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Nature-inspired innovation policy: Biomimicry as a pathway to leverage biodiversity for economic development

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ABSTRACT

One of the most important challenges of the 21st century is the quest for economic development models that respect the planet's ecosystem. Rather than imposing our industrial systems on nature, why not let nature influence our industrial and innovation systems?

From wind turbine blades to bullet trains and solar cells, many of the technologies we rely on today have been inspired by solutions found in nature. Although relatively widespread in the fields of architecture and engineering, biomimicry/biomimetics remains largely overlooked in economics, public policy, and development studies. This is paradoxical because the world's remaining biodiversity stock-a knowledge bank of solutions to both current and unknown challenges- is largely held in developing economies and can be leveraged as a source of inspiration for -and entry door to- industrial innovation. This paper, therefore, investigates the relevance of biomimicry in the formulation of sustainable development strategies in biodiverse developing countries and maps out the national policy landscapes that can advance it.

Several findings arise from this study. First, despite the exponential growth of biomimicry as a field and our understanding of its economic impact, what drives nature-inspired innovation remains elusive. Second, the biomimicry innovation landscape is dominated by industrialised economies that have relied on proactive policy interventions, while virtually no developing country has adopted biomimicry as an innovation strategy, consolidating the exploitation of the biodiversity in the developing world by firms in high-income nations. Third, by drawing on empirical evidence from a selection of Latin American countries, this paper shows that while biomimicry presents tremendous opportunities to leapfrog towards high value-added knowledge-intensive activities by using local biodiversity and related expertise as factor endowments, policy, and institutional factors have led to the persistence of important coordination failures that hinder the expansion and commercialization of biomimicry-based R&D. This paper concludes by discussing the public policies needed to support the integration of developing nations at the innovation frontier through biomimicry.

1. Introduction

> "Imitation is not just the sincerest form of flattery – it's the sincerest form of learning."
> –George Bernard Shaw
> "Learn from nature: that is where our future lies"
> –Leonardo Da Vinci

To tackle climate change, considerable efforts need to be deployed towards biodiversity protection. But how can countries generate prosperity while ensuring biodiversity protection? More precisely, how can developing countries benefit economically from the changing sustainability and innovation landscape? And how can biodiversity support innovation in those countries?

In the past two decades, the growing concerns for the synergies between the economic and the natural world also led to the burgeoning of concepts such as eco-efficiency (Huppes and Ishikawa, 2009; Welford, 1998), bioprospecting (Reid et al., 1993; Barrett and Lybbert, 2000); industrial ecology (Frosch and Gallopoulos, 1989; Graedel and Allenby, 1995), and industrial symbioses (Chertow and Ehrenfeld, 2012); though

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examples in practice remain limited (as noted in Muradian and Gómez-Baggethun, 2021). To contribute to this growing scholarship at the intersection of economic development and ecological sustainability,[1] this study explores the role of biomimicry as providing a pathway for aligning innovation, economic development, and biodiversity protection objectives in biodiverse countries.

The concept of biomimicry, popularized in Benyus (1997), is an innovation method that relies on the inspiration, learning from, and imitation of the strategies found in nature to solve human design challenges to create a healthier, greener, and more sustainable future. From the kingfisher-inspired design of the design of Japanese bullet trains; the burrs-inspired invention of Velcro, and wind turbine blades whose shapes are inspired by the ridges on the pectoral fins of humpback whales that create an aerodynamic flow in water, many of the (green) technologies we rely on today have been influenced by solutions found in nature. Though our natural environment has inspired design since prehistoric man fashioned spears from the teeth of animals, the development of a methodological framework for translating biological strategies into design innovations is a recent one (Kennedy and Marting, 2016). Biomimicry is aligned with the idea that the 3.8 billion years of evolution have produced optimized designs and solutions within our natural ecosystem which can often provide better alternatives to technologies used today (Benyus, 1997). Acting as natural R&D, evolution has selected the most efficient and optimal designs and discarded the non-functional ones (Pawlyn, 2019).

Though the study of biomimicry is relatively widespread in the fields of architecture, design, engineering, and biology (e.g. Altomonte, 2008; Rao, 2014; Zari, 2010; Fecheyr-Lippens and Bhiwapurkar, 2017; Benyus, 1997), it remains much less studied in the social sciences, and in the economics and public policy literature more specifically. As a result, the topic of biomimicry -and its economic and development impact- has rarely – or perhaps never- been investigated from a policy perspective in the academic literature.[2] By establishing an analytical link between biomimicry as an innovation method, the stock of biodiversity in developing countries, and the sustainable development agenda, this study contributes to filling this gap. In doing so, this paper also contributes to challenging the widespread limiting focus of developing countries as consumers – rather than producers – of new technologies in the literature on the economic opportunities arising from low carbon transitions.[3]

Creating and strengthening technological capabilities has often not been easy in developing economies, due to the presence of not only market failures but also system and learning failures (Lee, 2019). But rather than accepting the lack of technological capabilities and market failures as a *fait accompli* and assuming that countries have gotten where they are by supposedly exploiting their preexisting comparative advantages, the key question we should ask is *how* they have acquired new technological capabilities. Such a process often involves specific public policy interventions to overcome market constraints in the process of technological capabilities accumulation. It is through such an approach that this paper tries to explain the dynamic process of biodiversity-inspired technological innovation. Why did some nations promote biomimicry – thereby reaping its economic effects- and not others? What was the role of public policies? What lessons can be learned and replicated in other regions, and to what extent do biodiverse nations have an 'easier' route to developing biomimicry activities due to their proximity to a diverse range of environmental assets? These are some of the questions that this study aims to help answer.

To investigate the opportunities and obstacles for countries to leverage their biodiversity to generate knowledge-intensive and value-added activities beyond ecotourism (which remains the prevalent form of capture of the economic value of biodiversity in developing nations), this paper draws on the rich insights from evolutionary and neo-schumpeterian economics, which focus on innovation dynamics, national innovation ecosystems, and changing structures; and adopts a dynamic approach to the concept of comparative advantages, which considers the role of learning, technological upgrading, productive capabilities, and public policies.

Given its attempts to bridge the developmentalist and conservation agenda, this study may have some overlapping features with utilitarian environmentalism, but it should be clarified that in it does not in any way support the idea that the satisfaction of economic interest is the only intrinsic value of environmental assets. Instead, this study aims to promote a true commingling of different disciplines, to demonstrate to development economists the core usefulness of biodiversity protection in the context of economic upgrading, and to ecologists the importance of adopting developmental and innovation perspectives in the conservation debates. Indeed, although R&D, economic upgrading and biodiversity conservation do not necessarily go together, this paper outlines how biomimicry-based R&D can help support both developmental and conservation efforts, thereby challenging the notion that economic development and sustainability are mutually exclusive. In doing so, this paper also contributes to the existing scholarship on the value of biodiversity as a source of information that can feed into industrial and innovation processes (see Weitzman, 1992, 1998; Simpson et al., 1996; Swanson, 1996; Benyus, 1997, Goeschl and Swanson, 2002; Pearce and Pearce, 2001; Bartkowski et al., 2015).[4]

Section 2 of this paper provides a theoretical discussion on the implications of ecological concerns for the role of innovation for economic upgrading in latecomer economies, before exploring the potential that biodiversity holds for innovation for biodiverse countries Section 2 also explains the global trends witnessed in the biomimicry sector over the last two decades and explores the opportunities it entails for developing countries. Section 3 provides a policy landscape of the field of biomimicry across the globe and shows that biomimicry has developed substantially in North America, East Asia, and Europe thanks to significant policy support and industrial policies. In contrast, very few developing countries have implemented policies that promote R&D in biomimicry, which has generated an uneven distribution of value within the sector and high entry barriers through the exploitation of biodiversity in the 'Global South' by industries in the 'Global North'. Section 4 provides an analysis of the integration of Latin American firms into the biomimicry value chains and identifies key obstacles. This analysis relies on both quantitative and qualitative data collection that has been conducted by consulting both primary and secondary sources, such as government reports, policy documents, and patents data. Such data collection process has been complemented with fieldwork conducted in Costa Rica and Ecuador between December 2020 and November 2021 to generate deeper insights into the opportunities and constraints to the development of biomimicry activities. The fieldwork involved

[1] The tensions and connections between ecological and economic conditions have been the source of long-standing academic debates, starting with the concepts of sustainable development (as reviewed in Robinson 2004 and Sneddon et al. 2006), and sustainability economics (Baumgärtner and Quaas, 2010).

[2] Though Benyus (1997) ends by mentioning the important of 'niche-shifting tools' to herd or nudge the system towards sustainability, this pioneering book does not discuss the policy tools that can promote the emergence of biomimicry-based innovations. This paper thus responds to this call and aims to contribute to our understanding of the nature-inspired innovation policy landscape and future possibilities.

[3] Some studies on biomimicry have been conducted in the context of industralised economies such as the USA, Germany and more recently in the case of China (see Fermanian Business and Economic Institute, 2020) and South Korea (Bae et al., 2019; Reaser et al., 2020).

[4] This study also aligns with the early insights by Carlota Perez and her collaborators that developing regions such as Latin America should utilize their natural resources to leap forward with the next technological revolution (Perez, 2010; Marin et al. 2015).

interviews with over 40 individuals across governments (ministries of science and technology; environment; and trade), research institutions (university and laboratories) and the private sector." Section 5 outlines the key findings and policy implications of this research. Section 6 provides concluding remarks.

2. Economic leapfrogging through biodiversity-based innovation

2.1. Innovation (still) matters for (sustainable) development in the 21st century

To highlight the links between present choices and future production possibilities, it is worth investigating what the context of climate change and sustainability imply for the role of innovation and upgrading in global value chains as a development strategy in latecomer economies.

