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A Collaborative, Systems Approach for the Development of Biomass-Based Value Webs: The Case of the Acrocomia Palm

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Abstract: The diversification of biomass resources is key to the transition towards a bioeconomy. *Acrocomia* spp., a neotropical genus of palms, is an example of plants' diversity potential for a sustainable bioeconomy. Acrocomia's adaptability to environments outside rainforests, its specific fruit properties and high yields has generated the interest of researchers and entrepreneurs, triggering its introduction as a multipurpose oil crop. Developing sustainability-oriented and knowledge-based acrocomia value webs requires a collaborative, systems approach from the outset. Fostering an inter- and transdisciplinary dialogue on acrocomia through a participatory workshop with both academic and non-academic actors contributed to this endeavor. This allowed the identification of priorities, knowledge gaps, and stakeholder roles, and served as the basis for the co-creation of a research and development roadmap. Key steps for the introduction of acrocomia include intertwined technical aspects relating to the development of planting material, cultivation systems, processing technologies and applications, market entry, and value web governance aspects. A broad collaboration among scientists, the public and private sectors, farmers, and civil society, is required for the development of acrocomia value webs. The incorporation of sustainability and a consideration of context in the design and development phases are fundamental to fostering the sustainable performance of acrocomia value webs.

Keywords: *Acrocomia* spp.; *Acrocomia aculeata*; bioeconomy; biomass-based value web; biobased value chain; agricultural value chain; agroforestry; biorefinery; macaw palm; macaúba; coyol; mbokajá; minor crops; novel crops; oil crops; palms; systems approach; social-ecological systems

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1. Introduction

The transition towards a sustainable biobased economy as a pathway to achieve a low-carbon, fair, and resilient society relies—from a resource-use perspective—on the sustainable production, use, and diversification of renewable resources (i.e., biomass) to supply a range of human necessities. This must be seen in the context of urgent actions for climate change mitigation, biodiversity conservation, environmental protection, and social equality. As a consequence, the biomass demand is expected to increase in the next decades [1]. To meet these demands sustainably, novel biobased production systems that deliver both biomass and multiple ecosystem services need to be identified and developed [2]. In this context, the sustainable intensification of agriculture [3] and the use of novel plants and underutilized crops are key [4,5]. Thus, agricultural diversification based on the local diversity of vascular plants has the potential to establish multi-functional production systems for the bioeconomy. This is the case for *Acrocomia* spp., a genus of palms endemic to the neotropics, that is in the early phase of domestication (i.e., *A. aculeata*) and has manifold artisanal and industrial applications, primarily using its oil-bearing fruits [6–9]. The diverse uses of acrocomia fruit fractions—husk (exocarp), 17.9–34.7%; pulp (mesocarp), 41–53.3%; shell (endocarp), 15.7–31%; and kernel (seed), 3.1–9% [6]—have been investigated for the production of vegetable oils (20.2–55.7% oil content in pulp (dry basis) and 45.8–68.9% in kernel of acrocomia fruits [6,10–14]) and raw materials for the food, feed, pharma, cosmetic, bioenergy, and chemical industries [4,7,10,15–21]. This can allow the development of acrocomia biorefinery systems based on pulp and kernel oils. Such systems should integrate processes for oil extraction, refining, and valorization of by-products (e.g., deoiled pulp and kernel, husk, and endocarp) into high-added-value products (Figure 1) [6].

