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The promise of access and benefit-sharing is met through holistic policy reform: Insights from Colombia's genetic diversity and innovation landscape during COP16

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Abstract: To tackle the global biotechnological innovation divide, Parties to the Convention on Biological Diversity (CBD) are negotiating policies to fairly share the benefits from the use of digital sequence information (DSI) on genetic resources. The policies aim to transfer money, knowledge and technologies from technology-rich developed to biodiversity-rich developing countries in order to bolster the latter's capacities to achieve the CBD's objectives. However, by focusing predominantly on scientific capacities, these policies overlook the complex interactions between various actors, conditions and infrastructures that collectively constitute a country's innovation capacity. In the first-time application of the National Innovation System approach in this policy context, we identify many factors contributing to an innovation gap in Colombia, the host country of COP16, resulting in barriers to study and valorize biodiversity and in lost opportunities for the country to benefit from new technologies. This analysis calls for consideration of broader policy reforms in access and benefit-sharing (ABS) negotiations, and illustrates how holistic policy interventions are needed in countries that benefit from ABS instruments to effectively use financial, scientific and technological resources. Without such an approach, efforts to enhance benefit-sharing from genetic resources and DSI risk reinforcing inequalities in innovation capacity. Finally, we discuss actions countries could take to use their current resources better, as well as how scientists and companies as users of genetic resources and DSI can pursue mutual interests by tackling innovation bottlenecks.

[Para una versión en español del resumen, por favor consulte los Datos suplementarios – For a Spanish version of the abstract, please see Supplemental data*]*

Keywords: Bioprospecting, access and benefit-sharing, digital sequence information, capacity building, distributive justice, Cali Fund, innovation divide, national innovation system

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Introduction

The completion of the human genome kick-started the 21st century for biotechnology and bioinformatics. With the rapid decrease in sequencing costs, large swathes of genetic sequence data from wild and domesticated species are being generated. These data help researchers and companies understand the threats species face and identify valuable genetic traits in them, such as drought resistance or the ability to break down plastic. Globally, however, there is a growing divide between countries with and without this capacity to reap scientific and economic benefits.

For many years, most benefits from the use of digital sequence information (DSI) on genetic resources have been accrued by high-income countries (HIC), while most biodiversity, and therefore potential DSI, is found in low- and middle-income countries (LMIC). This inequality has been the subject of access and benefit-sharing (ABS) negotiations under the UN Convention on Biological Diversity (CBD) (Rohden & Scholz, 2022). At COP16, held in Cali, Colombia, in 2024, the CBD negotiated the functioning of a multilateral mechanism for benefit-sharing from the use of DSI, including the Cali Fund for the disbursement of monetary benefits, and

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called upon large and medium-scale businesses that use DSI to contribute 1% of their profit or 0.1% of their revenue (CBD, 2024). This mechanism, which, according to some, could potentially generate USD billions per year (LSE Roundtable Team, 2024), is expected to be used by recipient governments to fund conservation projects, meeting the self-identified needs of Indigenous peoples and local communities (IPLC), technology transfer and capacity-building. Scientists and companies are expected to contribute to the latter activities under the banner of non-monetary benefit-sharing.

Literature on a multilateral benefit-sharing mechanism has focused on alignment with research needs, its underlying ethical principles and directions for allocation of the funds (Bagley, 2021; Deplazes-Zemp, 2019; Scholz *et al*, 2022). While the Cali Fund details are being further negotiated, it remains unclear why certain countries fare better in developing their innovation capacity to access, generate and utilize genetic resources and DSI than others. Without that knowledge, benefit-sharing from the Cali Fund risks being ineffective and even unjust. COP host Colombia, an upper-middle-income megadiverse country with advanced science but a small biotech sector, and a likely beneficiary, is an excellent case study to investigate this research question.

Initially, innovation scholarship assumed a linear relationship between government-funded basic and applied research, the development of products and their diffusion in society (Godin, 2006). ABS frameworks arguably mirror this view by regarding research on genetic resources as a stepping stone for commercial bioprospecting and benefit redistribution by governments (Secretariat of the Convention on Biological Diversity, 2011). Biotechnological trajectories, however, are embedded in and formed by institutions and their interactions (Chaturvedi, 2005; Hall, 2005). From early on, the capacity to create and share benefits as an incentive to promote conservation has been part of the rationale behind ABS policies (Sirakaya, 2022). However, assumptions that benefit-sharing automatically translates to enhanced innovation capacities are far too simple. Bilateral ABS agreements have long been criticized for oversimplifying how genetic resources are used in research and development (R&D) (Sherman *et al*, 2025). The factors that make R&D in a country possible in the first place are, however, still overlooked in the ABS literature.

It is important that ABS policies also recognize this institutional complexity so that to-be-shared benefits strengthen these interactions. That gap in understanding is evident in the recurring tendency to attribute scientific capacity development challenges to resource deficiencies. For example, making more data, information and communication technologies, and training resources available may increase individual scientists' capacity but obscures "insidious" patterns of inequality (Bezuidenhout *et al*, 2017). Precisely because knowledge production is sustained by institutional, economic, organizational and political factors (Mormina, 2019), taking into account and strengthening the knowledge structures wherein monetary and non-monetary benefits are created and received is as important as facilitating benefit-sharing itself. In a nutshell, these insights call for holistic, country- and issue-specific capacity-building and investments by the Cali Fund and by users of genetic resources and DSI.

The moral value at stake here is the fair and equitable sharing of benefits from genetic diversity. We reiterate two distributive justice claims here. Distributive justice requires a fair distribution of both benefits and scientific capabilities to create benefits (Mormina, 2019). That means that aside from an equal distribution of resources and opportunities in science, structural biases and barriers in the use of genetic resources and DSI are dismantled. Furthermore, the (non-) monetary benefit transfers do not change the overall direction of R&D, but distributive justice demands from users of genetic resources and DSI an integration of the needs and priorities of beneficiaries upstream at the onset of the R&D cycle (Kreiken & McCarthy, 2025; De Jonge & Korthals, 2006). So, instead of maintaining the status quo, HIC as dominant valorizers of DSI and LMIC as beneficiaries, we argue that the CBD and its stakeholders should target countries' innovation capacity gaps to create and retain benefits.

The reason for undertaking this study is to assess how a country's creation and retention of benefits from genetic diversity is influenced by institutional, economic, historical, organizational and political factors. We now turn to the policy rationale behind this study in relation to ABS policymaking and the ongoing development of the Cali Fund.

While most capacity-building programmes of the ABS Initiative and Global Environment Facility focus on legislative capacities to implement ABS policies, there are so far fewer programmes focused on scientific and innovation capacity deficits to use DSI and genetic resources. Recipients of the Cali Fund are expected to primarily direct funding towards activities that contribute to conservation and sustainable use of biodiversity, which can include scientific research and capacity-building to "generate, access, use, analyse and store [DSI]" (article 18 of Annex Decision 16/2 (CBD, 2024)).

Innovation and institutional capacities to valorize scientific research on DSI and genetic resources are overlooked, however. Currently, there are indications that the vast majority of their economic value ('the pie') is captured at the end of the bioprospecting value chain in patents acquired in HIC (Dunshirn & Zhivkoplias, 2024). While historically LMIC have benefited greatly from conserving and developing their biodiversity, for example, by having a rich crop and animal breed variety with nutritional and medicinal value, not all of these benefits have translated to financial gains or technological development. This valorization gap should be considered significant in the context of the premise of ABS to transfer money back to LMIC for conservation and capacity-building purposes. Charting out a path to economic self-sustenance in ABS policy is important because the contributions to the Cali Fund so far remain voluntary, making expectations about it being a sustainable source of finance for LMIC perhaps unrealistic. Additionally, the COVID-19 pandemic laid bare the vaccine dependency of LMIC, leading to calls for greater biotechnological sovereignty (Guzman *et al*, 2024).

Simply put, if the innovation divide is left unchanged, the monetary benefits that LMIC will receive through ABS ('crumbs') are marginal relative to the economic gains realized in HIC in the long term. For context, in unequal exchanges in raw materials and labour with the Global North, the losses the South incurs exceed the aid it receives thirtyfold (Hickel *et al*, 2022). Disregarding the innovation divide is a missed opportunity because countries with genetic diversity-based industries may direct innovations and tax revenue to nationally relevant goals, including conservation and scientific research, also because we assume that R&D activities in LMIC are more easily matched to the needs of the country and its vulnerable groups than downstream R&D activities in HIC. In addition, we expect that companies will be more willing to contribute to the

Fund if beneficiary countries have clearer ideas of issues that can be addressed through the Fund and have long-term plans for greater economic self-sustenance. These assumptions do not disregard the need for fair and equitable benefit-sharing.