A vast body of literature has evidenced the key role of innovation in economic catch-up. In the 1930s, Joseph Schumpeter had already made the distinction between mere growth and structural economic change. He argued that economic development is based on transfers of capital from one sector to another utilizing new technologies and innovative methods (Shapiro and Taylor, 1990). Aghion and Howitt (1990) later also explained how technological innovations influence economic growth by making use of Schumpeter's concept of creative destruction, the competitive process whereby entrepreneurs constantly seek new ideas that will render their rivals' ideas obsolete. More recently, several scholars (such as Eichengreen et al., 2013; and Lee, 2013) have also argued and demonstrated that innovation capabilities are the key binding constraint for escaping the middle-income trap. This view is also consistent with the notion that middle-income economies would tend to fall under a trap because they get caught between low-wage manufacturers and high-wage innovators; their wage rates are too high to compete with low-wage exporters and the level of their technological capability is too low to enable them to compete with 'advanced' industrialised economies (World Bank, 2010).

The role of innovation for structural transformation remains relevant in the context of low carbon transitions. Sustainability is increasingly considered the next innovation frontier (Nidumolu et al., 2009) as demonstrated by the growing literature that attempts to bridge the environmental urgency with economic and industrial development.[5] For instance, Dechezleprêtre et al. (2013a,2013b) find that spillovers from low-carbon innovation are over 40% greater than conventional technologies in energy production and transportation sectors. In that perspective, several scholars have emphasized the role of innovation-driven industrial policies in the context of climate change (see Anadon et al., 2016; Doblinger et al., 2019; Mercure et al., 2016; Naudé, 2011). However, the 'innovation' dimension of low carbon transitions is less frequently attempted by developing countries (with some exceptions such as China and Brazil, see Lema and Lema, 2016), which has implications for their ability to seize a larger share of the socio-economic benefits of the global green transition (Anzolin and Lebdioui, 2021).

To understand how latecomers can compete at the innovation frontier in the age of sustainability and extend developmentalist perspectives to the context of biodiversity protection, the rest of this paper explores how developing countries can leverage their biodiversity for innovation, which remains a largely unexplored strategy in developing nations.

2.2. Biodiversity's value as an input for innovation

Nature is often perceived by utilitarian environmentalists -and in the ecosystem services (ES) and nature's contributions to people (NCP) frameworks more specifically- as being instrumental for economic prosperity and growth (Daily, 1997; Norgaard, 2010), a proposition that constitutes the foundation of the notion of the green economy (Muradian and Gómez-Baggethun, 2021) andthe field of "sustainability economics" (Baumgärtner and Quaas, 2010). It should however be stressed that the conceptualization of the economic value of environmental assets goes far beyond mere monetization and is also used to increase societal support for the protection of ecosystems (Braat and De Groot, 2012). It is in that sense that the innovation value of biodiversity can be understood in the context of a broader conversation agenda.

Beyond their essential ecological value, natural ecosystems can hold considerable value as a source of information that can feed into innovation processes. Several economists have described the R&D process as one of information utilization, application and diffusion (e.g. Arrow, 1962) and dependent upon a stock of "information" for its generation of useful innovations (Stoneman, 1983). In that perspective, biodiversity is one of the primary sources of a stock of information that may be accessed for possible solution concepts to socio-biological problems (Swanson, 1996). Biodiversity generates direct benefits to humankind in the form of new genetic material for drugs, agriculture, and increasingly ecotourism (Pearce and Pearce, 2001; Swanson, 1996) but also have value as sources of information that can feed into research, innovation, and industrial processes (see Benyus, 1997; Simpson et al., 1996; Swanson, 1996). Swanson (1996) demonstrates the extent to which biodiversity is relied on as an input into the R&D process in various industries (e.g. pharmaceutical and agricultural industries) and that this reliance is so substantial that the elimination of biodiversity could be disastrous for these important industries.[6] Furthermore, because it is increasingly possible to transfer strategies between organisms and living systems in ways that were not possible in the past, the technological frontier in the area of the bio-industries should dramatically increase the value of biodiversity in R&D processes (ibid.).

We can further distinguish two main ways in which biodiversity holds value for innovation processes, as mapped out in Fig. 1. Beyond the above-mentioned information value as a provider of genetic material, through a process known as *bioprospecting*, environmental assets can also hold value as a source of inspiration for innovation (and can be emulated by form, process, or ecosystem), which leads us to the concept of *biomimicry* (discussed in section 2.3).

It is useful to note that the notion of the value of biodiversity as a source of inspiration for innovation would cut across the different types of values in Pearce's environmental valuation framework because environmental assets that inspire innovation have direct, indirect, as well as option value: Indeed, there is market value in biological information, although it cannot easily be monetized; and such assets may also be preserved for future use/inspiration.[7] The notion that that the innovation value of environmental assets can result in their possible preservation for future use leads us to an important question: Does biodiversity-based innovation help conservation?

[5] See Porter and van der Lynde, 1995; Aiginger, 2015; Pollin, 2015, Garret-Peltier, 2017; Cantore and Cheng, 2018; Fraccaschia et al., 2018; Fouquet, 2019; Lema and Lema, 2016; Anzolin and Lebdioui, 2021; for instance.

[6] Between 25 and 50% of pharmaceutical products are derived from genetic resources and around 70% of drugs used for cancer are natural or are synthetic products inspired by nature (IPBES Global Assessment on Biodiversity and Ecosystem Services, 2019).

[7] In his pioneering work on economic valuation of environmental assets, Pearce (1992) distinguished between the direct use value, indirect use value, option value, and the existence value. Direct use value relates to goods that have a direct economic value (e.g., arable land from which agriculture income can be generated). Indirect use value relates to 'ecological functions' (e.g. a tropical forest might help store carbon dioxide). Option value relates to the amount that individuals would be willing to pay to conserve a tropical forest for future use (e.g. salt lakes in Bolivia that attract many tourists every year). The existence value of an environmental asset consists in what individuals are willing to pay for its mere existence, which tends to increase with the uniqueness of the asset (ibid.).

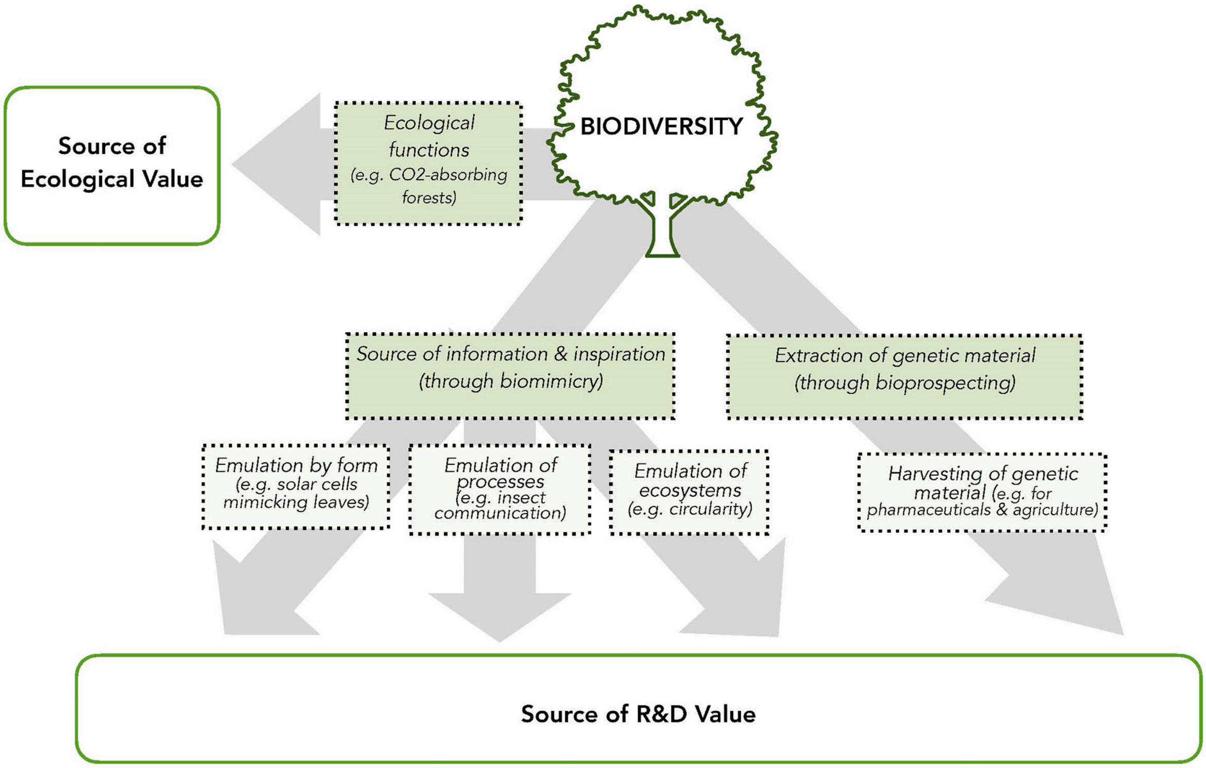

Fig. 1. Mapping the channels between biodiversity and its value as input into R&D processes.
Source: Author's elaboration.