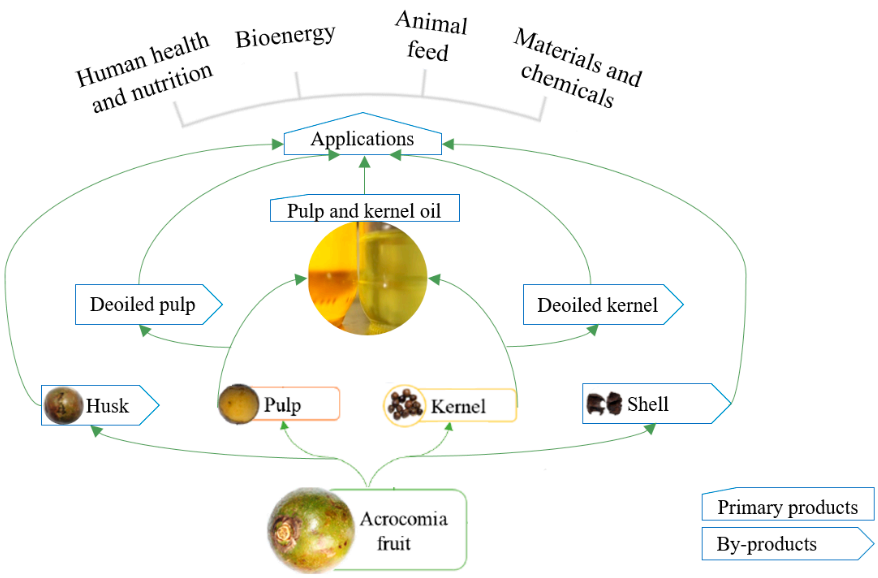

Figure 1. Integral use concept for acrocomia fruits, including oils (primary products), by-products, and targeted sectors. Fruit-to-product pathways (green arrows) vary, for instance, in some regions the primary use of acrocomia pulp is the manufacture of flour, soft drinks, sweets, jellies, and ice creams [6,7,11,21,22]. Figure adapted from [4,7,10,15–21,23].

In contrast to the African oil palm (*Elaeis guineensis*), the eco-physiological suitability of acrocomia throughout tropical and subtropical areas of the Americas, ranging from Mexico to north Argentina, confer its high potential for cultivation outside the vulnerable tropical rainforest biome [8,11,15,24]. The palm's ability to be cultivated in agroforestry systems on degraded pasture lands indicates that it could provide nature-based solutions associated with land restoration, carbon sequestration, and the promotion of ecosystem services [15,25–27]. In this way, it could contribute to various ecosystem services in addition to the provision of biomass. Moreover, various communities in Latin America have benefitted from natural populations of acrocomia for a long time in diverse ways, demonstrating the possibility and need to implement inclusive strategies that provide livelihood options to smallholder farmers in rural areas [5,8,11,15,16,23,25,27–32]. Brazil and Paraguay are leading the development of value chains based on acrocomia fruits and first cultivation systems are in the establishment phase [6–8,11,27].

Acrocomia's capacity to deliver multiple products and ecosystem services indicates the potentiality of this novel crop for the bioeconomy. The sustainable establishment of novel perennial crops, such as acrocomia, and the derived value chains, involves complexities and multidimensional factors associated with physiological suitability, plant productivity, biomass quality, processing technologies, farming systems, value chain governance, financial instruments, and market uncertainty. Existing frameworks, such as the 'biomass-based value web', allow a systems, integrative, and multi-dimensional approach to biobased production systems and multi-purpose crops [33–35]. This framework is an extension of the value chain concept and promotes the understanding of complexity from a web perspective. It reflects the multiple uses of biomass through its cascading use (i.e., successive use of by-products), resulting in interlinked value chains. This contributes to the integration of ecological, social, economic, and governance aspects, as well as relationships between actors [33–35]. Thus, biomass-based value webs rely on stakeholder relationships and interaction. This paper explores the consideration of a systems approach to acrocomia research and development against the background of the biomass-based value web framework. As a first step, we identified research networks making significant contributions to the acrocomia knowledge base. This analysis set the baseline for conducting a multi-actor workshop on acrocomia, with the aim of promoting the adoption of a systems approach and fostering inter- and transdisciplinarity as well as stakeholder involvement in the context of bioeconomy transitions [36]. The dialogue with academic and non-academic actors allowed the identification of priorities, research gaps and needs for setting a roadmap for the development of acrocomia as a future-oriented and sustainable crop for the bioeconomy.

