

EMBRAPA AND THE BIO REVOLUTION – THE CONVERGENCE OF SCIENCE AND TECHNOLOGICAL INNOVATION FOR SUSTAINABLE AGRICULTURE

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Abstract: The Embrapa BioRevolution Portfolio aims to advance Brazilian agriculture by integrating cutting-edge biotechnologies, nanotechnology, artificial intelligence, and bioinformatics. This initiative plays a pivotal role in fostering a new technological paradigm within the sector, emphasizing sustainability, enhanced productivity, resilience of biological systems, and strengthened food supply and security systems amidst growing climatic and demographic challenges both now and in the future. The primary objectives include the development of groundbreaking solutions that enhance agricultural value, support and strengthen the bioeconomy, and mitigate reliance on external inputs. Anticipated outcomes include the generation of novel crop varieties and genetically engineered organisms, advancements in algorithms and platforms for biological analytics, sustainable production methodologies in biofactories, innovative molecular entities, intelligent nanostructured fertilizers, pesticides, and sensors, advanced packaging solutions, nanotechnological animal feeds, biosensors for veterinary diagnostics, biopesticides, and degradable bionanocomposites. The conclusions underscore Brazil's strategic positioning at the forefront of agro-industrial biotechnology, driving innovations that contribute to a more productive, resilient, and sustainable agricultural paradigm.

Keywords: biotechnology, nanotechnology in agriculture, innovation, omics science.

EMBRAPA E A BIORREVOLUÇÃO – A CONVERGÊNCIA DA CIÊNCIA E DA INOVAÇÃO TECNOLÓGICA PARA UMA AGRICULTURA SUSTENTÁVEL.

Resumo: O Portfólio Biorrevolução da Embrapa visa impulsionar a agropecuária brasileira através da integração de biotecnologias avançadas, nanotecnologia, inteligência artificial e bioinformática. A importância do trabalho reside em sua capacidade de promover uma nova revolução tecnológica no setor, focando em sustentabilidade, aumento da

produtividade, resiliência dos sistemas biológicos e segurança alimentar em um cenário de crescentes desafios climáticos e populacionais. Os principais objetivos incluem o desenvolvimento de soluções inovadoras que agreguem valor à agropecuária, promovam a bioeconomia e reduzam a dependência de insumos externos. Entre os resultados esperados, destacam-se a criação de novas variedades e organismos geneticamente modificados, avanços em algoritmos e plataformas para análises biológicas, processos de produção sustentável em biofábricas, moléculas inovadoras, pesticidas e fertilizantes nanoestruturados e sensores inteligentes, embalagens e rações nanotecnológicas, biossensores para diagnóstico animal, biopesticidas e bionanocompósitos biodegradáveis. As conclusões apontam para o posicionamento do Brasil na vanguarda da biotecnologia agroindustrial, com a geração de inovações que contribuem para uma agropecuária mais produtiva, resiliente e sustentável.

Palavras-chave: biotecnologia, nanotecnologia na agricultura, inovação, ciência ômica.

1. Introduction

The challenges posed by the 21st century—including climate change, ecosystem degradation, and escalating demand for nutritious food and renewable resources—necessitate urgent, coordinated interventions grounded in scientific and technological advancement. In the agricultural sector, this imperative entails not only enhanced productivity but also reduced environmental impacts and optimized utilization of natural and genetic resources. A seminal example of this approach is the Brazilian Agricultural Research Corporation (Embrapa), established in 1973 to foster innovation in tropical agriculture and significantly expand national food production. Its transformation of the Cerrado into a productive region and its development of sustainable farming technologies exemplify the integration of science and environmental stewardship. Through a network of research centers and international collaborations, Embrapa continues to demonstrate how agricultural progress can be aligned with global sustainability goals.

Biotechnology has long played a central role in this transformation. In Brazil, for instance, innovations such as biological nitrogen fixation, already applied to over 40 million hectares, generate annual savings of more than USD 25 billion and prevent the emission of approximately 230 million tons of CO₂ equivalent per harvest. Yet, despite these achievements, biological fertilizers still represent only 10% of total usage, revealing a vast potential for expansion (Gomes, 2023).