The links between the biodiversity-based innovation agenda and the conservation agenda are generally poorly understood. Most of the literature on the link between innovation and conservation focuses on the applications of new technologies towards biodiversity conservation (such as the use of surveillance technology to enforce regulations in marine areas for example), but there is scarcer literature on the conservation effects of innovations that rely on biodiversity. The two processes are extremely different and have different implications for the conservation agenda. Does biodiversity-based innovation always strengthen conservation efforts, or can it put it at greater risk? How can bioprospecting or biomimicry practices be modified to ensure harmonization with biodiversity conservation? This paper cannot fully answer these issues but can contribute to improving our understanding of some of the different – yet not mutually exclusive- mechanisms through which biodiversity-innovation can support conservation:

- *The co-dependence between biodiversity-based innovation and conservation:* As highlighted in Srivastava and Smith (1996) and Swanson (1996), there is a co-dependence between biodiversity and innovation in various sectors (such as agriculture and the pharmaceutical industry) and its destruction implies that biodiversity-based innovation cannot progress, which also threatens potential sources of rent. The recognition that conservation is essential to innovation has often motivated the creation of genetic 'banks' and conservation initiatives (such as the Parque de la Papa in Peru).
- *The social recognition of the innovation value of environmental assets*: the role of biodiversity for innovations can lead to an increase in social awareness among various stakeholders involved in conservation even if the possible use of the environmental assets for innovation is not immediate and is expected far into the future.
- *Benefit-sharing / local distribution of value and financial rewards:* That is if biodiversity-based innovation contributes to supporting the livelihoods of local populations with otherwise limited income options (entailing some sort of compensation) for the provision of ecological services as an alternative to practices that increase pressure on local natural ecosystems. In such instances, biodiversity-based innovation contributes the logic and diffusion of payments for ecological services, but also offers a source of local and public revenues that can fund conversation initiatives (which motivated the recent creation of a bio-innovation hub in the Galapagos islands, as an alternative to volatile ecotourism revenues, see section 3.2).
- *The development of ecologically friendly technologies through biodiversity-based innovation*: biological solutions have been time-tested by billions of years of evolution and embody successful strategies for thriving on earth (Benyus, 2013), which is why innovations inspired by such solutions (as further discussed in section 2.3) may have ecological benefits and long terms effects indirect on biodiversity protection (e.g. solutions developed from plastic eating bacteria).

Nevertheless, it is worth noting that the above-identified mechanisms are not necessarily systematic. There may be certain conditions under which biodiversity-based innovation may operate independently from a conservation agenda, and may even hinder it:

- *If biodiversity-based innovation practices (bioprospecting or biomimicry) are conducted in ways and on a scale that damages the environment. For instance, the disruptive construction of scientific facilities in biodiverse areas could pose a threat to local fauna and flora.*
- *If information is extracted from biodiversity in an ad hoc fashion without surrounding legal and institutional framework to support the conservation of environmental assets (existing biopiracy practices by foreign firms and researchers).*
- *If financial rewards do not accrue to the locals that are responsible for the conservation of biodiversity, which implies that those who can protect the asset are not benefiting from the innovation value generated by the said asset, leading to a principal-agent problem (e.g. the underlying reasons for the failure of the Yasuní-ITT initiative in Ecuador, seesection 4.2).*

Therefore, though the biodiversity-based innovation and the biodiversity conservation agenda are intrinsically ties, as the former can hardly exist without the latter, a wide range of institutional factors and practices can influence the nature of this relationship.

2.3. Leveraging the innovation value of biodiversity through biomimicry

Biomimicry (also referred to as biomimetics, biodesign, or nature-inspired innovation) involves learning from and emulating biological forms, processes, and ecosystems tested by the environment and refined through evolution (Benyus, 1997, 2013). The term 'biomimetics' was coined by Otto Schmitt in the 1960s to describe the transfer of ideas from biology to technology, while the term 'biomimicry' was popularized in the 1990s by Janine Benyus. Biomimicry is different from harvesting organisms to accomplish a function: rather than "using an organism to 'do what it does', biomimicry aims to instead leverage the design principles embodied by the organism (Kennedy and Marting, 2016). This is the equivalent of the difference between using fireflies themselves to produce light, and understanding and applying the complex chemistry involved in bioluminescence (Helms et al., 2009; Kennedy and Marting, 2016). As mentioned earlier, biomimicry also holds the potential to contribute to the development of green technologies because biological solutions embody successful strategies for thriving on earth (Benyus, 2013) and can for instance support the circular economy model, based on the utilization – and inspiration- of nature's cycles for preserving materials, energy and nutrients for economic use (Korhonen et al., 2018; D'amato and Korhonen, 2021).

The field of biomimicry has been booming over the past 20 years. There has been a twelvefold increase in biomimicry patents, scholarly articles, and research grants between 2000 and 2019, as shown in Fig. 2. Between 1985 and 2005, there were proportionally more biomimicry patents filed than other patents (Bonser, 2006). The rate at which patents related to biomimicry were filed also increased rapidly following the 1990s and into the early 2000s (Pawlyn, 2019). The rapid development of biomimicry as a field is also evidenced by a growing demand for training in biomimicry theory and practice (Lepora et al., 2013).

Index, 2000 = 100. The Da Vinci Index (created by the Fermanian Business & Economic Institute and launched in 2011) measures activity in the field of bioinspiration by monitoring the number of scholarly articles, patents, grants, and dollar value of grants

Source: Fermanian Business & Economic Institute.

Biomimicry activities can generate large spill overs in terms in value and employment creation. Estimates from the Fermanian Business and Economic Institute (2013) suggest that biomimicry could account for as much as USD425 billion of the GDP of the United States and USD1.6 trillion of global output by 2030 (ibid). Bioinspired products are also expected to increase employment and productivity in various sectors with the largest single-industry contributions in the construction, transportation, chemical manufacturing, and the power sectors (see Fig. 3).

2.4. An opportunity for developing countries?

The development of the field of biomimicry is worth investigating not only because of its economic prospects (as shown above), but also because of its tremendous relevance in the formulation of development strategies in biodiverse developing countries, as it offers prospects for leveraging local biodiversity as a factor endowment for innovation to 'leapfrog' towards high value-added sectors. The fact that the discussion on leveraging the innovation value of biodiversity has overlooked the context of developing countries is particularly paradoxical since most of the existing biodiversity hotspots are in the developing world (in Latin America, Central Africa, and South East Asia more specifically) as shown in Fig. 4 A and B.

There is also a vast body of local (and often indigenous) knowledge of biodiversity processes in several developing regions that has often been neglected in innovation and development processes. In addition, the considerable experience and knowledge of Latin American researchers, firms, and communities in the discovery, mapping, and understanding of the usefulness of local flora and fauna, provide related capabilities for biomimicry activities, in line with the theory of product relatedness.[8] However, such domestic knowledge of biodiversity has often been extracted by foreign firms without recognition or compensation, as shown by the increasing number of complaints against biopiracy in developing nations. Biopiracy is the practice in which indigenous knowledge of nature is used by others for profit without authorization or compensation to the indigenous people themselves (EJOLT, 2015). Biopiracy often benefits firms located in high-income economies. For instance, a recent report from the Ecuadorian government identified the United States, Germany, the Netherlands, Australia, and South Korea as the countries that requested the most patents for products derived from Ecuador's endemic resources (Senescyt, 2016). The 'biopirates' in these countries did not request authorization from Ecuador to access the genetic resources used in these patents. If we consider that biodiversity represents the source of inspiration for the global nature-inspired technological innovation landscape, the provision and maintenance of biodiversity in developing countries could be compared to the supply of raw materials in a traditional value chain. In the context of such a 'nature-based innovation value chain', biopiracy implies that no value at all is shared locally for exploiting biodiversity as a source of information.[9]

3. The uneven policy landscape for nature-inspired innovation

Whilst the biomimicry sector is still in relatively early stages compared to its envisioned potential, several governmental support programmes have sprung up in the past two decades. As shown in Table 1, the leading countries in which governments have begun supporting biomimicry R&D through various programmes and grants are Germany, South Korea, the United States, as well as France (and the UK to a lesser extent). The fact that the nature-inspired innovation landscape has been dominated by a handful of high-income economies in the global north echoes the concern in Swanson (1996) regarding the substantial reliance of northern-based industries on southern-based biodiversity for R&D processes in various industries.

The development of biomimicry-related innovation in advanced economies relies on proactive policy support. In the United States, the development of biomimicry has been spearheaded by several government agencies. The Pentagon's research and funding arm, the Defense Advanced Research Projects Agency (DARPA), has been the largest financial supporter of biomimicry research following the recognition that, if understood properly, biological strategies could inform new defense capabilities (Johnson, 2010; Kennedy et al., 2015). For instance, in a very direct application of biomimicry principles, DARPA has contributed USD4 million to AeroVironment since 2006 to create a prototype "hummingbird-like" aircraft (which can move in three axes of motion) for the Nano Air Vehicle (NAV) program (Henningan, 2011). DARPA has also funded the development of BigDog, a dynamically

[8] Hausmann and Klinger (2007) sustain that every product requires capabilities (knowledge, physical assets, infrastructure needs, regulatory requirements and so on) that are highly specific to that activity and sector. If two goods need the same capabilities, a country that has a comparative advantage in one would thereforebe well positioned to acquire a comparative advantage in the other (ibid.)

[9] There has been some recognition of traditional knowledge rights in some of the international agreements such as the Nagoya protocol and in the World International Property Organization (e.g. the case of the Neem Tree-related patents, see Marden, 1999), but in practice, difficulties remain to reflect the contributions of inspiration from natural assets in intellectual property rights as discussed in section 5.3.