2. Methodology

Given the complexity of developing sustainability-oriented, biomass-based value webs from novel crops, such as acrocomia, collaborative systems approaches in research and development become fundamental. To evaluate this premise, we first analyzed the acrocomia research landscape. We then organized a multi-actor workshop on acrocomia to gain insights from the perspective of academic and non-academic stakeholders.

2.1. Identification of Research Networks

As groundwork for the multi-actor workshop held in September 2019, leading research networks on acrocomia were identified by selecting the authors of scientific publications associated to multiple fields. These were retrieved from the Scopus database using the following search query, which includes the genus name and vernacular names of acrocomia in various Latin American countries: Acrocomia OR Macaw palm OR Mbokaya OR Coyol OR Macauba OR Macaúba OR Palma de corozo. These terms were searched for in publication titles, abstracts, and keywords, using a self-developed algorithm built on R [37] and Bibliometrix [38]. A total of 366 articles published up to 2018 were retrieved, of which 15 were excluded due to their low relevance with regard to the purpose of the study, or due to duplications. The selected manuscripts (n = 351) were divided into fundamental and applied research, following the approach for the classification of scientific literature described by Vargas-Carpintero et al. [6]. Applied studies were then allocated to three categories relating to the biomass-based value web concept: biomass production, processing and products, and sustainability.

In order to analyze patterns of collaboration between authors, a research network analysis was performed [39]. This allowed the identification of academic interaction between the authors of the selected literature and leading scientific clusters in research and technological development [40]. Connections were considered to be established where researchers were listed as co-authors on scientific publications [41]. Authors included in the network analysis were selected based on their published contributions to acrocomia research. For this purpose, the SJR (SCImago Journal Rank) metric 2017 was applied, allowing academic journals to be ranked according to journal popularity, prestige, and research impact [42]. The SJR of each journal was attributed to the authors of the corresponding publication. So, for example, an author who published 10 publications in journals with a score of 100 each was allocated an overall score of 1,000. For publications with more than one author, all authors received the SJR score of the journal. For the construction of collaboration networks, the authors' names and affiliations as presented on the publications were standardized to allow for any differences in spelling. A benchmark was set for the inclusion of authors in the network: a minimum of 3.4 SJR accumulated points in more than one publication. Minor publications, such as correspondence or short entries, were not considered in the analysis. The selection of authors based on SJR was performed computationally and triangulated manually to reduce possible errors. Co-authorship analysis was performed by means of a self-developed algorithm built on R [37]. For the visualization of the collaboration network, the software VOSviewer was used [43]. A second search of publications from 2019 was performed using the same database and search query to identify emerging networks in the acrocomia research landscape.

2.2. Multi-Actor Workshop

In September 2019, a multi-actor workshop was held at the University of Hohenheim with the participation of academic and non-academic experts to gather empirical evidence on the prospects of acrocomia. The research networks identified in this study facilitated the selection of scientists invited to take part, with the aim of covering a variety of research areas, topics, and organizations, as well as regions of Latin America. This allowed a comprehensive representation of acrocomia research areas, from agriculture and biomass production to advanced applications, including environmental, social, and economic aspects. In total, 33 academic experts participated: 13 affiliated to the host (University of Hohenheim, Stuttgart, Germany), 13 to Brazilian research organizations, and the others from institutions based in Argentina, Paraguay, Costa Rica, and Mexico. Non-academic experts and practitioners from five German-based companies and one multinational corporation active in the food, cosmetic, personal, or home care sectors took part. In addition, an acrocomia fruit processing company located in Paraguay, the multi-stakeholder 'Forum for Sustainable Palm Oil (FONAP)', and the Fiat Panis Foundation (a research funding organization on food security in developing countries), participated in the dialogue.

