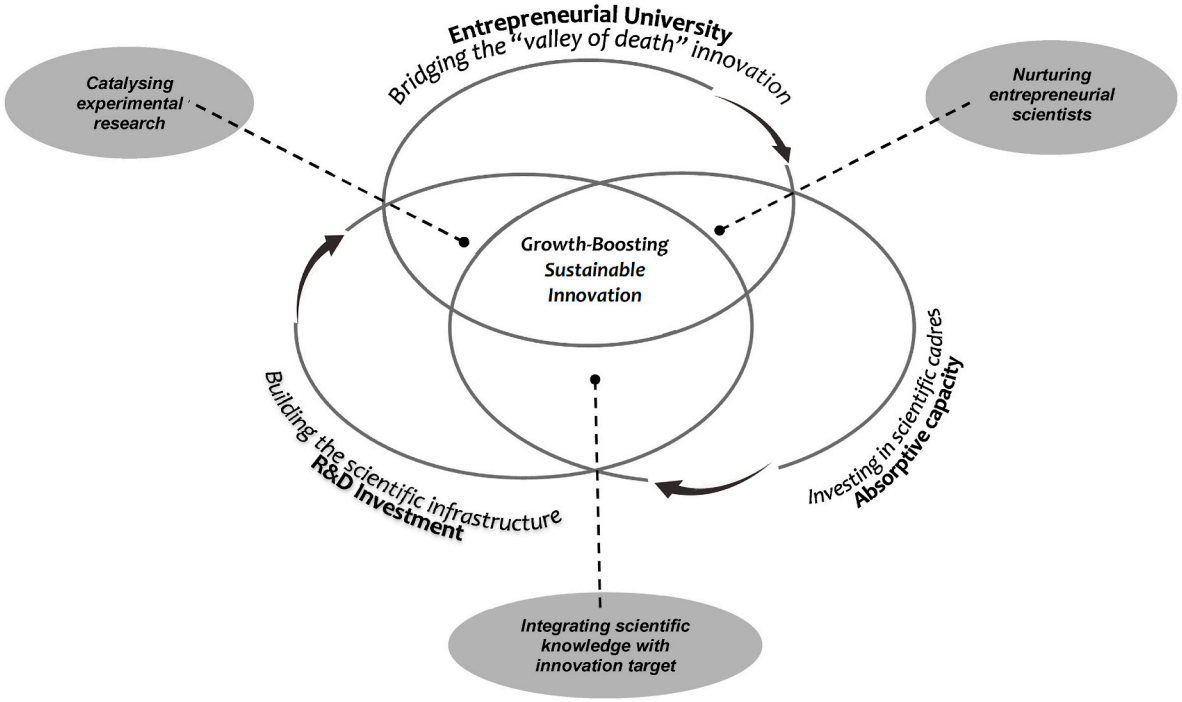

Fig. 2. A unified model of the three pointers in a growth-boosting sustainable innovation system.

Table 1
Growth-boosting sustainable innovation strategies and signature organizing practices.

Innovation Strategy	Signature organizing practices
Nurturing entrepreneurial scientist	• Providing entrepreneurial training • Training environmentally concerned scientific cadres • Commercializing innovation ideas • Incorporating economic value into basic research • Promoting university-industry collaboration
Integrating scientific knowledge with innovation target	• Matching research output with industry needs • Initiating demonstration projects for innovation concepts • Developing eco-innovations with ubiquitous use • Measuring research impact on growth and sustainability
Catalysing experimental research	• Focusing on sustainability-oriented research • Providing research labs, material, and resources • Investing in hard-to-find talents • Adopting modern technology for research

corresponding innovation strategies to highlight how the innovation potential of our model could be realised in practice.

While not exhaustive, the practices we highlight are also not rooted in data. Rather, they are meant to provide some conceptual clarity about potential organizing practices that could shore up the growth-boosting outcomes of the dyadic relationship.