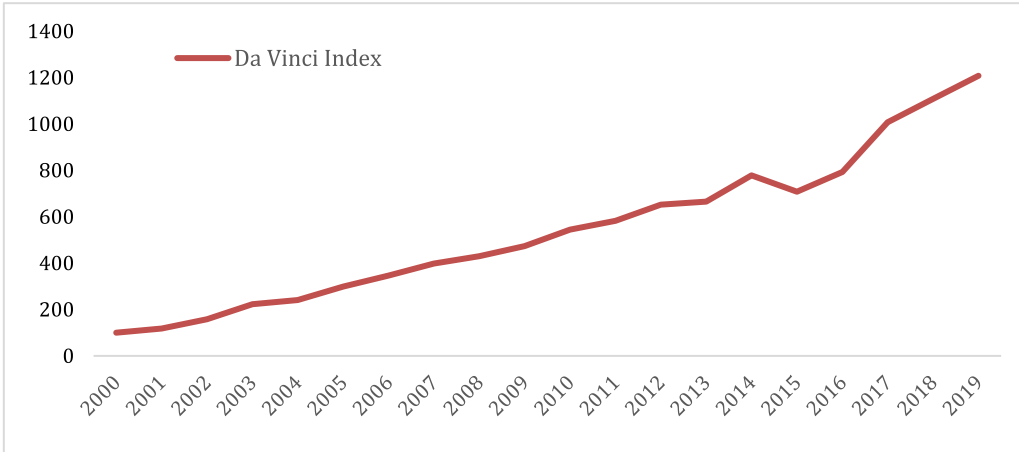

Fig. 2. Evolution of biomimicry-related research and patents (Da Vinci Index).

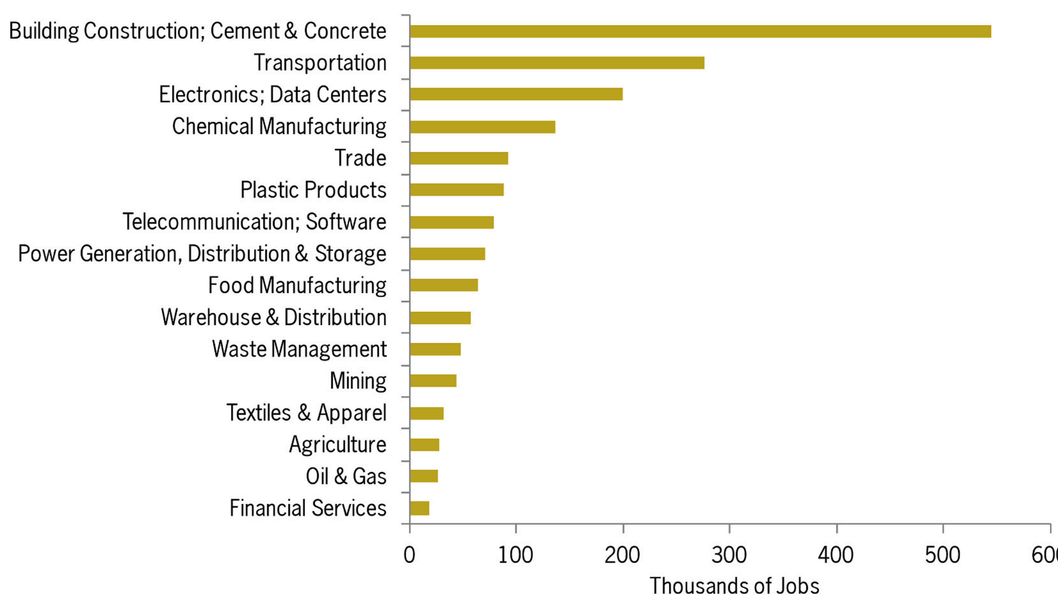

Fig. 3. Bioinspired innovation's forecasted impact on employment in 2030.
Source: Fermanian Business and Economic Institute (2015).

stable quadruped robot that can run over rough terrains and carry heavy loads, which mimics quadruped mammal leg articulation (Kennedy et al., 2015). More recently, DARPA has also been funding research to learn from nature to design artificial intelligence frameworks.[10]

Germany is another leading country in biomimicry research, with over 100 public research institutions conducting biomimicry-related R&D, and two institutional research networks (*BIOKON and KompetenznetzBiomimetik). The German government has invested over 120 million euros in those networks since 2001.*

In France, Biomimicry has been identified as a key innovation area in the national ecologic transition strategy *(Stratégie nationale de transition écologique vers un développement durable 2015–2020).* The economic impact of the development of biomimicry on the GDP of the sole Nouvelle-Aquitaine region has been estimated to EUR 575 million to EUR 3.2 billion, with the creation of 5626 to 31,082 jobs (Vertigo, 2018). A pioneering research centre in biomimicry (the CEEBIOS) has been established in 2014, alongside the creation of higher education programmes in biomimicry. Over 175 research teams and 100 firms are now active in biomimicry research in various sectors, such as energy, construction, and cosmetics (Le Monde, 2018).

South Korea has also witnessed impressive developments in the field of biomimicry in the last decade. The country's Da Vinci Index increased 8 times between 2000 and 2019 (Bae et al., 2019; Kim et al., 2020). Today, South Korea has the world's second-largest number of biomimicry technology patents (29%) after the United States (Lee, 2020). Local biomimicry development (commonly referred to as blue technology in the country) will generate an estimated value of USD62 billion and 650,000 new jobs by 2035, and a further USD 382 billion and 2 million new jobs by 2050 (Kim et al., 2020).[11] Until 2019, most policies supporting R&D and commercialization of biomimicry-based products

[10] For instance, the US military research funding department is looking to insects because, anatomically, they are very efficient creatures when it comes to energy and size, and they have a unique way with problem solving, which can be useful for computational strategies (Hinchliffe, 2019)

[11] It is also predicted that biomimicry development could lead to significant environmental savings of up to USD1.22 billion and USD 3.74 billion by 2035 and 2050 respectively, through reductions of pollution, carbon dioxide emissions, as well as other environmental harms (Kim et al., 2020).

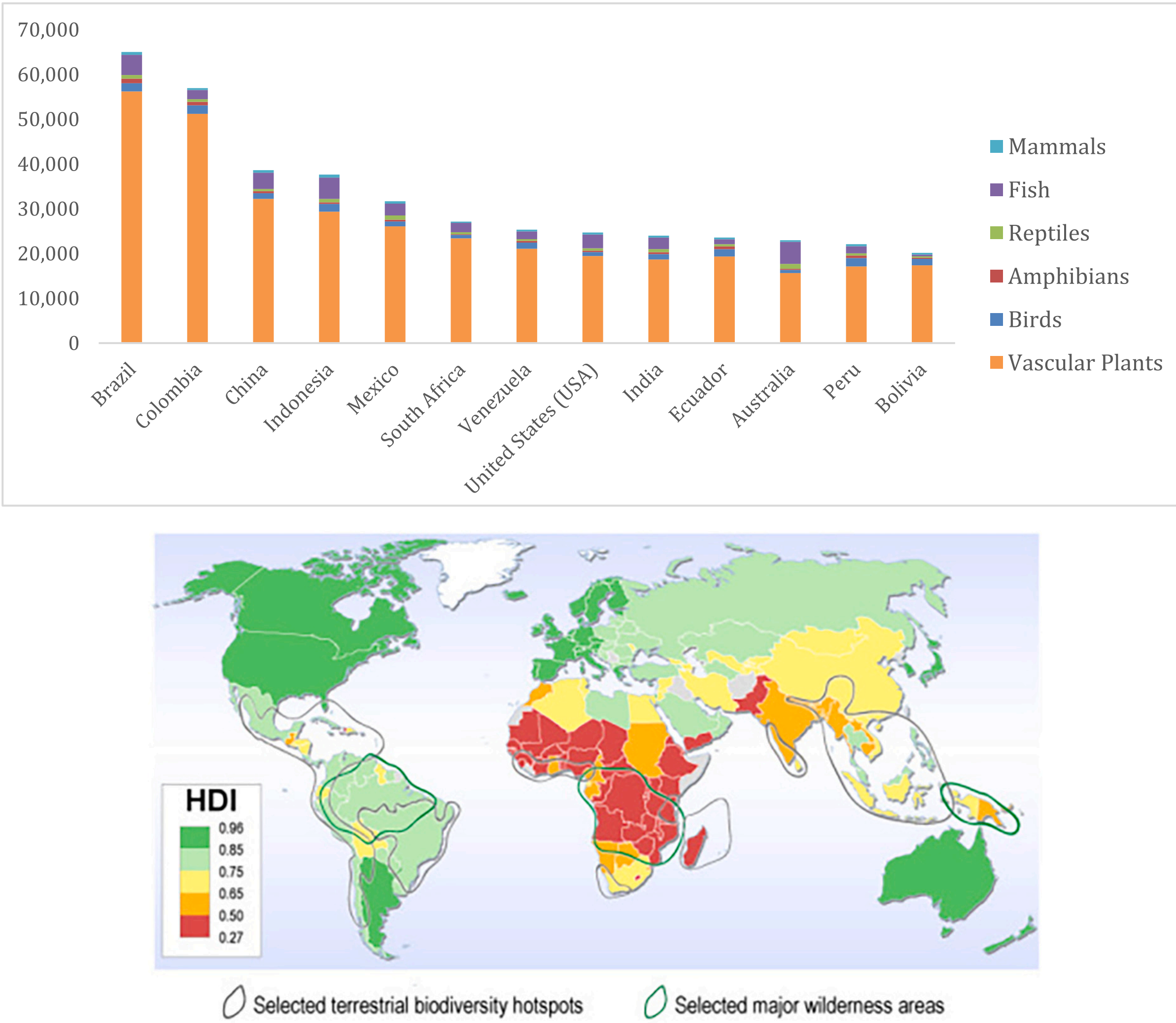

Fig. 4. The Developing world's lion's share of (remaining) biodiversity. A Biodiversity Index based on the total number of amphibian, bird, fish, mammal, reptile, and vascular plant species, by country. 4A. Biodiversity Index based on the total number of amphibian, bird, fish, mammal, reptile, and vascular plant species, by country.
Source: Data compiled in Mongabay, usingdata from the World Conservation Monitoring Centre of the United Nations Environment Programme,2004; Fishbase; Birdlife International; AmphibiaWeb; IUCN; and the Reptile Database.
4B. Map of biodiversity hotspots world-wide
Source: UNDP (2004); Conservation International (2004).

were led by provincial governments (in the North Gyeongsang and South Jeolla provinces), rather than at the national level (Lee, 2019; Kim, 2019).[12] The national orientation of biomimicry-related policies began in October 2019, with the proposal of the Blue Technology Development Promotion Act in the National Assembly to promote the development of biomimicry technologies through systematic governmental support (Na, 2019). This bill encourages national-level support for the R&D of biomimicry technologies, as well as the provision of education and skills required for the future development of the sector through the establishment of a national biomimicry research centre, biomimicry information management institution, research as well as a biomimicry technology impact assessment (Lee, 2020).[13]

The government of China has also more recently embraced biomimicry as an innovation strategy, with several prominent institutes conducting research, all receiving governmental funding. Biomimicry has been included in the government's development strategy, especially related to design and architecture (Polites, 2019).