The workshop comprised two phases: (i) exploration of research efforts, challenges, and future possibilities, with regard to fundamental and applied research on plant and biomass production, primary processing, advanced applications, and sustainability aspects; and (ii) the co-creation of an acrocomia research and development (R&D) roadmap. During the first phase, the 'World Cafe' method was applied. This method facilitates collaborative dialogues, knowledge sharing, and the discovery of opportunities [44]. Academic experts were allocated to three interdisciplinary working groups, namely: (i) plant and biomass; (ii) harvest, postharvest, and primary processing; and (iii) advanced applications. Tailor-designed templates with guiding titles were laid out to structure the conversation process. The second phase involved both academic and non-academic participants. A forum-like dialogue space was held, followed by the identification of requirements and opportunities for acrocomia R&D. For this purpose, a mapping tool with two dimensions was used: stakeholder groups (i.e., research, industry, civil society, and government) and research areas (plant and biomass; harvest, postharvest, and primary processing; advanced applications; and sustainability). Each phase was facilitated by scientists selected according to their area of expertise. Experts' claims were confirmed by the results in a recent literature review on acrocomia [6].

3. Results and Discussion

The analysis of the acrocomia research landscape resulted in the identification of key research networks that have contributed to expanding the knowledge base of acrocomia (Section 3.1). In addition, the multi-actor workshop revealed advances, priorities, and gaps in the development of sustainable acrocomia value webs (Section 3.2). Our findings indicated the need to approach acrocomia R&D from a collaborative, systems perspective. Based on this, in Section 3.3 we describe a R&D roadmap to set up sustainability-oriented acrocomia value webs, highlighting the territorial embeddedness, the interconnectedness between biomass, processes and products, and the multi-actor collaboration.

3.1. Acrocomia Research Landscape

The analysis of acrocomia's scientific community led to the visualization of the research landscape (Figure 2) that reflects the interconnectedness (co-authorship) of a selection of authors based on their contribution to acrocomia research. The evaluation of the network structure allowed the identification of leading institutions, key topics, research clusters, and collaboration patterns.