Therefore, this article's insights into the factors that hamper or boost scientific research and innovation for conserving and sustainably using genetic diversity, contribute to informing investment priorities for Cali Fund recipients and broader business engagement. In the next sections, we first elaborate on the National Innovation System model that guides our analysis and data collection. After an overview of Colombia's relevant laws, state of biodiversity and bioeconomy, the findings are categorized per aspect of the value chain and linked back to components of the analytic model. Finally, we make a call to action to rethink domestic and ABS policymaking and the Cali Fund's investment priorities.

Materials and methods

Framework: National Innovation Model

In this section, we explain how the recognition of institutions and interactions enhances our ability to answer the research question. Figure 1 represents a simplified value chain of genetic resources and DSI in Colombia, according to a linear innovation view.

To integrate institutional complexity, science policy analysts have used the National Innovation System (NIS) since the 1980s to analyze individual systems of innovation and their interactions, like the alignment of education with business priorities (Godin, 2009). The commonly used framework for NIS is shown in Figure 2 and includes actors and processes that enable knowledge- and innovation-based economic development (Kuhlmann & Arnold, 2001). As a whole, the NIS model reflects the underlying mechanics of a society's innovation capacity, which is "the context-specific range of skills, actors, practices, routines, institutions and policies needed to put knowledge into productive use in response to an evolving set of challenges, opportunities, and technical and institutional contexts" (Hall, 2005).

Following this definition, we include various users and providers of genetic resources, contextualize the work in relation to ABS and science policy in Colombia, and consider biodiversity loss as the main challenge and the bioeconomy as the main opportunity. For the purpose of the article, and not uncommonly, we enlarge the basic NIS model with three additions to form a nature-based biotechnological innovation system (see Figure 3). In line with the potential of NISs for positive environmental impact (Brás & Robaina, 2024; Fernandes *et al*, 2022), we hypothesize that increased benefit-sharing contributes to the conservation and sustainable use of biodiversity. Because genetic resources and DSI can be considered inputs to the innovation system (Bruynseels, 2020), we include a 'natural system' and a detailed

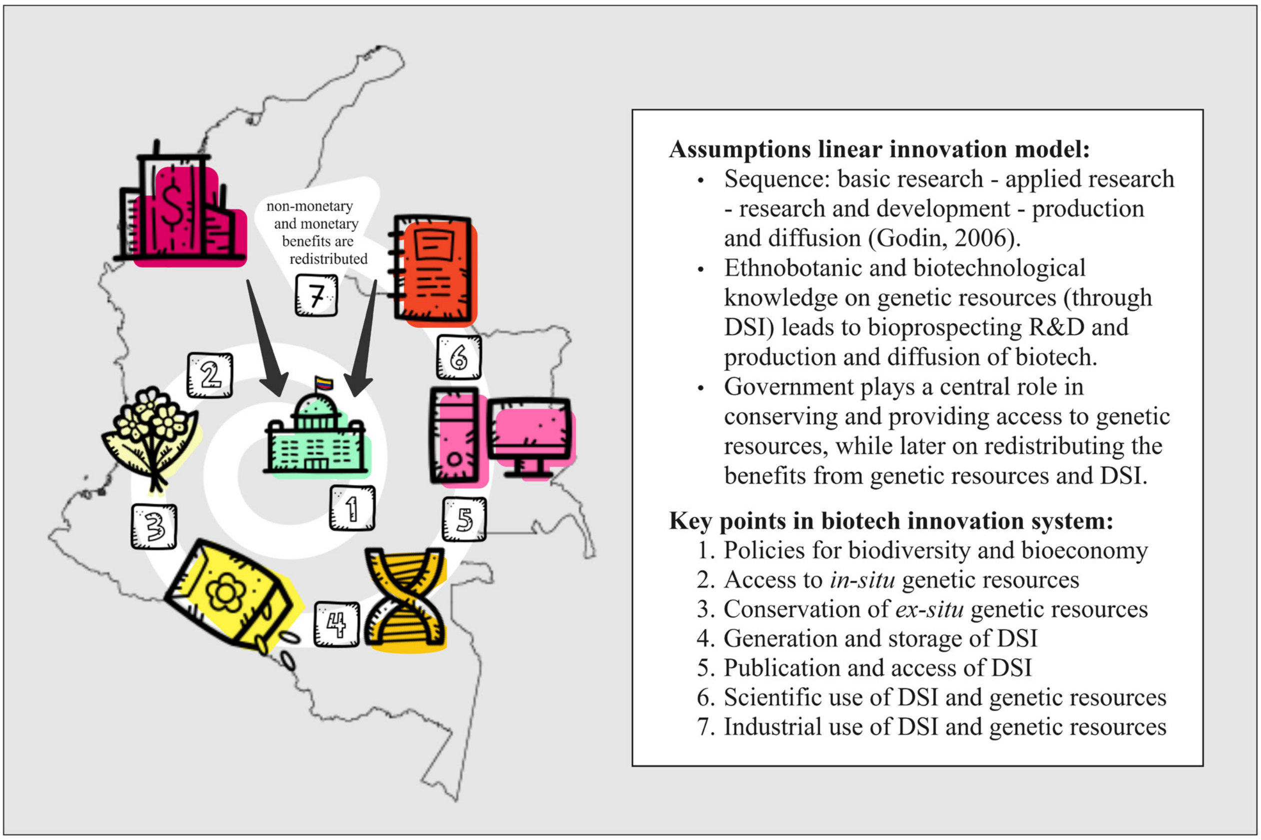

Figure 1. Linear representation of innovation in Colombia. Adapted imagery from Icons8.

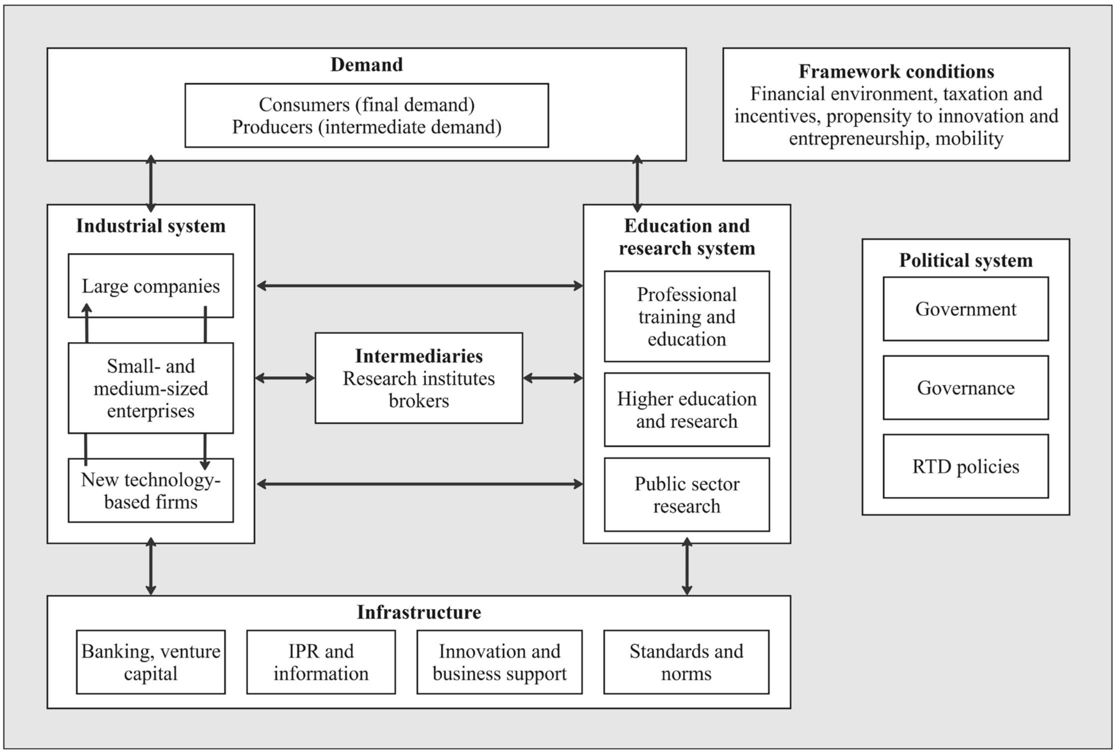

Figure 2. The National Innovation System model (adapted from Kuhlmann & Arnold (2001)). The NIS shows all institutions and actors in various systems that play a role in driving a country's innovation. Well-performing linkages between systems, represented by the arrows, are equally important. For example, actors in the industrial system react to consumer demand and government demand for R&D by commercializing innovations that were developed or co-developed with actors in the education and research systems. Activities in the industrial, education and research systems are influenced by a country's infrastructure, which can range from (un)available venture capital to code of conduct and strong/weak protection of intellectual property rights.

subcategory for DSI-related research infrastructure. Secondly, traditional knowledge associated with genetic resources and DSI is included in the education and research system. Thirdly, because supranational science, technology and innovation policies are gaining more influence on NISs (Weerasinghe *et al*, 2024), and because we want to know the (potential) impact of international ABS policies, we include the 'international policy and political system'. Altogether, Figure 3 shows that the value chain of genetic resources and DSI, as represented in Figure 1, is sustained and influenced by various systems and interactions.