While biomimicry has been increasingly identified as a strategic innovation sector and supported by a range of policy tools in a handful of high-income industrialised economies, its potential has been mostly overlooked in developing countries. Besides the existence of biodiversity museums such as in Brazil and Panama, intended to spread the scientific value of forests and the importance of biomimicry, very few public policies have been designed to promote the domestic development of nature-inspired technological innovation, as detailed in section 4.

[12] In 2015, the North Gyeongsang Province announced its plan to enhance research and commercialisation of nature-inspired products, and formed a "blue technology industrial cluster" as well as a "blue technology council" to achieve that objective (Lee, 2019). Similarly, in 2016, the South Jeolla Province introduced an outline of the blue technology industrialization plan (Lee, 2020) with close cooperation with the Gwangju Institute of Science and Technology (Kim, 2019).

[13] South Korea's Ministry of Environment has also committed to invest 25 billion won (around USD20million) on biomimicry R&D projects between 2019 and 2023, to develop and commercialize biomimicry technologies (Ministry of Environment, 2020).

Table 1
Leading biomimicry-related policy initiatives across the World.

Country	Key Public Agencies	Programme/Policy	Further details
France	Ministry of Ecological Transition Ministry of Agriculture & Foodstuff Economic, Social and Environmental Council	Centre Européen d'Excellence en Biomimétisme (CEEBIOS) Strategie Bioeconomie Pour La France, Plan d'Action 2018–2020	CEEBIOS was launched in 2014 to coordinate academic research with over 200 laboratories and firms dedicated to biomimetics in France. Set up of biomimicry norms (optimization and methodology)
Germany	Federal Ministry for Education and Research	BIOKON *KompetenznetzBiomimetik*	The Bionics Competence Network (BIOKON) hosts the 28 major players in the field of bionics and biomimetics in Germany and aims to demonstrate the possibilities of bionics to business and industry, science, and the general public, and subsequently tap its full potential *The German government has invested over 120 million euros in those networks since 2001*
South Korea	National Government Ministry of Environment North Gyeongsang and South Jeolla provincial governments	Blue Technology Development Promotion Act to promote the development of biomimicry technologies through systematic governmental support Creation of various industrial clusters, councils, and industrialization plans based on biomimicry	South Korea's Ministry of Environment has committed to invest 25 billion won (around USD20million) in biomimicry R&D projects between 2019 and 2023, to develop nature-inspired environmental pollution management systems, and to commercialize existing biomimicry technologies.
Switzerland		*Inter-university centre (bringing together the* university of Fribourg, EPFL and ETH Zurich) dedicated to bio-inspired materials.	*This programme involved an investment of* EUR26 million.
United Kingdom	UK Government	NIM (Nature Inspired Manufacturing (Previously known as BIONIS) Small Business Innovation Research (SBIR) program	The Biomimetics network for industrial sustainability (BIONIS) was set up in 2002, with the help of UK government funding to promote R&D and cooperation regarding biomimicry
United States	Department of Defense Department of Energy National Science Foundation	Bio-inspired Manufacturing (Small Business Innovation Research program) The Defense Advanced Research Projects Agency (DARPA) Advanced Research Projects Agency-Energy (ARPA-E) The Global Innovation through Science and Technology initiative	Funding of early-stage technologies Identification of priority and strategic biomimicry R&D.

4. Preliminary analysis of the latin american context

Given Latin America's vast endemic biodiversity and unique natural ecosystems, biodiversity-inspired innovation can be a transformative force for the economic development of the region. Nevertheless, to date, most of the initiatives related to biomimicry have been isolated and small in scale given the lack of national coordination efforts and appropriate policy frameworks.

4.1. The Latin American context

The focus on Latin America is justified by the region's singular physical geography, which explains why it contains more than half of the thirteen most biodiverse countries in the world, namely Brazil, Colombia, Mexico, Peru, Ecuador, Bolivia, and Venezuela (see Fig. 4A). The interplay between the region's biodiversity and economic activity is a vitally important narrative in Latin America, and for many years, this interplay tipped in favour of resource extraction and use (Purkey, 2021). Nevertheless, the growing global focus on sustainable development and ecological sustainability increasingly prompts a discussion between the continued reliance on traditional extractive economic activity and the desire to preserve the region's unique natural treasures (ibid.) Against this backdrop, it is worth exploring the role of biomimicry as providing a sustainable economic alternative to deforestation and extractive activities in the region. The natural biodiversity of the Latin American region has inspired several interesting inventions and innovations *outside* the region and holds great promise in terms of potential and future innovations (see Annex 1). The localization of biodiversity-inspired R&D in Latin America is further justified by the fact that many of the fauna and flora species are endemic to the region and not found elsewhere, as well as the fact that the transport of genetic resources is often restricted by legal frameworks anchored in the Nagoya Protocol on Access and Benefit Sharing (as further discussed in section 5.3).[14]

It is worth mentioning that the region has already witnessed efforts to capitalize on the innovation value of biodiversity, but mostly through bioprospecting. As further discussed in 5.2.2, the most well-known initiative took place in the 1990s in Costa Rica, with the creation of the National Biodiversity Institute (INBio), which worked under the premise that a country will be able to conserve a major portion of its wild biodiversity if this biodiversity generates enough intellectual and economic benefits to make up for its maintenance (Mateo et al., 2001). Nevertheless, serious doubts have been raised regarding the relative economic and developmental benefits of bioprospecting (see Barrett and Lybbert, 2000).

Despite its considerable potential, the biomimicry sector has so far been in rather nascent stages across Latin America and has received far less attention than bioprospecting. Across the countries surveyed only a few government policies exist, and entrepreneurship and research have so far been rather minimal as shown in Table 2. Governments in Mexico, Colombia, and Chile have taken non-negligible steps in terms of both research and firm-level activity, while policy support for biomimicry activities is quasi-non-existent in countries such as Argentina, Brazil, Ecuador, Costa Rica, and Panama. Brazil, despite being the most biodiverse country in the world, has particularly lagged in terms of building up a biomimicry ecosystem. This can be partially explained by the economic downturn of previous years, which led to many organizations cutting R&D capabilities and a lack of governmental investment in biomimicry programmes (Di Domenico, 2019) Biomimetics is also an

[14] Two recent reports of the United Nations Economic Commission for Latin America and the Caribbean identified biomimicry among the possible bioeconomy development routes (Rodríguez et al., 2019; Gramkow, 2020). Nonetheless, these mentions remain very brief, and no study analysing biomimicry as an innovation strategy in Latin America has been conducted to date.

Table 2
Preliminary Mapping of Biomimicry research, initiatives, and policies in Latin America.

Country	Biomimicry research/training programmes	Number of firms identified as of January 2021	Existence of public policies
Argentina	3 (UNL; UNRC; INTA)	1	No policy identified
Brazil	1 (INPA)	5	No policy identified, beside the set-up of the Amazonia Science Museum to "emphasize the importance of biomimicry".
Chile	4 (U. Aldofo Ibáñez; U. de Chile; U. Catolica; U. de Santiago).	3	*The Explora* programme as part of the National Commission for Science and Technology (CONICYT)
Colombia	1 (Universidad Pontificia Bolivariana)	4	Identification of biomimicry as a strategic sector by the Government but otherwise limited policy support.
Costa Rica	4 (U. de Costa Rica; Veritas University; Lanotech)	0	National Bioeconomy strategy
Ecuador	3 (ESPE; U. Nacional de Loja; IKIAM).	1	No policy identified
Mexico	2 (UNAM; CICY)	5	The government has funded two key biomimetic research centres in the last 5 years (LaNSBioDyT; Biomimic Scientific and Technological Cluster).
Panama	2 (Geoversity; Universidad Tecnológica de Panama)	0	No policy identified
Peru	1 (Universidad de Ingeneria y Tecnología)	0	No policy identified

area of great potential for Chile given its diverse ecosystem and number of endemic species. For example, over 62% of Chile's marine species are endemic to the country and not found elsewhere (CONICYT, 2016). Nevertheless, the sector remains nascent.