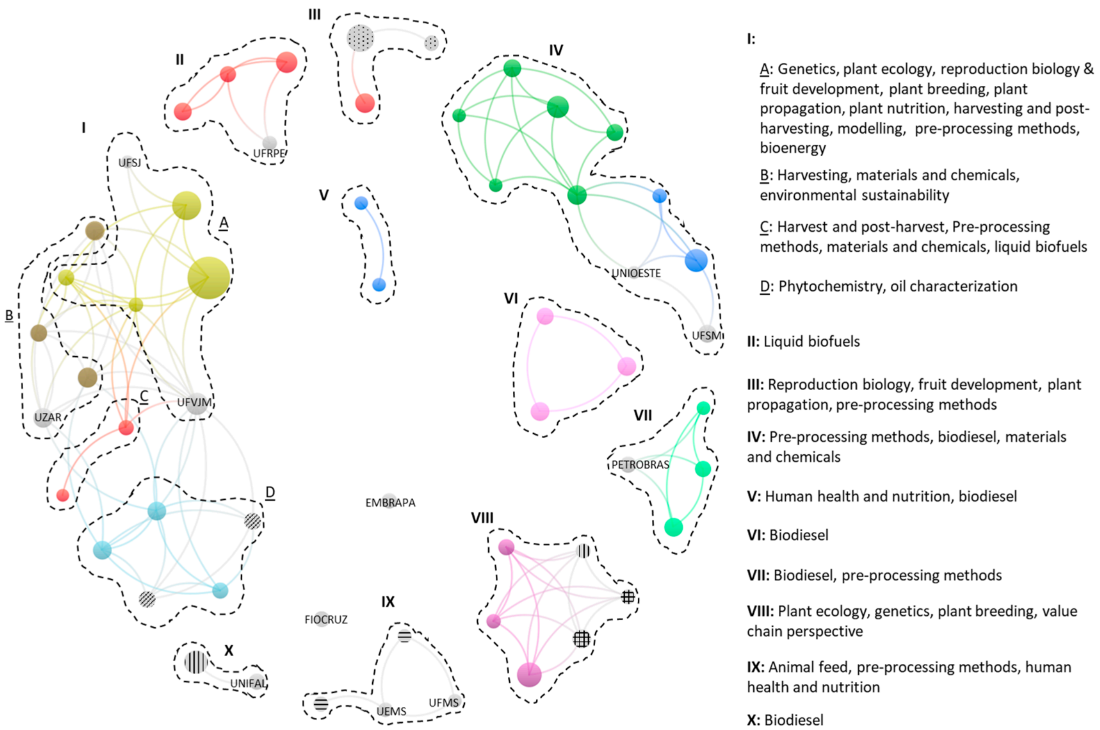

Figure 2. Research networks and foci of leading acrocomia researchers. Colors indicate affiliation, size of nodes correspond to researcher's SJR, and interactions depict co-authorship. Affiliations: red: Federal University of Minas Gerais (UFMG); green: Federal University of Santa Catarina (UFSC); yellow: Federal University of Viçosa (UFV); dark blue: State University of Maringá (UEM); purple: Agronomical Institute of Campinas (IAC); light blue: Institute of Natural Resources and Agrobiology of Seville (IRNAS); light green: Federal University of Rio de Janeiro (UFRJ); pink: University of Campinas (UNICAMP); brown: University of Valladolid (UNIVALL); gray (∴): State University of Montes Claros (UNIMONTES); gray (#): São Paulo's Agency for Agribusiness Technology (APTA); gray (≡): Federal University of Grande Dourados (UFGDM); gray (|||): University of São Paulo (USP); gray (///): University of Wisconsin-Madison (UWISC), gray: Federal University of São João del-Rei (UFSJ), Federal University of Vales do Jequitinhonha e Mucuri (UFVJM), University of Zaragoza (UZAR), Federal Rural University of Pernambuco (UFRPE), Federal University of Alfenas (UNIFAL), Mato Grosso do Sul State University (UEMS), Federal University of Mato Grosso do Sul (UFMS), Western Paraná State University (UNIOESTE), Federal University of Santa Maria (UFSM), Brazilian Agricultural Research Corporation (EMBRAPA), Oswaldo Cruz Foundation (FIOCRUZ). Covered period of analysis: 1878 (first acrocomia-related publication retrieved from Scopus)–2018.

3.1.1. Identified Research Networks

A total of 57 scientists were identified based on the SJR indicator and according to the defined benchmarks. From this, a research network was drawn up to illustrate the co-authorship relations between them (Figure 2). It displays each author's affiliation (color), rank in terms of accumulated SJR score (size of node), and co-authorship (linkages between nodes).

Ten research networks were identified with varying degrees of interdisciplinarity and specialization on specific topics, as illustrated in Figure 2. Together, they represent key research areas in the development of acrocomia value webs, and contribute to the advancement of acrocomia cultivation, products, and markets. The networks deliver fundamental and applied knowledge on acrocomia, particularly *A. aculeata*'s genetic diversity, botanical aspects, plant breeding, processing routes, and diverse energetic and material uses. The majority of groups concentrate primarily on the technical knowledge of processing and products, biodiesel being one of the main applications investigated. However, transversal essentials relating to economic aspects, social conditions, and institutional factors are not represented in the networks. For instance, the use of agroforestry approaches could enable marginalized rural communities to be integrated into biobased value chains and provide new opportunities for income generation [45,46]. Therefore, research to identify inclusive value chain governance mechanisms is required. Environmental sustainability is only covered to a limited extent by the research network I in Figure 2.

3.1.2. Organizations in Research Networks

Of the 57 authors included in the identified networks, 48 are affiliated to Brazilian research organizations. The largest research network (I, Figure 2) shows multiple interactions among authors from various Brazilian and non-Brazilian institutions. This regionalized knowledge base, particularly in the regions of São Paulo and Minas Gerais (networks I, II, VI and VIII), has contributed to the development of acrocomia as a novel crop, evidenced by initial plantations led by private companies in these areas.