This growing relevance is reflected in the rapid expansion of Brazil's bio-inputs market, which has been increasing at an annual rate exceeding 35%, reaching USD 1.2 billion in 2023. On the global stage, major companies such as Bayer have invested over USD 1 billion in the so-called Bio Revolution, with applications in both agriculture and health.

In this context, biotechnology, when integrated with predictive algorithms, advanced molecular tools, nanotechnology, artificial intelligence, and high-performance computing infrastructure for big data analysis, forms the cornerstone of a new agricultural revolution. This convergence of technologies lays the foundation of Embrapa's BioRevolution Portfolio, which aims to unlock transformative and sustainable innovations to shape the future of food and farming.

The synergy between cutting-edge molecular biology approaches, such as gene editing (e.g., CRISPR_Cas system), RNA interference (RNAi), genome synthesis, and artificial intelligence (AI), accelerates the development of high-value germplasm tailored to current and future agricultural demands. A notable and recent example of the integration of emerging technologies addressed by the BioRevolution Portfolio was the launch of two

gene-edited soybean cultivars: one with improved nutritional quality and the second with drought tolerance. This entire body of work, which culminated in the development of these cultivars, resulted from extensive genomics studies (including genome sequencing, pan-genome construction, and population genetics analyses) as well as advancements in transcriptional and post-transcriptional regulation (including RNA-seq, epigenetic studies, and multi-omics database development), all developed by Embrapa Soja and its partners (Tian et al., 2025). Embrapa's strategy leverages Brazil's vast biodiversity, to drive technological independence and strengthen the national bioeconomy.

Embrapa's R&DI Portfolios serve as strategic management instruments designed to structure research, development, and innovation (R&D&I) programs, platforms, and projects around critical thematic domains aligned with global agendas—such as food security, climate resilience, sustainable agriculture, and the bioeconomy. The overarching mission of portfolios is to steer R&DI capabilities toward globally relevant challenges and their interfaces with national priorities, to ensure continuous refinement of programmatic planning; eliminate duplication of efforts; optimize the allocation and impact of public R&D investment and strengthen multi-level coordination of expertise and resources.

Therefore, this article aims to communicate the strategies and guiding principles of the Embrapa Bio Revolution Portfolio, which seeks to enhance the competitiveness of Brazilian agriculture, livestock, and agro-industrial sectors, while ensuring long term sustainability, through the integration of cutting-edge scientific approaches and technological innovation.

2. Materials and Methods

The BioRevolution Portfolio adopts a multidisciplinary R&D framework structured around eight integrated technology axes:

1. Omics sciences: genomics, transcriptomics, proteomics, metabolomics, phenomics, metagenomics, and epigenomics;
2. Genome editing and synthetic biology: for precision improvement of plants, animals, and microorganisms;
3. Nanotechnology: including the development of smart nanofertilizers, nanopesticides, sensors, packaging, and composite materials;
4. Bioinformatics and Artificial Intelligence: for molecular design, predictive analytics, and data-driven decision-making;
5. Metabolic and protein engineering: to generate novel molecules and optimize biosynthetic pathways;
6. Cryobiology and cell biology: for genetic resource conservation and ex situ preservation;
7. Digital phenotyping and predictive models: to accelerate breeding programs and optimize productivity under stress;
8. Biomanufacturing and biofactories: for scalable production of enzymes, bioplastics, vaccines, and other biomolecules of industrial interest.

All activities are guided by biosafety and regulatory standards, emphasizing responsible innovation aligned with national and international frameworks. To support strategic planning, a structured inventory was conducted to map and evaluate the portfolio's technological assets based on type, subtype, and TRL, using a corporate asset management system.

3. Results and Discussion

The results achieved through the development of projects under the BioRevolution Portfolio reinforce Embrapa's leadership in advancing biological technologies in Brazil. These outcomes are expressed through a dynamic and continuous innovation pipeline structured across different time frames. In the short term, the focus is on validating genomic prediction models integrated with multi-omics datasets, developing laboratory prototypes of genes and metabolic pathways using synthetic biology, and creating national software tools and bioinformatics pipelines. Medium-term goals include generating new GM/GE varieties and organisms with enhanced productivity and stress resistance, scaling up biofactories for enzymes, biopesticides, and biostimulants, and launching intelligent nanofertilizers, nanopesticides, nanostructured sensors, and smart packaging. In the long term, the portfolio aims to consolidate a digital innovation ecosystem for precision agriculture and accelerated breeding, enable large-scale production of biopharmaceuticals, vaccines, bioplastics, and high-value compounds, achieve full technological independence in genetic engineering platforms, and position Brazil as a global leader in sustainable agrobiotechnology.