Although this is the first application of the NIS model in this policy context, we are cognizant of the empirical gap and challenges with its application to developing countries. In a general sense, the developing context is characterized by weaker intellectual property rights (IPRs), incremental technological development, unstructured business interactions, and low levels of knowledge, demand and investment (Egbetokun *et al*, 2017). Many developing countries also lack adequate data to allow for international comparison (Weerasinghe *et al*, 2024).

Data collection

At the start, we conducted a short scoping review of literature and policy documents on biodiversity research, biotechnology and the bioeconomy. With approval from a human research ethics committee, online and in-person semi-structured interviews with professionals throughout the enlarged NIS were conducted during one month of fieldwork during and after COP16 in the fall of 2024 (Table 1). COPs are a good field site because host countries position themselves strongly with regard to the CBD's objectives (Lee *et al*, 2021), and because they have an unprecedented concentration of stakeholders. The research questions and conceptual framework were revised cyclically during and after the fieldwork (Lew, 2010). Beforehand, interviewees were identified and contacted via LinkedIn, based on their contributions to relevant research articles and webinars. Further interviews were secured at COP16, which was separated into a Blue Zone for negotiations and associated events, and a Green Zone for more Colombia-specific events. Furthermore, two business conferences were attended, the Expo Bioingredientes in Cali and the Open Innovation and Investor Summit in Bogotá. Visits to the biochemical laboratory of Icesi University in Cali, and the bioprospecting laboratory of INVEMAR in Santa Marta, complemented findings on research infrastructure. Finally, three ecotours to Farallones, Chingaza and Tayrona Park helped to understand the conservation context. The English and Spanish transcripts from the 53 interviews were open-coded and thereafter clustered under one or more of the NIS model's components. Preliminary findings were presented to bystanders in the hall of the COP16 Blue Zone's venue, and later in a seminar on the COP outcome and DSI at Universidad de Los Andes for several key stakeholders. Interviewees were requested to validate the results section and give written permission to be cited anonymously or with their full name.

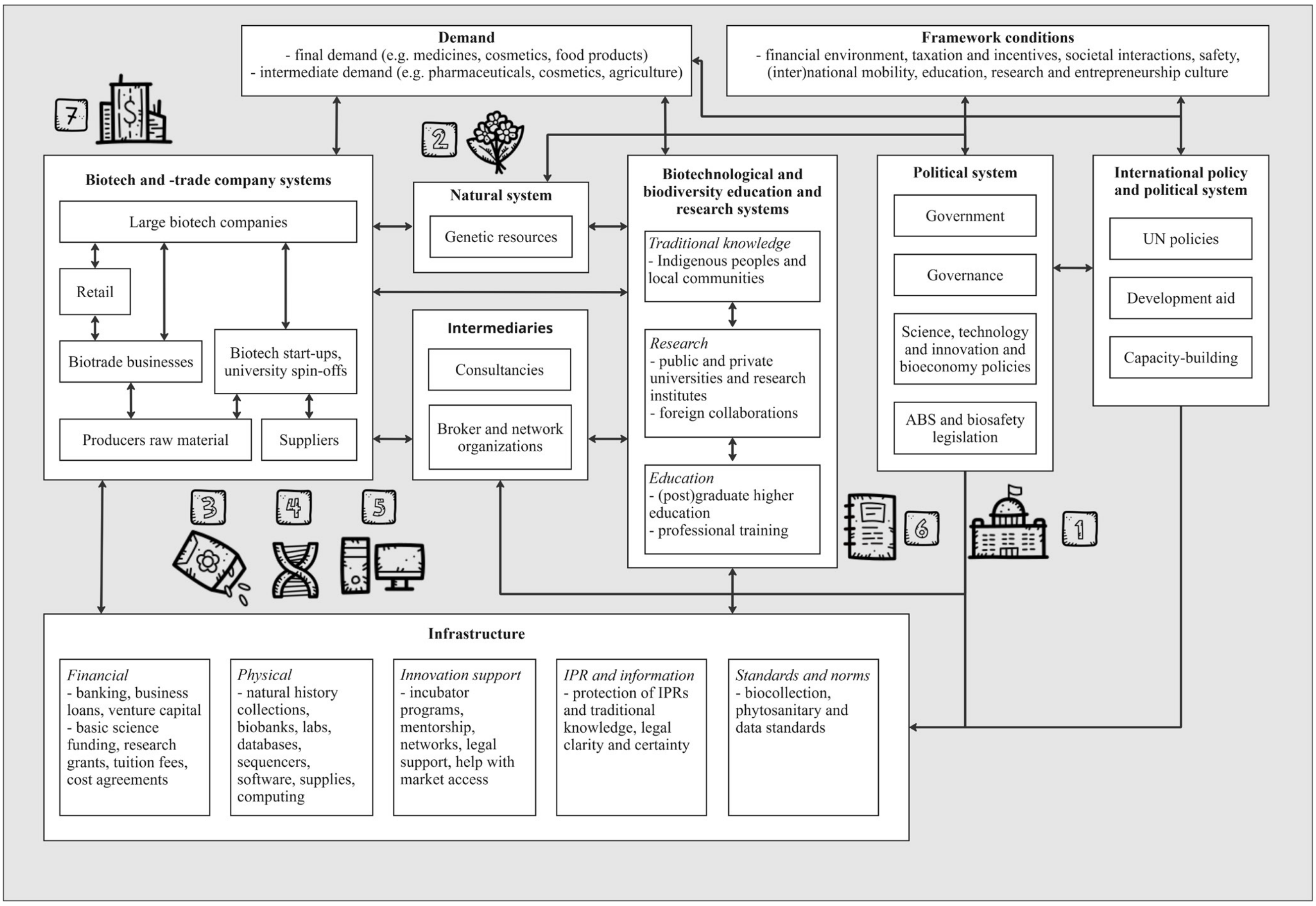

Figure 3. Overview of a nature-based biotechnological innovation system. The different aspects of the value chain of genetic resources and DSI are positioned near the related systems, and new relationships are included compared to Figure 2. The international policy and political system interacts with the political system (e.g. domestic implementation of UN policies, tax system as framework condition), demand (e.g. accessibility to new markets), and infrastructure (e.g. technology transfer and monetary benefit-sharing). The political system influences access to genetic resources and the conservation of the natural system, and potentially the availability of intermediaries (e.g. funding of incubator programmes).

Results

The results are represented in order of the key aspects of the value chain (Figure 1) and with the relevant NIS components with which they interact (Figure 3).

Policies for biodiversity and bioeconomy

NIS components: framework conditions, natural, research and political systems

Colombia has clear policies to boost its nature-based biotechnological capacity that are grounded in its natural, political, historical and socio-economic context. In between the Pacific and Atlantic oceans and divided by the Andes and Amazon, Colombia is the world's second most biodiverse country. Because of its proximity to key markets, biodiversity is described as an international "competitive advantage" (Melgarejo, 2013) and regarded as an opportunity for nationwide cultural and economic transformation (Aparicio, 2022). Minister of the Environment and COP16 Chair Susana Muhamad (resigned in February 2025) aspired to increase the share of GDP from the bioeconomy from 0.8% to 3% by 2030 (The City Paper Bogota, 2024a). Internationally, the government repeatedly associates the country with its natural wealth. In his COP16 opening speech, President Gustavo Petro referenced the words of Indigenous peoples about creating the "idea [of Colombia] as a world power of life as a national mission" (Presidencia de la República de Colombia, 2024). Petro envisions development without neoliberalism, the use of fossil fuels, or the extraction from nature, and "harmony with nature" is included in the National Development Plan 2022–2026 (Vallejo Zamudio, 2023).

The minority Afro-Colombian and Indigenous populations have endured violence, land-grabbing and subjugation to Western scientific ontologies and Christianity, first under Spanish colonization, later under Colombian governments, and recently by corporations and armed groups (Goyes & South, 2016; Chaves-Agudelo *et al*, 2015). In a "vicious cycle of biopiracy", genetic resources and traditional knowledge from these marginalized and impoverished groups are at risk of misappropriation (Goyes & South, 2016). Biopiracy, particularly DSI-enabled 'digital biopiracy', also causes national concerns, leading Susana Muhamad to call for measures to ensure "sovereignty over genetic information" (The City Paper Bogota, 2024b).