The largest network (I) was found centered on the UFV (Figure 2). Other organizations integrated in this network include UNIVALL, IRNAS, and the UFMG. The second largest network (IV) comprises 10 authors from various scientific groups, mainly UFSC and UEM. A further five networks are predominantly driven by specific research units. Of these, network VIII works under a common umbrella organization in São Paulo (IAC and partners), network VII is based in Rio de Janeiro (UFRJ), network VI is centered on UNICAMP, and network II around the UFMG.

A second search performed in this study, to identify on-going research activities from 2019 until 2021, indicated the further development of already established research networks (those depicted in Figure 2) with respect to research foci (new topics) and interactions with other research organizations, as summarized in Table 1. Overall, we observed higher specialization on specific fundamental and applied areas and increased collaboration with other institutions in some of the established research networks. It signals the growth of networks I-A and III. In the case of the network I-A, the diversity of topics confirms its interdisciplinary approach. Emerging networks in the acrocomia research landscape include organizations that have played a prominent role in the expansion of the acrocomia knowledge base, as well as Brazilian and non-Brazilian organizations that are newly specializing in specific research branches along the acrocomia value web. New actors in the acrocomia research landscape and their research foci are listed in Table 1. These include the interaction between authors affiliated to the University of Hohenheim and the University of Costa Rica in the areas of acrocomia oil properties and nutraceuticals. On-going research projects between the University of Hohenheim (Germany) and UFV focus on environmental impacts on flowering in acrocomia.

Table 1. Expansion of the acrocomia research landscape since 2019 indicating growth of established networks and emergence of new networks integrating one or multiple research organizations.

	Author's Affiliation	Research Area		Author's Affiliation	Research Area
New actors and topics in established networks	UFV and UFVJM (network I-A) + EMBRAPA, Federal University of Goiás, State University of Maranhão, Federal Institute of Mato Grosso do Sul (IFMS), Federal Institute of Maranhão	Agroforestry, crop production and management, post-harvest, oil quality/content, agroecological zoning, plant breeding, propagation, biomaterials, residues valorization	Emerging networks (ii)	Federal University of Vales do Jequitinhonha e Mucuri, the Federal University of Uberlândia, UFMG [1], National Nuclear Energy Commission	Charcoal, biodiesel, and aviation fuel
	IAC (Network VIII) + Federal University of Paraíba, La Salle University, Federal University of Pernambuco, UFMS	Pests, co-pollination, genetics		EMBRAPA [1] and Federal University of Southern and Southeastern Pará (UNIFESSPA)	Embryogenesis
	UEM (Network IV) + USP	Oil extraction		National Center for Scientific Research of Cuba	Pharmacological oil properties
	UEM (Network V) + Federal Technological University of Paraná	Phytochemicals, bioenergy		UNICAMP [1]	By-product valorization
	UNIMONTES and UFMG (network III)	Seed germination and seedling development		EMBRAPA [1] and UFV [1]	Genetic diversity, yield modelling
	Federal University of Vales do Jequitinhonha e Mucuri (Network I-A)	Potential cultivation areas		Dom Bosco Catholic University, EMBRAPA [1] and UFMS [1]	Nutritional oil/fruit properties, post-harvest
Emerging networks (i)	University of Hohenheim and the University of Costa Rica	Oil properties, nutraceuticals, and value chain development		Universidade Estadual do Centro-Oeste (UNICENTRO) and USP [1]	Gene flow, genetic diversity
	Delft University of Technology	Social sustainability of biofuels		Federal University of Pernambuco (UFPE)	Nutritional properties
	Brazilian Center for Research in Energy and Materials and UNICAMP [1] (with network X)	Biofuels		Wageningen University and Research	Animal feed
	Federal University of Lavras (UFLA) (with network I-UFV)	Fruit harvesting		Federal University of Piauí, Federal Institute of Maranhão, UNICAMP [1]	Biodiesel production
	Federal University of Alagoas	Biodiesel, by-product valorization		USP [1] and United States Department of Agriculture	Genetics, taxonomy
	University of Coimbra, Clinical Academic Center of Coimbra and Coimbra Health School (with network IX)	Pharmacological properties of acrocomia leaves		UFMG [1], Dublin Institute of Technology (with Network II)	Vegetable oil quality and processing
	UFMG [1] and Agroceres Multimix	Animal feed		Nuclear and Energy Research Institute—IPEN	Biochar
	University of Brasília (UnB), Agência Nacional de Petróleo, Gás Natural e Biocombustíveis (ANP)	Biopolymers, biochemical, biodiesel		Goiano Federal Institute, Federal University of Goias	Bioactive properties, germination, genetic diversity
	São Paulo State University (UNESP), University of Sheffield, University of York	Biochemicals		UFRJ [1]	Biodiesel, biojet fuel