4.2. *Successes and failures to leverage the economic value of biodiversity in two cases: Costa Rica and Ecuador*

This section provides a deeper analysis of the country-level contexts of Costa Rica and Ecuador. Costa Rica and Ecuador are considered among the most biodiverse countries in the world despite their small land surface, which explains why biodiversity has constituted a central issue in the development policy debate in both countries. However, while Costa Rica has pioneered policy efforts to leverage the economic value of biodiversity, the policy initiatives in Ecuador have tended to be narrower in terms of the ways in which the country's unique biodiversity could be leveraged as a lever for development. This is well reflected

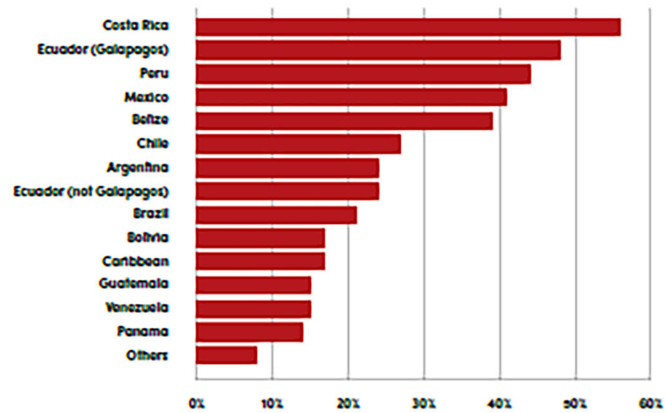

Fig. 5. Percentage of US-based ecotourism operators offering products by country.

by the Yasuní-ITT Initiative, which aimed to leave oil in the ground in the Yasuní National Park, one of the most biodiverse hotspots in the world. This initiative failed due to the lack of international coordination to compensate for biodiversity protection (from which the whole world benefits),[15] but also the lack of concrete developmental alternatives to oil exploitation and poor utilization of biodiversity as a more sustainable source of revenues beyond ecotourism.[16]

4.2.1. *The limits of the reliance on ecotourism as a biodiversity-based development model and attempted shifts towards innovation activities*

Ecotourism's appeal rests in its potential to provide local economic benefits while maintaining ecological resource integrity through low-impact, non-consumptive resource use (Stem et al., 2003). It has become increasingly popular across Latin America as a way to promote environmentally friendly growth. Both Costa Rica and Ecuador (in the Galapagos Islands more particularly) are among the major ecotourism destinations in the world (see Fig. 5). Nevertheless, overreliance on ecotourism has often posed important environmental and developmental risks (Purkey, 2021). Ecotourism cannot be viewed as a benign, non-consumptive use of natural resources in biodiverse nations (Jacobson and Lopez, 1994), which is why it is crucial to identify alternative ways to capture the economic value of biodiversity conservation to complement -and at times supplement- ecotourism.

Source: Purkey, 2021.

The risks associated with dependence on ecotourism are demonstrated by the experience of the emblematic Galapagos Islands, which have become overdependent on tourism as a source of funding for biodiversity protection:

1. *Environmental damage*: In 2007, due to the uncontrolled development of tourism, the Galapagos were even included in the Danger List of the UNESCO World Heritage Sites.
2. *Lack of value-added:* It is highly unlikely that ecotourism can generate sufficient skilled jobs and knowledge spillovers to act as an engine of

[15] See Gatti et al. (2011) for a discussion of the failure to recognise the contributions of the South to the production of cooperative surplus; Drupp et al. (2018) and Baumgärtner et al. (2017) on the social willingness to pay for environmental public goods and distributional effects to ensure justice.

[16] The Government of Ecuador initially proposed to keep almost a billion barrels of oil underground if the international community contributed with at least half of the opportunity cost of exploiting it (Larrea and Warnars, 2009). The initial support from international institutions, European governments, and NGOs worldwide did not translate into concrete action and the 2008/9 financial crisis also added pressure on Ecuador's international sources of financing, which pushed President Correa to pursue the plan to drill for oil if contributions were not received (ibid.).

growth and therefore a sufficiently attractive alternative to biodiversity exploitation/extractive activities.

3. *Revenue Volatility:* Revenues from tourism are highly vulnerable to external shocks, as demonstrated by the COVID crisis. The number of tourists visiting the islands dropped from by 75% between 2019 and 2020. While nature has gained some relief, the revenue drop has jeopardised the local economy and livelihoods, as well as the public budget to maintain local natural ecosystems.

As a result of those downsides, the local government of the Galapagos Islands is attempting to develop research and innovation activities to replace tourism as the main source of local livelihoods and funding for biodiversity protection (Norman Wray, Governor of the Galapagos Islands, personal interview, April 2021). While 85% of the Galapagos Economic activity used to depend directly or indirectly on tourism before the pandemic, "it has become essential to recover economic activity in a way that is productive, inclusive, resilience, and environment-friendly" (Luis Felipe López-Calva, UNDP director for Latin America, cited in UN 2020). Holding the second marine reserve in the World, the Galapagos Islands are often referred to as a 'the largest live biodiversity laboratory of the world' and have famously inspired Charles Darwin's evolution theory, which shows the value its local ecosystems hold as a source of information. However, such potential has been mostly unfulfilled to date given the limited local R&D capabilities to conduct biomimicry activities, such as the lack of specialized local universities (the only higher education institution is an extension of the USFQ which provides mostly non-technical courses). As a result, local populations have struggled to gain the required skills for the development of a local nature-inspired innovation ecosystem.[17] As a first step towards a new innovation-based development model, an innovation hub was created in May 2021 under Ecuadorian law. This innovation hub is the first public policy aiming to promote innovation activities in the Galapagos. (Norway Wray, Governor of the Galapagos Islands, personal interview, April 2021). Though bio-innovation does not ensure conservation (see section 2.2), and the impact this initiative will have on the long-term conservation efforts is not clear yet, it represents a promising step forward because it identifies synergies between biodiversity and innovation, as well as its orientation as a potential alternative source of financing for conservation.

In Costa Rica, eco-tourism has also gained appeal as a strategy to align both conservation and development, but existing assessments of its impact in the country have also been mixed (the negative impacts raised in the literature include solid waste generation, air pollution, habitat destruction, and sociocultural ills; see Jacobson and Lopez, 1994; Stem et al., 2003; Koens et al., 2009). In their study of the effectiveness of ecotourism as a conservation and development tool in Costa Rica, Stem et al. (2003) find that scale influences tourism's benefits and negative impacts and that, where ecotourism dominates local economies, towns may become economically vulnerable. Ecotourism is most effective as a component of a broader conservation strategy and if embedded in a broader process of capacity building. Costa Rica has taken important steps in that direction. For instance, Costa Rica's Payments for Environmental Services Program (PES) is a financial mechanism created in the 1990s whereby landowners receive direct payments for the ecological services that their lands produce when they adopt environmentally friendly land uses and forest management techniques (Malavasi and Kellenberg, 2002). Costa Rica's Forest Law (adopted in 1996) recognizes four environmental services provided by forest ecosystems: (i) mitigation of GHG emissions; (ii) hydrological services, including the provision of water for human consumption, irrigation, and energy production; (iii) biodiversity conservation; and (iv) provision of scenic beauty for recreation and ecotourism. Though there have been criticisms on the degree of environmental additionality of PES and warnings regarding their over-reliance in Costa Rica and elsewhere (Sierra and Russman, 2006; Muradian et al., 2013), it should be recognized that ecotourism in Costa Rica has been clearly embedded in a national vision for leveraging the economic value of nature, and the government has historically shown more ambitious efforts to capture the innovation value of biodiversity (although almost exclusively through bioprospecting), as discussed in the next section.

4.2.2. Isolated biomimicry-related initiatives in the context of limited state support

The potential development of biomimicry activities in both Costa Rica and Ecuador is considerable because of the existence of large shares of the world's endemic biodiversity, but also the existence of related frontier research capabilities domestically, such as the mapping and discovery of new species, which often involved partnerships between local and foreign research teams.[18] Nevertheless, notwithstanding these countries' considerable potential for nature-based technological innovation, the persistence of market and institutional obstacles remain key challenges to be addressed.

Costa Rica has shown far greater policy initiatives towards capturing the economic and innovation value of biodiversity. Besides the country's bioprospecting efforts in the 1990s (see Table 3), in the more recent context of the recovery from the COVID crisis, several key initiatives to promote bio-innovation were launched, such as the National Bioeconomy strategy (2020), to promote a green knowledge economy; and the Biomaterials hub, funded by the IDB Lab and led by Costa Rica's investment promotion agency (CINDE), to promote R&D around biodiversity for domestic firms that do not have R&D capabilities. Those laudable efforts remain largely focused on utilizing natural assets as a source of genetic material rather than a source of inspiration, which imply two different R&D processes (see Fig. 1). Meanwhile, efforts towards exploiting the country's biomimicry potential more specifically have been limited and no biomimicry initiatives have been identified in the country besides four university-level research projects currently undertaken at the Universidad de Costa Rica, LANOTECH, Veritas and Universidad Nacional.[19] None of these university research projects have evolved into businesses to date. In Ecuador, public policy support for biomimicry is quasi-non-existent. As a result, most biomimicry activities conducted in the country appear to be university spinoffs (such as the biofilter company Anuka) that have not managed to scale up due to the lack of available funding and the high cost of laboratory operations.[20]

Fieldwork interviews with a range of stakeholders in both Costa Rica and Ecuador between January and November 2021 further shed light on a range of bottlenecks (most of which are common across both countries) hindering the development and commercialisation of biomimicry activities (see Table 3). Resolving these coordination failures that are stunting the growth of biomimicry activities requires the strategic use of policy interventions. For instance, the provision of funding, facilitation

[17] Low internet connectivity is also an obstacle to the development of innovation activities in the islands (a plan to install fibre optic cables in 2022 is expected to increase the connectivity of the islands).

[18] The need for foreign firms and researchers to collaborate with local researchers is notably due to restrictions in the access to local genetic material and permits required from the Ministry of Environment, as well as the fact that local teams often have better knowledge of the local natural ecosystem.