Colombia has a broad legal basis for IPR to protect innovations abroad (ProColombia, 2024), which is similar to that of other countries. Biopiracy related to genetic resources

Table 1. Overview of interviewees in Colombia (details available in Supplemental Material 1)

Type of system and work	No. of interviews
Education and research	
Animal biology	4
Botany and crop research	8
Omics and bioinformatics specialists	4
(Industrial) biotechnology and -chemistry	5
Students biochemistry (group interview)	7
Bioprospecting specialists	6
Law, ethics and human rights	6
Subtotal	40
Biotrade, -tech and -economy	
Biotrade companies	3
Biotech start-ups and spin-offs	4
Bioeconomy experts	1
Innovation broker	1
Subtotal	9
Politics and policy	
Policymaker and diplomat	1
Politician	1
Embassy worker	1
Subtotal	3
Other	
Non-governmental organization	1
Total	53

through patent acquisition is inhibited by Colombia's IPR system. Particularly important to genetic resources is Andean Decision 486 (Andean Community, 2000) on the Common Provisions on Industrial Property which contains various provisions to prevent biopiracy (Salas, 2020), most importantly: (1) the requirement in Article 3 that biological and genetic heritage and traditional knowledge underlying inventions was acquired in accordance with the law, so as not to breach provisions of Decision 391 on ABS, (2) the exclusion in Article 15 sub b of patents on biological processes and material and genomes or germplasm, and (3) a requirement in article 26 sub h to disclose an access contract in the patent filing if traditional knowledge of IPLCs was obtained.

The state of biodiversity in Colombia today is heavily influenced by the aftermath of the 2016 peace agreement between the government and the FARC guerrilla group, which has enabled increased deforestation and illicit coca production, but also biodiversity exploration (Huddart *et al*, 2022; Irwin, 2023). Without measures to curb the expansion of agriculture, a major employment sector in Colombia, biodiversity loss could accelerate by 38 to 52% by 2033 (Guerrero-Pineda *et al*, 2022). Faced with the need to conserve and simultaneously sustainably use biodiversity and the need to integrate thousands of people from previous conflict zones back into society, then President Manuel Santos reinvigorated the 2015 Colombia Bio programme, a nationwide policy agenda focusing on biodiversity research, bioprospecting, product valorization, institutional strengthening of value chains and public awareness of biodiversity (Irwin, 2023). According to both interviewees and expert institutes, Colombia Bio is internationally recognized as an exemplary bioeconomy programme. Colombia defines the bioeconomy as an "economy that efficiently and sustainably manages biodiversity and biomass to generate new products and processes with added value, based on knowledge and innovation" (Consejo Nacional de Política y Economía Social, Citation, 2018), p. 26, as translated in Johnson *et al* (2022)). The Bioeconomy Mission, a national policy launched in 2020, has five focus areas: biodiversity and ecosystem services, sustainable agricultural production, biomass and green chemistry, biointelligent Colombia, and health and well-being. Central to achieving each of these goals is boosting the use of biotechnology, omics and bioinformatics.

Access to *in situ* genetic resources

NIS components: framework conditions, research, industry, natural, political and international policy system, physical and IPR and information infrastructure

Considerable barriers to researchers' access to and collection of Colombian genetic resources are administrative, legislative burdens, customs and safety challenges. For fair access to genetic resources, a balance must be struck between user burdens and user rights (Collins *et al*, 2020). But among biodiversity researchers, Colombia's access regulation is notoriously burdensome, sometimes leading to researchers giving up a study (Fernández, 2011; Wight, 2019).

To date, Colombia has not ratified the Nagoya Protocol . The legal bases for ABS are Article 81 of the Constitution (Senado de la República de Colombia, 1991), Andean Decision 391 (Andean Community, 1996), and various subsequent decrees (Reep, 2025). Access permits are evaluated and granted by the genetic resources team in the Ministry of Environment and Sustainable Development. Users usually have to report yearly to this team and negotiate another contract in case of commercial interest. In addition, users have to comply with the National Parks Service's and other regulations for responsible and sustainable sampling. This patchwork of regulation means that to access just one sample, a foreign scientist may have to acquire seven different documents (Collins, 2019).

While most interviewees did not express concern with the objective and content of the ABS legislation, they experienced high red tape and delays related to its implementation, which affected graduate and short research projects the most. This, in turn, affects international collaborations, as exemplified by the experience of a Colombian university biologist:

> *"One time, I had my application filed already three months before a research visit of five months in Germany. After personally returning to Colombia, it took another three months before the sample could be exported to Germany, long after the visit ended."*

Interviewees report stories of researchers secretly shipping samples in their luggage to avoid delays. ABS's adverse impacts on research are not well-received. Among interviewees, law enforcement gaps in extractive industries created the strong feeling that regulation "harms honest people while bad people continue to destroy biodiversity." Fortunately, scientific access has become easier over the past years with regulatory changes. Another promising development is that Colombian institutions are increasingly signing a Memorandum of Understanding with international collaborators to facilitate standardized access to samples.

However, red tape still looms large for commercial research, which is key to kickstarting the bioeconomy (Silvestri, 2016). Back in 2013, less than a third (27%) of all bioprospecting permits were accepted and three-quarters of applications took longer than eight months to be processed (Güiza & Bernal Camargo, 2013). The red tape and delays caused a high degree of informality, estimated at three-quarters (77%) of bioprospecting activities (Güiza & Bernal Camargo, 2013). Apparently, some companies manage the business risks posed by red tape by delaying permit applications for genetic resources with unknown or prior obvious commercial potential until after completing R&D and reaching the final investment decision stage. According to an interviewed policymaker, the major cause of the permit delays is insufficient human resources in the team to handle the requests, which are only increasing. Legal unclarity and "coordination failure between institutions" are to blame for the delays (Güiza & Bernal Camargo, 2013). But delays are also caused frequently by users who submit insufficient and inaccessible documentation. Interviewees shared that in-house legal counsel for scientists is essential to gaining permits fast and avoiding legal repercussions. This highlights how administrative burdens disproportionately affect small research institutions and companies.

Until recently, there were no specific procedures for access to genetic resources on Indigenous and Afro-Colombian lands, complicating bilateral ABS negotiations (Silvestri, 2016). The state pursued an extractivist policy for genetic resources tailored to industrial interests, while Indigenous peoples were hardly consulted (Nemogá, 2014). The Interior Ministry has to verify whether a consultation with IPLCs is necessary before the genetic resources team can grant an access permit. But history-related distrust and the self-protective attitude of IPLCs, that an interviewee describes as "¿Gano yo?" ("What do I win from this?"), in combination with legal unclarity, have made such negotiations very complicated. Regulatory changes alone will not rebuild that trust.

Sampling also involves costs for already constrained research budgets. The government Instituto Agropecuario de Colombia charges between 500 and 3,000USD for risk analysis services before seed of a species can be imported (AgriBrasilis, 2022). All subsequent importers receive a waiver, disincentivizing first-users to pay the fees for species without direct economic benefit.

The prohibitive cost or lack of cargo services is another challenge. Interviewees have experienced degradation or destruction of samples due to delays in customs, caused by personnel's distrust of equipment like nitrogen containers, and because samples were not stored in the right conditions during transit at some airports in Colombia. This has considerable negative effects because fieldwork in remote regions is often too costly to undertake twice.

A last factor of limitation in sampling is violence. While the safety situation has improved considerably since 2016, narco-trafficking is rampant in remote regions. One research team was limited to conducting research directly in the surroundings of an army base and later had to abort the project due to a deteriorating security situation. We assume that such security precautions increase fieldwork costs and limit participatory processes with IPLCs.

Conservation of *ex situ* genetic resources

NIS components: framework conditions, research, political and international policy system, financial, physical, and standards and norms infrastructure

Colombia's biocollections mostly face financial and organizational challenges, while there are opportunities to be found in increased research, education and benefit-sharing activities. *Ex situ* conservation is organized at various scales, including in botanical gardens, the Future Seeds genebank of the Centro Internacional de Agricultura Tropical (CIAT), and in four public research institutes, namely AGROSAVIA for crop research, Sinchi for Amazonian research, INVEMAR for marine and coastal research and the Humboldt Institute for nationwide biodiversity research. Universities also maintain their own, sometimes outsourced biocollections, and some IPLCs store seeds of nutritious and culturally relevant plants in community seedbanks.

Generally, interviewees reported insufficient funding for biobanking, although agricultural research receives more support than biodiversity research. Economic challenges are energy price swings and the salaries of permanent contract staff. Meanwhile, research funding is decreasing and the government's re-valuation of grants at the end of each year creates a lot of job insecurity, making it hard for institutes to retain their staff. Interviewees indicated that the decoupling of biocollection funding from research project funding would be desirable.

University biocollections experience unclear assignments of responsibilities and degrading infrastructure. Some scientists have a curator's responsibility on top of their day-to-day research tasks, leading to decreased vigilance for incidents. At one time, a researcher lost almost a complete tissue collection when a freezer thawed without raising an alarm. The lack of dedicated curators also means that access to others' samples becomes more dependent on personal favours by the researcher who facilitates access, thereby slowing down overall research. An opportunity for cost reduction lies in the centralization of biocollections and service provision.