A structured asset inventory was conducted to support strategic planning and monitor technological evolution within the BioRevolution Portfolio, which currently includes 99 technological categorized assets offering a comprehensive view of Embrapa's innovation pipeline and its potential for application, scalability, and impact (Figure 1).

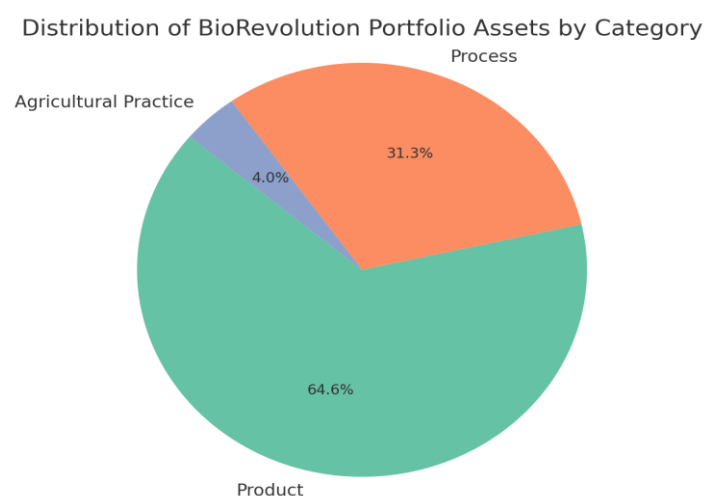


Figure 1. Distributions of BioRevolution Portfolio Assets by Category.

Products account for 64.6% of the total, reflecting a strong emphasis on applied innovation. Within this category, transgenic and gene-edited cultivars stand out (21.9%), alongside a wide variety of biological inputs, therapeutic products, fertilizers and substrates, nanostructured materials, and packaging technologies. This composition highlights a strategic orientation toward genetic innovation and technological diversification, in response to the evolving challenges of modern agriculture.

Processes represent 31.3% of the portfolio and are primarily aimed at enabling the production, scale-up, and industrialization of these technological solutions. The process-related assets include manufacturing workflows for fertilizers, inoculants, substrates, agrochemicals, food products, and packaging materials, such as coatings and films. These technologies serve as essential enablers for bringing lab-stage innovations into real-world agricultural and industrial environments.

Agricultural practices, though representing a small portion (4%), include strategic

applications in seed conservation, animal feeding, and nutrition, complementing technological innovations with sustainability-oriented management solutions.

An important highlight from the asset inventory is the significant proportion of items classified under 'other products' (31.3%) and 'general product manufacturing processes' (38.7%). These open-ended categories include technologies that do not fall neatly into existing classifications, highlighting the portfolio's flexibility to incorporate emerging and unconventional innovations.

Regarding technological readiness levels (TRL), the portfolio exhibits a concentration of assets at intermediate development stages. Among product-related innovations, most are situated between TRL 4 and 5 (64%), corresponding to proof-of-concept and early validation phases. Process-related assets exhibit a similar trend, with 38.7% at TRL 4 and 29% at TRL 6, indicating significant potential for further development and eventual commercialization.

The portfolio composition reflects an integrated strategy to tackle agricultural challenges through innovation, with a strong pipeline of early to mid-stage technologies poised to drive future breakthroughs in sustainable agriculture.

4. Conclusions

The Embrapa BioRevolution Portfolio represents a strategic milestone for Brazilian science and innovation. By integrating biotechnology, nanotechnology, AI and other converging technologies, it strengthens the foundations for a more productive, resilient, and sustainable agricultural system. Through the generation of proprietary assets and the promotion of collaborative partnerships, the portfolio enhances Brazil's technological sovereignty, supports food and nutritional security, and increases global competitiveness. Its implementation positions Brazil as a key player in the emerging global bioeconomy, paving the way for a more prosperous, inclusive, and innovation-driven agro industrial future.

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