4. Discussions and implications

Classical innovation has indeed reached a dead end in the face of the existential threats of climate change. With the world shifting focus towards developing clean technologies, the objective now is to achieve an economic boom that is essentially powered by sustainable innovations. More importantly, this objective is oriented towards addressing socio-economic challenges by finding ways to make ubiquitous use of green technologies and to provide widespread economic gains. The ability to respond to the heightened calls for sustainable innovation projects in response to the increasing demand for climate-smart innovation is, however, centred on intensive R&D efforts. In this regard, we argued that expenditure on R&D must be pursued in combination with increased outlay for EUs and the absorptive capacity of scientific cadres. We presented a conceptual framework and developed propositions to argue that aligning and entwining R&D investments with talents and learning institutions forms the principal axis around which the ability to develop growth-boosting sustainable innovation is made possible. Specifically, we argued that improvement in the skill composition of talented scientific cadres is a crucial pillar in our sustainable innovation efforts and therefore must not be an expenditure backwater. We advocate for investing more intensely in skill training and expanding the R&D personnel pool to facilitate the appropriation and exploitation of knowledge for sustainable economic growth. In addition, as knowledge remains the principal component in the process of devising sustainable innovation machinery (Scarrà and Piccaluga, 2020; Vrontis et al., 2017), it is of utmost importance that the stock of technological knowledge that serves as a substrate upon which novel ideas are developed and commercialised is enriched (Furman et al., 2002). Therefore, by giving credence to novel conceptualisations that are conceived from existing ideas, or what is widely known as the *standing on shoulders effect*, we highlighted the significance of absorptive capacity in producing breakthrough sustainable innovation. We also emphasized that EUs play a pivotal role in this dynamic interplay between the pointers of R&D as, among other vital contributions, they help to bridge the "valley of death" between innovation research and successful commercialisation outputs (Adegbile et al., 2021).

4.1. Implications

The innovation landscape currently is inundated with incentives to reduce the capital cost of R&D investments such that firms are motivated to spend a lot more on developing eco-friendly innovations (Jaffe et al., 2003). The commitments being made by private organisations, such as Amazon spending close to $36 bn on green R&D (Watanabe and Tou, 2019) and Breakthrough Energy collaborating with international organisations to make massive investments in R&D into sustainable energy sources (European Commission, 2021), are illustrative of the huge investment efforts being made to fulfil the climate pledge. These investments are crucial in redesigning methods by which value can be created and appropriated in sustainable ways (Nylund et al., 2021). In this regard, a major implication of this paper lies in the objective to highlight the interdependency between the performance of each of the three pointers of R&D as the mainstay for gaining greater innovation capabilities to achieve widespread eco-economic decoupling. In this respect, this paper posits that expanding the R&D budget alone is not an absolute solution to providing growth-boosting innovation outputs. Rather, going beyond expenditure silos to consider R&D investments, learning institutions, and well-trained scientists and talents as an *en bloc* component is the ultimate means to construct economically viable sustainable innovation machinery.

Furthermore, we acknowledge that there are lingering concerns about much of today's research becoming too highbrow, thereby posing a challenge when advancing its relevance for practice (The Economist, 2021a). Tightening this Gordian knot further is the *publish or perish* culture in academia, which some scholars argue is less effective at producing relevant and applicable research that would produce growth-boosting innovations (The Economist, 2021d; Bhattacharya and Packalen, 2020). However, our arguments imply that basic research and academic publishing remain ever more important in our quest to solve real-world challenges (Melnychuk et al., 2021; The Economist, 2021d). Therefore, the heterogenous ways in which research conducted by learning institutions, with the provision of rich talents and knowledge pool, are vital to generating innovation outputs that are close to industry needs. This also implies that scientific publication is a key channel through which growth-boosting gear is infixed in the innovation machinery (Llopis et al., 2021; Prettner and Werner, 2016; De Marchi and Rocchi, 2000). Therefore, we advocate that the academic community's commitment to sustaining the close links between sustainability science and the intellectual traditions of innovation management should consider approaches that could inculcate 'commercial logics' in research to stimulate the entrepreneurial behaviour needed to address socio-economic and environmental challenges (Hahn et al., 2018).