An interviewee noted that here, again, violence is a risk. During the major unrest of the National Strike in Cali in 2021, protestors blocked off entire roads, including towards Palmira, where the Future Seeds bank is located. Only at the last moment, a truck carrying liquid nitrogen was exempted by the protestors, showing the external fragility of even the most secure collections.

Altogether, these threats to biocollections must be seen in the light of sequencing efforts, since when funding for sequencing finally becomes available, sample quality must be maintained, especially for long reads. Additionally, the informational value of DSI that becomes available through sequencing builds on the characterization work and advanced regeneration practices at biocollections. Enthusiasm for the use of next-generation technologies could bias capacity-building efforts toward sequencing and ignore current capacity deficits in *ex situ* conservation. However, both capacities need to be strengthened to realize mutual benefits.

Interviewees also considered it important that samples in biocollections "do not just sit there" and additional measures are taken for value creation. The Humboldt Institute's seed bank in Boyacá, which has species from the whole country, for example, hired an ethnobotanist to add more value to the collection for society. The marine research institute, INVEMAR, is exploring the expansion of its natural history museum, which is currently limited to a small exposition in the wet collection, to teach the public about marine biodiversity. Apart from creating value for the public, biocollections can address concerns specific to IPLCs by helping them conserve seeds that are vulnerable to weathering in glass and mason jars with training, freezers, and seed repatriation. These ideas highlight that capacity-building activities aimed at biocollections should not only focus on conserving genetic diversity *ex situ* but also support biocollections' aspirations to maximize value for the public and stakeholders.

Generation and storage of DSI

NIS components: research, industry and political system, physical infrastructure

Contrary to 'each its own sequencer' thinking, the capacity to generate DSI in Colombia is primarily constrained by import costs of reagents, infrequent maintenance of sequencing equipment, and customs issues to import sequencing, laboratory equipment and reagents. This, among other factors, has caused significant biodiversity data gaps in Colombia. DSI is only available for one in twenty species, with the vast majority of the available data describing bacteria or being related to just a few projects (Noreña et al, 2018). To increase the availability of genome sequence data, in 2019, a new node of the Earth Biogenome Project network was founded, EBP-Colombia, which was also embedded in bioeconomy programmes like Colombia Bio (Huddart *et al*, 2022). However, there have been no updates for some years now, raising the impression that the project has been discontinued due to dried-up funding.

Despite decreasing costs, sequencing is still a costly exercise in Latin America (Noreña *et al*, 2018; Vilaça *et al*, 2024). In Colombia, it is much cheaper to ship samples abroad for sequencing. Although some institutions have sequencing capacity, others face limited or no access to these machines. Additionally, to make a purchase of such equipment cost-effective it is necessary to process a high volume of samples. Maintenance costs and delivery, as well as reagent costs, however, form the major bottleneck. There are long waiting times for maintenance workers to repair machines. Furthermore, whereas researchers in the USA can order reagents and get them delivered almost instantly, Colombian researchers have to wait for extremely lengthy periods, frequently more than a couple of months. The first cause for this delay is bureaucracy in academic institutions, which restricts purchase authorization to a small number of people. Secondly, obligated by national import regulations, researchers have to submit orders to licensed intermediaries that can import the reagents. But because there are few such intermediaries in Colombia, companies can charge higher prices, which is the main reason why reagents are two to five times as expensive as the original price in the exporting country. When the order is finally shipped, delays, damage and loss in customs are possible:

> *"A reagent for a RT-LAMP test took three months to arrive. The kit has a pH indicator, which usually is cherry red, which turns yellow with a positive test. But the kit arrived orange, meaning it can't be used anymore. We discovered that the cold chain broke during the shipping process because customs did not put it in a fridge for four days." [University biologist]*

With significant delays, technology software and service support by the sequencer vendor can become obsolete. One research team that faced more than two years of delay, therefore, renegotiated with the technology provider for a newer sequencer machine.

Conversations with interviewees suggest that to improve this part of the value chain, waste of research budget and time can be avoided by having the government shake up the intermediary market to enable researchers to access reagents more cheaply. Existing sequencing capacity can be used more efficiently if institutions advertise and rent or centralize their sequencers to achieve cost reduction. Greater sequencing capacity could come from investments in new businesses that produce reagents or provide maintenance in the Latin American region.

A recommendation to increase the availability of DSI from remote regions of Colombia is for research institutions to set up collaborations with businesses that collect biodiversity data through environmental DNA (eDNA) and other techniques for conducting environmental impact assessments. Although large-scale storage of DSI is organized by genetic databases in other countries, institutions may need local data servers and portals for digital genebanking and pre-analyses. Here, negotiations with software and cloud providers form an opportunity for cost reduction.

A mentality shift in biological research is probably also needed. According to an interviewee, instead of the "catch them all" mindset in biodiversity sequencing, researchers could perhaps better focus on collaborations on the generation of fewer high-quality DSI. Likewise, countries with overlapping biodiversity may avoid duplicate work and achieve scale benefits by forming regional collaborations wherein sampling, *ex situ* conservation, and the generation and storage of DSI are coordinated across borders. In Biodiversity Genomics Europe, for instance, tasks, resources, lessons learned and capacities gained along the genomic pipeline are distributed over institutions in different countries. Because diversity in ABS regulations may pose an issue, Colombia could best collaborate inside the Andean Community with Bolivia, Ecuador and Peru, as each country's ABS legislation builds on Decision 391 (Ljungqvist *et al*, 2025). Lastly, through international collaborations with producers of sequencing equipment, which are under the scope of the Cali Fund (CBD, 2024), researchers in LMIC can gain access to grants for generating DSI (PacBio, 2020).

Publication of and access to DSI

NIS components: education, research and international policy system, financial infrastructure

While challenges for LMIC scientists are reported with regard to data access and compliance with FAIR data standards in the literature (Shanahan & Bezuidenhout, 2022; Bezuidenhout *et al*, 2017), no particular issues were reported by the Colombian interviewees. When new biodiversity data standards are adopted, scientists require both capacity building and efforts to demonstrate their benefits – an experience that is common across countries. There are, however, significant challenges with regard to publishing DSI that originated from IPLC territories. Their unfamiliarity with DSI and distrust make initial conversations between them and scientists difficult. There are no standards yet for respecting traditional knowledge and maintaining best practices for intellectual property. IPLCs also reject unrestricted open data:

> *"When we have spoken with them about data sharing, they usually say: "We need some specific rules and safeguards about publishing the DNA data and how we will be reflected in these publications" They have their own needs that we, as scientists and data managers, need to meet." [Biodiversity data specialist]*

The alignment of data-driven research with community needs is recognized as an ethical priority by the C3Biodiversidad consortium (C3Biodiversidad, 2018a). Lessons to navigate this engagement are found in a collaboration of the Humboldt Institute and the organization Wise Ancestors with a Paisa community in Antioquia to produce two reference genomes for two critically endangered birds (Wise Ancestors, 2024). Five local collaborators received one year of salary and a broad training in sampling, bioinformatics and biomonitoring while Wise Ancestors guided them in genomics-based conservation management actions. Because the generation of a genome sequence as a research outcome is not directly relevant to the community, the project also worked on developing ecotourism as an alternative livelihood, and helped the collaborators to cultivate the edible mortiño berries (*Vaccinium myrtillus*), which benefit both the Antioquia Brushfinch (*Atlapetes blancae*), also called the 'Montañerito Paisa', and the community. Increasing the social value of genome sequencing required a new mindset:

> *"I think in the long run, with these social benefits, resources are better spent because the project is filling a community need that helps them to conserve nature. There is a growing detachment between what people learn in universities and the needs of Colombia. Studying the gene for a bird to be blue or yellow has very important scientific value, but that kind of information may not be in Colombia's list of highest priorities." [Gustavo A. Bravo, Curator of Ornithology at Instituto Alexander von Humboldt]*

For this change of mindset, university curricula have to include more ethics and responsible business conduct. It also necessitates a reorganization of research funding because, in a project with a strong participatory component like this, a sequence can be five times as expensive to obtain. Those costs illustrate that while scientists in the DSI discussions managed to be exempted from monetary benefit-sharing, the organization of research funding is indeed related to financial benefits for communities of interest. Yet, it is so far not clear to the project leaders how these benefits can be sustained over time because a genome publication is a one-time event and scientific project funding will dry up at some point. That means that sequencing projects by themselves are inadequate sources of funding compared to standard conservation funding.

DSI and genetic resources use in science

NIS components: framework conditions, education, research, industry, political and international policy systems, financial and physical infrastructure

In Colombia, advanced scientific capacity is held back by structural underfunding, brain drain, a lack of cyberinfrastructure, and inconsistent and increasingly short research grants. Opportunities arise mainly in public–private research partnerships and international scientific collaboration. Interviewees indicated that there already is advanced scientific knowledge, lab quality and technological development in Colombia. However, relative to comparable countries in the region, it has notably fewer biotechnological and bioinformatics publications (Benitez-Paez, 2010; Martinez *et al*, 2014). This may be explained by the following factors.