[19] The researchers leading these projects study the cooling properties of long-horned beetles; the adhesive properties of hydrogel secreted by a specie of worms; and antibacterial properties of *pineapple peel (Personal communications with lead researchers; October/November 2021)*.

[20] For instance, Anuka is a firm that takes advantage of the capacities of endemic volcanic microalgae of Ecuador, which offers more resistance to bacteria and to fungus than most microalgae found around the globe, to adapting them to reduce the presence of CO_2 in the environment. Anuka has later developed as a university-spinoff but the growth of the firm and the development of the commercial phase was stunted by the lack of domestically available non-repayable funding, and high laboratory operating costs in Ecuador.

Table 3
Identified hurdles for the development of biomimicry activities in Costa Rica & Ecuador.

Obstacle	*Explanations*
Lack of awareness regarding biomimicry and its potential	Investment in biomimicry has been suboptimal in both Ecuador and Costa Rica in part due to a lack of market signals and awareness regarding its impact and processes. Public policy support for biomimicry is quasi-non-existent in Ecuador, while in Costa Rica, despite far more policy awareness on the innovation value of biodiversity and the clear promotion of a bioeconomy, the specific theme of biomimicry has not been addressed in policy documents.
Limited bioprospecting to date (Ecuador) / Limited value derived from bioprospecting (Costa Rica)	Though the systematic and organised exploration of biodiversity for new sources of value (bioprospection) is a first step towards biomimicry, estimates suggest that less than 10% of Ecuador's biological diversity has been inventoried, let alone studied (Bellota, 2016), which is why supporting large-scale projects with universities and research centres to complete the inventory of biodiversity in the country is essential moving forward. In that perspective, key lessons can be learned from Costa Rica's mixed experience with bioprospecting, with the flagship National Biodiversity Institute (INBio) and more recently the BioAlfa project. INBio was created in the 1990s to conduct biological inventories, biodiversity prospecting, and management and distribution of Costa Rican biodiversity information (Zebich-Knos, 1997). After three decades of activity, it ceased to operate due to the dried-up funding sources – 80% of which came from the international community- and its inability to become financially sustainable (Personal Communication, Former Minister of Environment of Costa Rica, November 2021). In addition, doubts were raised regarding the relative economic benefits of bioprospecting, as illustrated by the celebrated deal between INBIO and the pharmaceutical company Merck, in which the royalties to be earned by Costa Rica should Merck develop a commercial drug are believed to be less than 5%, which is less than USD1.1 million (Meyer, 1996; Barrett and Lybbert, 2000; Campbell, 2002). More recently, in 2019, bioprospecting has reappeared in the policy agenda with the BioAlfa project, launched by a Presidential Decree, to generate more precise mapping and identification of every specie in Costa Rica through DNA barcoding, before placing this information in an open-source, publicly available database.
Lack of a critical mass of specialized human capital due to lacking interdisciplinary university training related to biomimicry	Very few universities provide the technical training required to translate the already existing local capabilities in biological mapping into technological innovations through biomimicry (except for the Yachay programme in Ecuador, which is anticipated to include education and research on bio-inspired topics, and the existence of bioengineering and nanobiotechnology programmes in the Universidad Nacional and CeNAT in Costa Rica). Interviews with the only Ecuadorian firm (Anuka) that has been identified in the biomimicry-based innovation sector further confirm that due to the lack of university programmes that provide biomimicry training, some of the team of researchers had to enroll in a second postgraduate degree in nanotechnology to complement their initial training in applied bioscience, at their own cost of time and financial resources. Meanwhile, in Costa Rica, the majority of researchers using biomimicry received interdisciplinary training overseas that is not available nationally.
Inadequate financial support	In Ecuador, the growth of the firm Anuka, and the commercialization of its nature-inspired technology, were stunted by the lack of domestically available non-repayable funding and high laboratory operating costs (due to the need to import laboratory equipment). The existence of high interest rates (which are even higher than consumption credits) also prevented the firm from securing loans from the domestic banking sector. Despite fulfilling its eligibility conditions, the firm was also denied funding from a government program, the 'Ideas Bank' (*Banco de Ideas*), which is part of the Secretariat for Higher Education, Science, Technology and Innovation, on the ground that the field of operations was not deemed strategic by the government (ANUKA's CEO, Personal communication, April 2021). Due to the lack of domestically available cheap or non-repayable sources of seed funding, the firm has almost exclusively relied on international awards and grants for opening and operating its laboratory.[a] As a result, it has considered moving its operations abroad, where the availability of funding, laboratory equipment, and prospective larger contracts for the installation of biofilters for municipalities offer better perspectives for scaling up.
Administrative hurdles and difficulty to obtain permits to conduct research using the nation's biodiversity.	An overwhelming majority of researchers interviewed as part of this study (over 20 individuals across five institutions) in Costa Rica raised concerns about the administrative hurdles posed by CONAGEBIO to handle genetic material for research. Facilitating access to the country's fauna and flora for research purposes for nationals -while ensuring strong protocols to avoid environmental damage- will be essential for the promotion of biomimicry as a widespread innovation strategy but remains a challenge.

[a] The firm developed as a university-spinoff after winning a USD 10,000 prize from the Inter-American Development Bank, which enabled the firm to create a laboratory, and later won several international awards and sources of funding (such as Startup Chile and the Global Innovation through Science and Technology initiative, which is a U.S. government program

of access to study biodiversity, and the promotion of integral and interdisciplinary education programmes in biomimicry processes will be crucial for the successful development of local nature-inspired innovation clusters. The theoretical and policy implications of these findings are discussed in the next section.

5. Policy and theoretical implications

5.1. Policy interventions to stimulate strategic and serendipitous nature-inspired innovation clusters

The analysis of the global nature-inspired innovation landscape and the Latin American context reveals a range of coordination failures that hinders the development of nature-inspired technological innovation. Creating and strengthening technological capabilities has often not been easy in developing economies, due to the presence of not only market failures but also system and learning failures (Lee, 2019). However, though constraints and market imperfections are more likely to hinder the development of biomimicry activities in developing countries, this agenda cannot be dismissed for various reasons. Firstly, as highlighted in section 2.1, innovation is a key determinant of economic development and of a country's ability to escape the middle-income trap. Secondly, biodiversity-based innovation provides an entry door for biodiverse nations that could leverage their proximity to the source of inspiration for innovation, in contrast to other innovation models where entry barriers are higher. Thirdly, institutional capabilities can be built over time, and market imperfections fixed. While static approaches to comparative advantage are path-dependent upon established capabilities, dynamic approaches to comparative advantage feature a wider scope for the role of public policies for technological upgrading, learning by doing, and the accumulation of new productive capabilities accumulation (e.g Dosi, 1982; Lall, 1992; Chang, 2003; Mazzucato, 2016; Lebdioui, 2019). In the context of biomimicry, such dynamic approaches to comparative advantages are more suited to explain the dynamics and policy tools that encourage the transition towards knowledge-intensive biodiversity-based activities beyond mere rent maximization from resource exploitation and biodiversity degradation.

Policy interventions that are enabling the successful development of biomimicry-related activities in leading countries have indeed gone far beyond fixing markets and instead are shaping the accumulation of technological capabilities. Those findings demonstrate the need for a systemic policy approach, in line with the literature on national innovation ecosystems, which highlights the role public institutions for R&D support, technological incubation, transfer, and diffusion (Andreoni and Chang, 2016; Lee, 2013; Lundvall, 2010; Malerba, 2002; Nelson and Winter, 1982). Public financing and the availability of long-term funding to support biomimicry R&D is particularly critical, which is in line with the scholarship on the role of public funding in stimulating the early-stage development of low-carbon technologies, especially when profits from innovation can only be expected far into the future (Mazzucato, 2013a, 2013b, 2016; Semieniuk and Mazzucato, 2019). In the absence of a functional national development bank tasked with the mission of funding structural transformation towards higher value-added activities, the domestic private banking sector, especially in developing countries, tends to be risk-averse and often fails to provide the conditions that enable long-term, and patient seed funding for innovation, as shown in the case studies of this paper.

Policy implications also arise from the fact that biomimicry can involve both strategic and serendipitous innovation. For instance, the biomimicry promoted in the United States by the Department of Defense is looking directly at specific species (such as insects or the hummingbird) to help achieve specific innovation objectives (computational strategies in warfare and new generation drones), while in contrast, it is while taking a walk through the woods that Swiss electrical engineer, George de Mestral, discovered the cocklebur is comprised of hundreds of tiny hooks that cling tenaciously to fabrics and animal fur, which inspired the invention of Velcro. There are consequently two main ways in which nature-inspired innovations can take place: a strategic/targeted approach, and a serendipitous/scouting approach.

1) *Strategic / Targeted approach*: this approach entails looking to nature to help address an already identified problem. It relies on some pre-existing understanding of our natural ecosystem and solutions it could offer, and the identification of specific species or natural phenomena that solves given challenge. (e.g. research on the hummingbird's morphology for flying backward; or photosynthesis for carbon capture).
2) *Serendipitous / Scouting Approach:* this approach entails general scouting for ideas by looking at nature. Sometimes, a problem is unknown until a solution is provided. While organizations invest heavily in systematic strategies to accelerate innovation, historical analysis and individual experience also suggest that serendipity plays a significant role in innovation (Fink et al., 2017). This approach however also relies on pre-exsting engineering and design knowledge, as to enable agents and firms to recognise useful solutions in nature when they see them (similarly to Velcro's founder).