In addition, given our emphasis on R&D as being central to sustainable-innovation-driven growth, the approach common in the literature has been to closely analyse the role of R&D performance in innovation (Pan et al., 2021; Engwall et al., 2021; Hung and Chou, 2013). Also, others have considered the mediating role of each the pointers of R&D in accelerating sustainable innovation in isolation (Melnychuk et al., 2021; Nylund et al., 2021; Wu et al., 2020; Tumelero et al., 2019). Our conceptual analysis, however, complements the literature with an integrative approach, providing clarity on the pointers as theoretically distinct but functionally inextricable dimensions in the academic disciplines of innovation management and sustainability science. Such insight provides a crucial thread that better connects works in these two intellectual traditions.

5. Future research

Although we clearly see the need to invest in the development of

innovations that would help the world adapt to the changing climate, a positive correlation between national R&D investment and national economic growth, and more importantly, identification of who stands to gain from such investments, is often contested (Edgerton, 2008). This general sentiment is fuelled by the notion that national innovation does not always lead to national success, as investing in R&D often leads to knowledge spillover, which creates a free-rider problem (Wareham et al., 2021; Scarrà and Piccaluga, 2020). However, we are of the opinion that "global innovation leads to national growth" (Edgerton, 2008, p. 1031), as the collective outcome is influenced by each actor's performance and contribution. Mowery et al. (2010), in their study on the technological policies needed to meet climate challenges, argued that technological solutions to mitigate the threats posed by global warming ought to be pursued on a global scale with huge financial commitment from both private and government sectors. This further suggests that it is the combined efforts of both private businesses and government investment in R&D that would help propel the engine of growth in the sustainable innovation machinery (Wiesenthal et al., 2012). Thus, within the ethos of collective growth and the survival of humanity, the world collectively becomes a beneficiary of investments in the research, design, and development of sustainable innovations. In this regard, it is imperative that scholarly enquiry into our three pointers of R&D is initiated to provide some empirical support for our arguments. Specifically, an interest in providing a statistical analysis to support our arguments calls for methodologies designed around quantitative enquiry, not least the potential to demonstrate a positive correlation between our *pointers* and growth-boosting sustainable innovation. This, we surmise, would help banish the techno-nationalists' fear about the *cui bono* of R&D investments.

In addition, the pervasiveness of the threats of climate change provides a basis for reflection on the prevailing intellectual property protection system, which focuses on enhancing the private appropriability of returns from R&D investments, thereby restricting the diffusion of knowledge outputs (Fabiano et al., 2021; Mowery et al., 2010; Cohen et al., 2000). This is important because, as already pointed out (see, for example, Verbeke and Hutzschenreuter, 2021; Mowery et al., 2010), climate change is a global challenge that must be addressed through the combined efforts of many actors. Hence, there is the need to implement policies and regulatory systems (Boakye et al., 2022; Mazzucato, 2018) that would support the dissemination and diffusion technologies that provide lasting solutions to the global climate challenge. On this basis, as the field of innovation management continues to adopt and adapt the ideals of sustainability, we advocate that future research initiate fresh conversations on the three pointers of R&D in an open innovation system, with caution regarding the paradoxes of openness (Wang et al., 2017; Greco et al., 2016).

6. Conclusion

From the classical to the most up-to-the-minute, the unremitting pace of evolution in the innovation landscape has found a new phase, one which is attuned to issues of sustainability. In this new chapter, the voices of scholars and policy makers are awash with concerns about how to reimagine the existing global socio-technical systems in a way that puts nature, people, and planet at the heart of its operation. More importantly, keen attention has been drawn towards stimulating R&D investments to produce climate-smart technologies that are crucial to the efforts to meet the current challenges of climate change. However, the discussions so far have given only moderate attention to identifying new ways to embed global economic gains in the research, design, and development of sustainable green innovations. In providing hot-wired solutions to fill this lacuna, we argue that R&D investment will only produce growth-boosting sustainable innovations if such investments align with talents and learning institutions. We therefore advance the case to give priority to strengthening the dyadic relationships between R&D investments to provide a modern research infrastructure, improve R&D personnel talents and absorptive capacity, and establish EUs. In support of our arguments, we advocate for further empirical studies into our assertion on the three pointers of R&D for sustainable-innovation-driven growth. The suggestions we have produced, however, are stimulated by the need for contemporary innovation research to draw on some deeply new, or inspiringly old, ideas to contribute to the development of a practical vision of the sustainable innovation landscape.

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