The first reason is related to education. In higher education, less than 10% of students follow bioeconomy-related disciplines (Alviar *et al*, 2021). For university graduates, there are few research positions, to such an extent that fewer are enrolling in PhD programmes, and many emigrate. Some researchers with a strong motivation to give back to the country eventually return, but their patience gets exhausted too. This poor economic perspective is also experienced by employed researchers, exemplified by a story from a public university scientist:

> *"In just one year, all three of my PhD students left because they were not being paid by the university as contractually promised. No research was done. Many professors tell me that the only students who end up graduating are the ones who are independently wealthy or those with scholarships." [University biotechnologist]*

This outflow of trained personnel, in combination with short-term research grants, places a burden on principal investigators who have to repeatedly train new researchers.

Another limiting factor is the cyberinfrastructure. Colombia has sufficient developers, administrators and bioinformatics expertise to run such infrastructure, but the availability of high-performance computing, computational training resources and data storage is limited (De Vega *et al*, 2020; C3Biodiversidad, 2018b). In other words, the strong human resource component is suppressed by a weak physical resource component (Figure 3).

Both interviewees and C3Biodiversidad (2018b) indicated that insufficient and unstable investment in R&D is the major challenge to knowledge production. Between 2000 and 2020, total R&D expenditure as a share of GDP in Colombia was, on average, 0.22% (World Bank, 2024). Although not uncommon in Latin America, that is very low when compared to regional leader Brazil, with 1.11%, and the OECD average of 2.40% over that same period. Meanwhile, under the current government of Gustavo Petro, the budget for higher education is declining by one quarter in real terms, even though the ambition was to increase R&D expenditure to 0.5% of GDP by 2026 (Fernández, 2023). As research grants decrease in size, competition among researchers increases, and the scope of projects becomes more limited. Structural underfunding and swings in government budgets particularly affect public universities, which receive less funding through tuition fees and private investment than private universities.

Interestingly, the tendency of new governments to tie science funding to political themes, thereby limiting research groups' consistency, has had a knock-on effect on public universities' collaborations with companies that prefer long-term and stable research relationships. Additionally, funding often does not arrive in time. Ten percent of the Sistema General de Regalías, a system for the distribution of royalties from industry, is invested in science. Yet only half of the budget was delivered during its first year of operation, raising suspicions of corruption with interviewees (Organisation for Economic Co-operation and Development (2014), p. 118). Irregularities and lost resources are recurrent to this day.

Opportunities mainly appear in public–private collaborations. The share of business expenditure in R&D (BERD) in Colombia in 2020 stood at 0.15% compared with the OECD median of 1.15%. Four-fifths of businesses in Colombia are reported to not invest in R&D (DANE (2023), as cited in Organisation for Economic Co-operation and Development (2024a)). BERD can complement university funding when basic research is co-financed by applied research. For example, in the Icesi Sustainable Industries and Applied Science Labs in Cali, one of the most advanced in Latin America, companies hire university researchers to design, validate or prototype bioprocess tests. EAFIT, a private university in Medellín, secured high-performance computing, known as the Apolo platform, in partnership with Purdue University, which now enables them to conduct paid services for companies. Hybrid positions wherein a researcher or student works part-time in a company are also smart from both a science funding and valorization standpoint. Despite these synergies, public–private research collaborations can have trade-offs, including the skewing of the research agenda toward commercial applications over basic research that can benefit the conservation and sustainable use of biodiversity, and a possible misalignment between the private sector's need to maintain a quick pace and patience-requiring participatory processes with stakeholders.

There are also improvements to be made in international science policies. Slightly less than half (43.5%) of Colombian scientists experienced feelings of language-based discrimination in article revisions and rejections (Ramírez-Castañeda, 2020). The country has low English literacy, and translating takes up a lot of research time and budget. High fees for open-access publishing can also be a barrier to publishing in high-impact and high-visibility journals.

Bilateral science diplomacy can help to enhance international scientific collaborations without the need for extra funding. The United Kingdom embassy in Bogotá contributed to the creation of BRIDGE Colombia, a network of Colombian and British scientists. Academics in BRIDGE Colombia then secured funding from the Global Challenges Research Fund for a flagship project called GROW Colombia, which aims to boost the country's bioeconomic innovation capacity. Bilateral science diplomacy can also help to flag science issues directly to governments or agencies and businesses. Feedback from scientists on the prohibitive cost of sequencing in Colombia, for example, was communicated through the embassy to British technology providers.

> *"Science diplomacy helps to connect UK science with Colombian priorities. There was a time when the UK came to 'teach' Colombian scientists. That is over now as a result of their joint research work. The bilateral collaboration operates now under a logic of equitable research partnerships. That is possible because Colombian science has been advancing to a point at which scientists from both countries work on a peer-to-peer basis." [Luis Calzadilla, Head of Science and Innovation at UK Embassy in Bogota]*

This facilitative role in accessing funding and enhancing equity in research is very important. Interviewees remarked that they increasingly have to find non-Colombian collaborators to be able to apply for grants abroad, which feels awkward and exploitative. In the opposite direction, it was felt by an interviewee that some foreigners just seek collaboration with Colombian scientists to access samples, without leaving meaningful work on the publication for their counterparts. This type of sample-focused "helicopter research" in collaborations with Colombian institutions is already reported in human genomics (Cock-Rada & Gomez, 2018).

Industrial use of genetic resources and DSI

NIS components: framework conditions, demand, education, research, industry, political and international policy systems, intermediaries, financial and IPR and information infrastructure

There is a major valorization gap in the country that is caused by a lack of entrepreneurship support and culture, investment unavailability, administrative delays, export challenges and tax burdens. Colombia has fewer large bioprospecting centres and biotechnology-based companies than similar countries in the region (Bueno & Ritoré, 2019). The country seems to suffer from "an absence of scientific governance" to direct R&D toward commercialization and toward knowledge gaps in genetic diversity conservation (Bueno & Ritoré, 2019).

Once university scientists find bioprospecting value, they struggle to valorize the findings. Marine botanist Enrique Peña at Universidad del Valle in Cali initiated studies for the application of two species of invasive red algae (*Sargassum fluitans* and *Sargassum natans*) that pollute the tourist beaches of San Andrés Island in the Caribbean as a feedstock for fertilizer production. Building a pilot plant on campus would cost approximately 1 million USD. Although Peña has already attracted interest from companies, domestically and abroad, funding or investment to initiate building the plant is still insufficient. Peña noted that an entrepreneurial mindset is still uncommon in public universities.

Private universities, once founded by business leaders, offer more support for entrepreneurship and valorization, such as business and finance courses in life sciences programmes, incubators, and mentorship programmes. Sciphage is a biotechnological start-up with its own R&D and some patents from research at Universidad de los Andes. It develops phage therapy for the livestock sector, an alternative method to antibiotics that has various health and environmental benefits (Mishra *et al*, 2024). Sciphage has already built a production plant outside Bogotá and is seeking investment to scale up production. The Pontificia Universidad Javeriana has another model where it creates spin-offs with its own patents. Dreembio is one spin-off that develops phytomedicines for cancer treatment based on ethnobotanical plant knowledge. The company is working with campesino or farmer communities to develop the raw material value chain.

These companies clearly show that innovation can have socio-environmental benefits. According to Arturo Luna, the former Minister of Science, Technology and Innovation, while the bioeconomy does require advanced biotechnology, it can include low-tech businesses too:

> *"There are already low-tech businesses in Colombia that add value to biodiversity and fit perfectly with the bioeconomy model. We have to invest in these businesses because this virtuous cycle will generate employment and financial resources and opportunities for biodiversity conservation. However, in order to add value to our biodiversity, more and sustained investments in biotechnology are required." [Arturo Luna, freelance]*

Take, for example, Kahai S.A. It managed to produce the jungle cacay tree (*Caryodendron orinocense*) on plantations. Because the nut's oil outperforms argan oil in some cosmetic applications, there is an enormous biotrade potential. To collaborate with international development agencies and have a better investment case, the company built a strong corporate social responsibility (CSR) component, including a reforestation programme and inclusion of IPLCs.

These three home-grown companies represent textbook examples of successful bioprospecting and biotrade. But they face numerous challenges, which are illustrative of the kinds of issues that limit the development of genetic resources and DSI in the natural products industry.

First, there is an investment gap in Colombia. Regular investors, like banks, lack advanced knowledge of biotrade and biotech. Throughout the country, there is an over-demanding investment culture with sometimes "aggressive pushing for unrealistic targets" and requests for proof of traction and several letters of intent from buyers before pre-seed or seed funding can be acquired. In other countries, interviewees experienced more eager investors who understand that break-even is far away and that not all investees will succeed.