National innovation clusters around biomimicry consequently need to be built to provide agents and firms more exposure and opportunities for both strategic and serendipitous innovation, by allowing the more systematic consideration of nature when trying to solve engineering and industrial problems. The creation of 'eco-labs' in biodiverse areas, where the natural ecosystem is preserved, and where appropriate physical and digital infrastructure can be built to host researchers and firms to explore and investigate the usefulness of various species for existing challenges, could also help enable more serendipitous innovations through biomimicry.

5.2. Education policy for nurturing biophilia and targeted human capital

The state has a key role to play as a catalyst of targeted human capital accumulation required for the development of new sectors, especially in countries with little pre-existing related capabilities (See Gerschenkron, 1962; Lebdioui, 2019, 2020). The development of biomimicry activities makes the role of education policy even more relevant because unlike many other 'traditional' sectors, it requires a strategy mix of skills (such as biology, chemistry, and engineering skills) which the standard curriculums do not provide. Biomimicry design processes rely heavily on biological knowledge, but also on design and engineering, especially when it comes to abstracting biological strategies into more broadly applicable design principles and implementing them to solve human challenges (Kennedy et al., 2015).

Such human capital dynamics are visible in the countries that have accumulated frontier R&D capabilities in biomimicry. For instance, in Germany, there are over 15 university degrees related to biomimicry, out of a total of 25 in Europe. In France, CEEBIOS involved 175 biomimicry research teams by 2019 (against 45 in 2012). To remedy the lack of university courses in biomimicry, two higher education institutions have created in 2020 pioneering courses dedicated to biomimicry (the *Ecole nationale supérieure de création industrielle* -ENSCI, and the *Université de Pau et des pays de l'Adour*). Such courses "finally put an end to this teaching in silos, which isolates biologists from physicists, chemists, and mathematicians" (codirector of the master's degree in bio-inspired materials of the University of Pau, cited in Le Neve, 2019).

Besides the introduction of higher education programmes related to biomimicry, the implications for primary and secondary education are also worth highlighting due to the possible role of biophilia in stimulating interest in biomimicry processes. Biophilia is a term coined by Edward O. Wilson and can be defined as a human tendency to interact and associate with other forms of life in nature. It is a tendency that can get induced and developed from a young age, which sheds light on the possible role of primary and secondary education to inculcate an appreciation of biodiversity in terms of both its ecological and innovation value. In Costa Rica, the state has implemented educational initiatives to encourage the development of sustainable environmental attitudes and biophilic behaviours; and environmental learning is required as part of both primary and secondary education in the national state school curriculum (Blum, 2008). In Ecuador, people who display biophilic behaviour, which includes indigenous communities, usually do not have access to the scientific skills and capabilities enabling them to engage in technological innovation (CEO of Anuka; Personal Communication; April 2021). Improving access to STEM field for local and indigenous communities could be key for the development of socially inclusive models of biodiversity-based innovation. Nevertheless, asserting whether biophilia is truly a prerequisite for the critical development of biomimicry activities would require further research, involving a larger sample of researchers that are involved in biomimicry, to understand their motives, education, and personal backgrounds, and which is beyond the scope of this current study. What remains clear from the findings of this study is that the promotion of biomimicry requires a collaborative framework between various actors, such as governments, education providers, and the business sector. Such collaboration is necessary to ensure the provision of the specific type of human capital needed to shape the dynamic innovation-driven processes taking place around biodiversity.

5.3. Revisiting legal frameworks for benefit-sharing

Even though environmental assets have considerable value as sources of information that feed into research, innovation, and industrial processes globally, the benefits from nature-inspired innovation have often failed to compensate for such value. The essential role of biodiversity as an informational input into fundamental industries highlights the importance of developing mechanisms for recognising this role and its value to those who invest in its retention, similarly to the ways in which human-based sources of information are compensated for through intellectual property rights (Juma, 1989; Swanson, 1996).

The institutional and property rights concerning the extraction of genetic material and local knowledge are well known (see Correa, 2001; Gupta, 2004; Von Lewinski, 2008) but the issue of biomimicry makes this problem worse, as it is more difficult to make claims of ownership or compensation for engineered solutions that mimic biodiversity than it is to make an intellectual property claim about a life science solution synthesised from natural organisms. This is because innovators and firms do not need to declare where they have drawn inspiration from, and it is more difficult -and not necessarily desirable- to restrict the process of inspiration – rather than extraction- from solutions that are available in nature as a public domain.[21] R&D using biological materials is indeed a dynamic, inter-temporal asset transformation process that requires dynamic governance rules and processes (Polski, 2005). Another issue is that getting inspiration from genetic resources does not require foreign direct investment or the purchase of exploration permits (as in the case of non-renewable resources). Inspiration from nature is, therefore, not equivalent to the acquisition of genetic material, which means that the policy mechanisms that regulate biopiracy and benefit-sharing surrounding the use of genetic material need to be differentiated from those regulating biomimicry.

As a result of loose intellectual property frameworks and the other above-mentioned factors, the use of biodiversity as informational input for R&D has often led to biopiracy – a practice in which the local knowledge of nature is used by others for profit without authorization or compensation (as explained in section 2.4) of this study. Notwithstanding the considerable difficulties in monetizing the value of environmental assets as a source of inspiration, ensuring rightful compensation requires the existence and enforcement of national and international legal frameworks. Such objectives were a central part of the Nagoya Protocol on Access and Benefit Sharing (ABS), which is a 2010 supplementary agreement to the 1992 Convention on Biological Diversity (CBD) (preceding the 2021 Kunming Declaration which calls for further action for biodiversity protection). It aimed to implement fair and equitable sharing of benefits arising out of the utilization of genetic resources (which includes R&D as well as subsequent applications and commercialization based on those resources) with the contracting party providing genetic resources, thereby contributing to the conservation and sustainable use of biodiversity. Nevertheless, this protocol has not always been respected. Furthermore, the United States has yet to ratify its participation in the CBD and has not even signed the Nagoya Protocol (while countries such as Australia, France, and Japan have signed but not ratified it yet).

The concept of benefit-sharing is also key to the connection between biomimicry and conservation (as noted in section 2.2.). In principle, although biomimicry relies on the availability – and by extension conversation- of natural assets (a biodiversity stock), the two processes do not need to be mutually re-enforcing. To associate the practice of biomimicry with a conversation agenda, appropriate legal frameworks and institutions are needed to back up resources for biomimicry with protected area status and protection of the biodiversity stock. This is particularly important in the context of serendipitous innovations, where there is uncertainty about how useful the organisms are from an R&D perspective, and their usefulness may only arise in the future because a country's biodiversity stock can be a knowledge bank of solutions to unknown problems of the future. In that sense, though there are no blueprints for benefit-sharing, given the importance of institutional learning in the implementation process of the access and benefit-sharing provisions around biodiversity (Siebenhüner and Suplie, 2005), the experiences (including both successes and limitations) of some countries (such as Costa Rica) with payments for environmental services and bioprospecting, as well as the benefit-sharing frameworks provided in other treaties such as the International Treaty on Plant Genetic Resources for Food and Agriculture, can hold important sources of lessons that can be adapted and applied in the context of biomimicry.[22]

6. Concluding remarks

The importance of the structural transformation agenda towards more sustainable sources of revenue and value addition in developing countries is heightened by the context of climate change. Two-thirds of developing countries, where the majority of the world's remaining biodiversity is concentrated, are dependent on the exports commodities that are intrinsically linked to climate change: fossil fuels are at risk of becoming stranded assets as the world decarbonizes its economic systems, while productivity in agro-commodities tends to be highly vulnerable to fluctuations in temperature and precipitation (Elgouacem et al., 2020; Lebdioui, 2022). The accumulation of new productive capabilities, and banking on the innovation value of biodiversity, are therefore key concerns in the context of 21st century economic development.

In the context of an urgent need for a greener structural transformation and the emergence of development models that allow for better biodiversity protection frameworks, this paper has shown that biomimicry represents a promising avenue for latecomers well-endowed with biodiversity to leapfrog to the innovation frontier by leveraging their biodiversity as a stock of information for R&D process. This paper, therefore, builds on evolutionary and developmentalist perspectives, according to which developing countries must create new value-generating activities as a means of searching for higher profits and employment from innovation to catch up, as opposed to statically maximise rents from an existing income stream.

To date, the landscape for nature-inspired innovation has been dominated by industrialised economies that have relied on proactive policy interventions, while virtually no developing country has adopted biomimicry as an innovation strategy. In selected cases across Latin America, this paper shows that the lack of policy and institutional support has led to the persistence of important coordination failures that have hindered the integration of domestic firms at the nature-inspired innovation frontier. A major rethinking of public policies supporting nature-inspired innovation ecosystem is therefore necessary.

The findings of this research have great potential for contributing to the current academic and policy debates in various biodiverse countries. Nevertheless, several areas for further research are needed to fully understand the developmental dynamics of biomimicry in developing nations. For instance, considering the lack of compliance with the Nagoya protocol, further research is needed to analyse the type of legal mechanisms that can be realistically implemented for benefit sharing and compensation for those who invest in preserving biodiversity from which important genetic materials and information are extracted.

[21] The role of vision and intuition tend to be under-reported: a study of 33 major discoveries in biochemistry "in which serendipity played a crucial role" concluded that "when it comes to 'chance' factors, few scientists 'tell it like it was' (Tria et al., 2014).

[22] Though focused on agriculture, the International Treaty on Plant Genetic Resources for Food and Agriculture, adopted in 2001, could offer interesting insights and a source of inspiration to adopt similar benefit-sharing frameworks in the context of biomimicry. This treaty recognized the enormous contribution of farmers to the diversity of crops that feed the world and ensured that recipients share benefits they derive from the use of these genetic materials with the countries where they have been originated.

Declaration of Competing Interest

I have no conflicts of interest to disclose.

Data availability

Data will be made available on request.

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