The second major challenge relates to the issuing of sales permits by Instituto Nacional de Vigilancia de Medicamentos y Alimentos (INVIMA), the government agency that approves products for human and animal health. Biotech companies experience the licensing process as a severe regulatory obstacle, which is attributed to the agency's perceived unfamiliarity with novel technologies, insufficient capacity and personal hesitancy to take risks to avoid liability. Biotrade companies also struggle, primarily with delays. Both Kahai S.A. and Pangea Natural Products, a company that sells medicinal herbal supplements, waited roughly five years for approval of their product, though the hefty permit costs of over 3,000USD were already paid. For starting companies, these costs are high, and delays can mean 'make it or break it.'

Another hurdle is the lack of domestic demand for natural products based on scientific research:

> *"Demand creation is a cultural process where you teach about the environment and the values of the product, but also [the positive] impacts for communities." [Legal expert]*

Colombia has the character of a 'follower market' and its consumer culture requires that companies first demonstrate product success abroad. While adapting to customer needs, companies struggle with strict import regulations such as those imposed by the EU. Network brokers, like local chambers of commerce, have an important role in helping companies access markets. Reducing global conference fees would help companies gain exposure to investors and clients.

The fourth challenge is Colombia's tax and fiscal policy, which, according to interviewees, stifles the growth of their companies and makes them strongly consider commercializing abroad. Compared with an average of 23.7%, Colombia's 35% corporate income tax rate is the highest of all OECD countries (Organisation for Economic Co-operation and Development (2024b), p. 20-26). Although the 19% value-added tax is close to the OECD average, it is still among the highest in Latin America. A policy proposal for a phased decrease in tax rates for small and large businesses is being debated in parliament.

Because the results show that universities strategically use patents for founding startups and spin-offs, it is also important to discuss the challenges and opportunities for the IPR system (described earlier in section 'Policies for biodiversity and bioeconomy'). In 2024, the Colombian government issued a compulsory license to start producing generic and more affordable versions of the drug Dolutegravir for tackling an emerging HIV crisis. This type of action, however, could have negative effects such as diplomatic repercussions, arbitration or decreased market entry by foreign drug companies (Landis, 2024). Such risks may be lower if Colombia can source more products from domestic companies. But here again, the country's funding landscape will need drastic adjustment to guide startups with acquired patents through the financially challenging Valley of Death phase between R&D and revenue generation.

On the other hand, there are opportunities at a national and international level. To begin with, universities should continue investing in their technology transfer and innovation offices that support researchers during R&D and connect them to industry. On top of that, universities can cover the costs of researchers' patent applications and create room in work schedules for entrepreneurship (Calza *et al*, 2020). At a national level, the government can implement patent pilot programmes to review the efficacy of patent dispute resolution by courts (Salas, 2020). Bilateral diplomacy related to IP can also facilitate the protection and export of Colombian products and technology. One tool is the Patent Prosecution Highway, which countries use to fast-track patent applications by companies that acquired patents in another country. To stimulate bilateral technology transfer between Colombia and countries with divergent IPR systems, it can develop mutual transfer agreements that contain Colombia's ABS provisions but are flexible enough to incorporate the other country's priorities (Fajardo *et al*, 2025).

There are also unresolved tensions in the IPR system with regard to the protection and empowerment of IPLCs, caused by CBD decisions that reinforced national sovereignty over genetic resources to the detriment of Indigenous self-governance (Fredriksson, 2019). Martha Gomez Lee, an ABS scholar, argues that the self-governance of IPLCs can be promoted by embedding article 31 of the UN Declaration on the Rights of Indigenous Peoples in the ABS system, which states: "… They also have the right to maintain, control, protect and develop their intellectual property over such cultural heritage, traditional knowledge, and traditional cultural expressions." Empowerment of IPLCs during the development of intellectual property may carry implications for the governance of DSI:

> *"In my opinion, the crux of the matter is that even before intellectual property rights, any initial digitization of a genetic resource and its deposit in any database must have explicit Prior Informed Consent." [Martha Gomez Lee, teacher-researcher in ABS and traditional knowledge at Universidad Externado de Colombia]*

Finally, it is worth noting here that companies think that working with campesinos is much easier than with IPLCs because the former are generally better organized (so engagement has a faster pace) and the latter have complex cosmovisions to engage with. Also, companies can use publicly available scientific knowledge on the function of species that may have been discovered by IPLCs in the pre-ABS era. This perhaps explains why there are, to date (and as confirmed by Martha Gomez Lee), zero signed annexes by providers of traditional knowledge as an intangible component to genetic resources, although the latest figures show that around 20 commercial ABS contracts and 400 ABS contracts overall have been concluded with the Ministry (Ministerio de Ambiente y Desarrollo Sostenible, 2021).

Discussion

Despite Colombia's large bioeconomic potential, many structural challenges remain. In Figure 4, we present the current issues (in text boxes) and provide recommendations (in italics). The majority of issues relate to underfunding, investment and regulatory capacity, and red tape. Existing research capacity is not used efficiently because of siloed R&D, high equipment and maintenance costs, and outflow of trained personnel. Moreover, the companies with bioeconomic potential that do emerge struggle to grow inside Colombia. Without considering these domestic policy issues, monetary payments, scientific capacity building and technology transfer as typical ABS tools, will have little effect on achieving that potential. Here, we reflect on what could be accomplished by Colombia itself, how specific needs could be addressed by ABS policies, the Cali Fund and non-monetary benefit-sharing from DSI, and lastly, the value of innovation system models for both holistic and targeted policy interventions.

Although subsequent governments have expressed strong bioeconomic intent, policies are being discontinued, and there is a coordination failure between government bodies. This aligns with Aparicio's (2022) finding that Colombia's narrative is focused on future high-tech-driven biodiversity exploration as a precondition for the bioeconomy, while questions over the current performance of value chains are pushed aside. On the other hand, the findings showed that the fostering of cultural pride in home-grown science and companies may be the next step for growing national interest in biodiversity and bioprospecting.

Colombia's combination of underinvestment and high taxation further lowers the creation of and erodes benefits from genetic diversity. This shows that bioeconomy policy should expand its scope from technology and biodiversity to bureaucracy, government capacity, science funding, factors for business growth and retention of companies. Immediate priorities to tackle are the delays in various permits and the degradation of biocollections. In our opinion, the bureaucracy, particularly, is a 'talent grinder' for people who intentionally do research or business for the benefit of the country. Greater engagement of scientists and entrepreneurs in policy-making that concerns them is recommended in order to help address their needs and decrease red tape. Mobilizing intermediaries and network organizations would be useful for this purpose and for enabling public–private partnerships that help scientists access new funding sources (Figure 4). Also, the export focus of companies due to a lack of domestic demand leads to missed opportunities to address local needs through valuable products, retain jobs and tax revenue. The government should therefore stimulate more demand for biotech and biotrade products and services (Weerasinghe *et al*, 2024), and, although very complex, incentivize private sector alignment with green rather than fossil-fuel biotech pathways:

> *"With some companies, there is a mentality that when you provide jobs, you already do enough. But business conduct is not per se sustainable and not per se benefit-sharing." [Ana Maria Castillo, Director of Competitiveness and Internationalization at the Cali Chamber of Commerce]*

The analysis has various implications that (Non-)Parties and observers to the CBD must consider. First, they should engage potential beneficiaries of the Cali Fund, like Colombia, to critically evaluate the effects of various policies on the full value chain of genetic resources and DSI. To enhance synergies between the political system and international policy and political system (Figure 4), (Non-)Parties to the CBD can link the biodiversity-focused negotiations to bilateral and multilateral diplomatic processes over scientific, technological and industrial cooperation, IP and technology transfer, taxation, development aid, and customs. Furthermore, the NIS model and similar approaches can help to diagnose issues and identify bottlenecks in countries, and steer a more effective and efficient use of monetary benefits from the Fund. For instance, it is smarter to invest in low-hanging fruits and missing cogs, such as public–private partnerships and reagent cost reduction for sequencing than in new sequencers. Additionally, investing in biodiversity-positive and IPLC-inclusive companies may have a higher return on investment in the long term than grants for short-term conservation projects. Ultimately, (Non-)Parties and observers to the CBD have to look further than physical infrastructural (Figure 4) capacity needs related to "generate, access, use, analyse and store" DSI (CBD, 2024). To embed this holistic perspective in ABS policy, Parties to the CBD are recommended to incorporate standard language related to innovation systems in the negotiation documents on DSI and

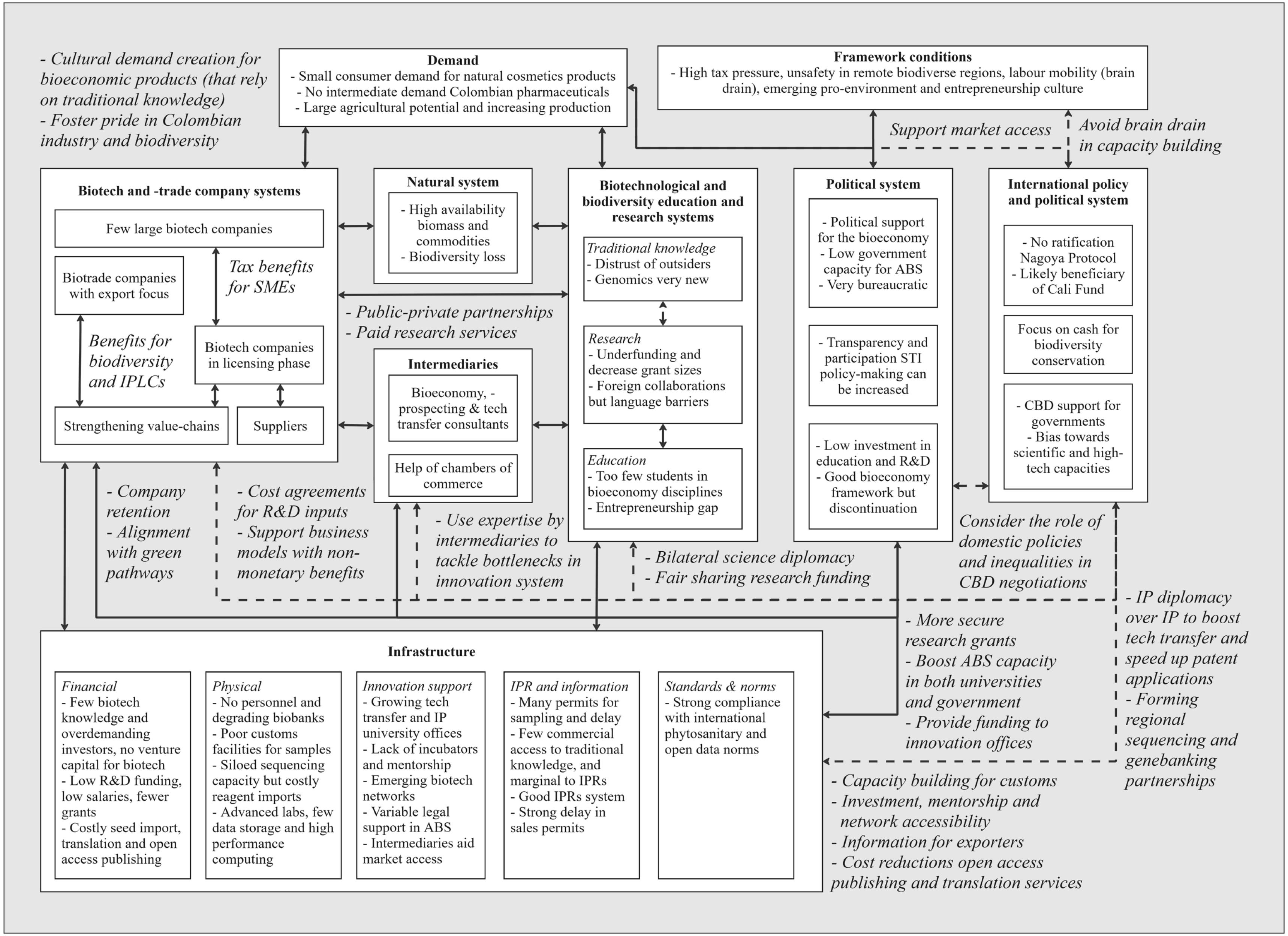

Figure 4. Identified challenges in Colombia's nature-based biotechnological innovation system with areas for improvement presented in italics. Acronyms: small and medium enterprises (SMEs); research and development (R&D); science, technology and innovation (STI); intellectual property (IP); intellectual property rights (IPRs).

ABS, for example, 'take into account and strengthen countries' capacity to innovate with genetic resources and DSI'.

The decision to distribute the Fund's money via national biodiversity funds instead of project-based applications deserves attention, too. Some companies' patent royalties that have been paid to the Ministry of the Environment and Sustainable Development through ABS mechanisms have not been distributed yet. Thus, governments' capacity to distribute funds and IPLCs' capacity to receive them deserve immediate attention to maintain company engagement and minimize overhead costs. Also, because many beneficiary countries are unequal (Colombia's Gini coefficient is among the highest in the world (Organisation for Economic Co-operation and Development, 2024a), care is warranted so that benefits are directed to the most disadvantaged actors in beneficiary countries. Apart from IPLCs, that would be female researchers (Paz & Pardo-Díaz, 2024), particularly in public universities in the underdeveloped regions of Colombia.

Seeing these issues, new opportunities for benefit-sharing emerge. Even though research and academia remain, rightly so, 'off the hook' from monetary benefit-sharing, their handling of resources certainly involves distributive questions. ABS policy should coordinate more with international efforts to map and decrease costs for LMIC scientists, such as open-access publishing and conference fees. And, as the Wise Ancestors and BRIDGE projects illustrate, North-South scientific collaborations and capacity-building projects may consider the fair allocation of research funding and joint application for research grants in HIC.

Although unconventional, there is also a big potential for non-monetary benefits from companies. To understand this, we draw on the concept of political corporate social responsibility (CSR). It holds that in the era of globalization, countries, especially developing ones, cannot fully regulate business conduct and that CSR activities have an increasingly political nature. This not only manifests itself in voluntary actions and initiatives for self-regulation but also in collaborations with governments to fill governance gaps or to provide public goods like science (Azizi, 2020; Frynas & Stephens, 2015). The COP16 decision reflects a narrow sense of justice in exchange by stating that users who make a payment "are considered to have fairly and equitably shared monetary benefits" (CBD (2024), para 15). But do benefits have to necessarily take the form of tick-the-box payments? Our findings show a clear need for companies in LMIC to access investment and loans, and mentorship in R&D, company leadership, market access and regulatory affairs. Eligible companies for payment to the Fund could play a huge role here and, in some cases, pursue mutual interests. For this, the CBD could also undertake a networking function to match companies between HIC and LMIC as a form of development aid (an example is PUM in the Netherlands), thereby allowing for better alignment of R&D than general capacity-building projects. Parties could consider legitimizing existing or new activities as monetary benefit-sharing. The risk is that the functioning of the Fund for biodiversity finance is undermined, and that the cost figures of the activities could potentially be skewed to meet the 1% of profit or 0.1% of revenue mark. In any case, initiatives should build and not erode trust in the UN and recipient governments. Analysts using the NIS approach may include an international industry system to guide these interactions, especially for analyzing cross-border industries.

On the nature-based biotechnological NIS (Figure 3), we note that the wealth of findings and the wide scope of the study limit the discussion of specific interactions between systems or actors in detail. While the article adopts a nationwide lens, many interactions happen on a local or regional level, especially in innovation hubs such as Medellín. A closer look may reveal regionally different interactions and systems, and possibly inequalities. Scholars using the NIS approach may reconsider the marginal position of traditional knowledge by including it under a separate system. It is recommended that their and civil society's perspectives be included more strongly in further research, although an effort was made to secure a balanced selection of interviewees (Table 1). We emphasize that because of the approach, we highlighted issues while the situation is not black and white. Many issues are also found in other countries, including HIC, and Colombia, as a case study, is likely not unique in that respect. More comprehensive studies and texts would allow for more comparison and insights into strengths and weaknesses. It is important to tailor the NIS to the unique context of the country of analysis, since the promotion of 'one-size-fits-all' ideas for development can disregard other ways of learning (Casadella & Tahi, 2023).

Conclusion

Facing accelerating technological progress and growing innovation divides, the CBD stands at a crossroads. Will it finally consider the fair distribution of scientific and innovation capacities and thereby put shared benefits to use effectively? Clearly, a business-as-usual continuation of capacity-building and benefit-sharing activities is unfit for current and emerging biotechnological innovation trajectories. The global political push to share benefits from DSI, therefore, has to be coupled with concerted efforts for policy reform in beneficiary countries, in ABS, and unconventionally in other policy domains. Holistic policy interventions, by principle, require governments to consult those who create benefits, educators, scientists, CEOs, and, of course, IPLC representatives. But perhaps not all can or should be solved by governments. Governance gaps invite country-specific contributions by users of genetic diversity that match technological niches and satisfy mutual interests. We eagerly await new research on innovation systems in the context of bioprospecting, so that policymakers can learn from countries' best practices and take advantage of regional opportunities.

Supplemental data

Supplemental Material 1. List of interviewees
Supplemental Material 2. Resumen en español (Spanish abstract)

Author contributions

Bob Kreiken: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing

Lotte Asveld: Conceptualization, Funding Acquisition, Project Administration, Supervision, Writing – review & editing

Conflict of interest statement

The authors report no conflict of interest.

Ethics statement

The methods in this research were approved by the Human Research Ethics Committee of Delft University of Technology, the Netherlands.

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