[1] Established organization in the research landscape with contribution of new affiliated author(s) different to those of clusters shown in Figure 2.

3.1.3. Specialized and Interdisciplinary Research Networks

Interdisciplinary and transversal foci along the acrocomia value web stand in contrast to specialized research networks. Among the networks identified, high specialization in specific research areas was observed, either on a certain acrocomia application or value web process. For instance, liquid biofuels (mainly biodiesel), is the most important topic for the majority of research groups. Some biofuel- and process-centered research networks also cover pre-processing aspects and diversified acrocomia-based products using oils and residual components as potential sources of nutrients, medicinal compounds, biobased materials and chemicals, and animal feed. Multi-faceted networks, especially networks I, III, IV, VIII, and IX, show a more diverse research portfolio, particularly oriented towards fundamental and applied research for both biomass and value-web development, covering aspects related to crop production, (pre-) processing, and biomass use.

3.2. Multi-Actor Acrocomia Workshop to Enable Collaboration

The development of sustainable knowledge-based acrocomia value webs relies on broad collaboration between diverse actors. For this purpose, a multi-actor workshop was organized with the participation of mainly academic but also non-academic actors. The participants engaged in discussions on the status of acrocomia and collaboratively contributed to the prospects of an agenda for establishing acrocomia value webs. Priorities, gaps, and needs in acrocomia R&D, as well as value-web governance, were identified in the roles of (1) research organizations, (2) industry and business associations, (3) government, and (4) civil society and farmers. The findings of these four actor groups are described in the following sections, highlighting advances, opportunities, challenges, and demands. These range from the primary production of biomass to advanced applications and transversal aspects, as depicted in Figure 3.

3.2.1. Research Organizations

This section briefly describes the knowledge advances and demands to be tackled by researchers for the development of acrocomia value webs, as identified by the workshop participants, and based on a recent comprehensive literature review on acrocomia [6]. It highlighted the need to involve a variety of stakeholders from the early stages of the design of technological solutions, and to consider context-settings to the facilitate transfer of knowledge and the adoption of solutions. In addition, research to develop decision-support systems, as well as the application of ex-ante and multi-dimensional analysis, were considered crucial to guide the establishment of sustainable acrocomia value webs suited to socio-ecological systems at territorial level. The participants emphasized the need to better connect existing research networks to address the challenges faced when developing acrocomia value webs through an interdisciplinary approach.

Advances

- **Botany.** Fundamental research on *Acrocomia* spp., especially *Acrocomia aculeata*, related to plant biology, genetics, plant ecology, reproduction, and fruit development, has broadened knowledge on this palm genus, providing a baseline for applied research directed towards plant domestication, cultivation and conservation strategies [6,7,11,15].
- **Seed germination and propagation.** Various advances in seed germination and propagation, particularly the development of methods to overcome seed dormancy and the use of somatic embryogenesis, have greatly contributed to the domestication of *A. aculeata* and the establishment of seedling production and nurseries for initial plantations in Brazil [6,15,47–59].

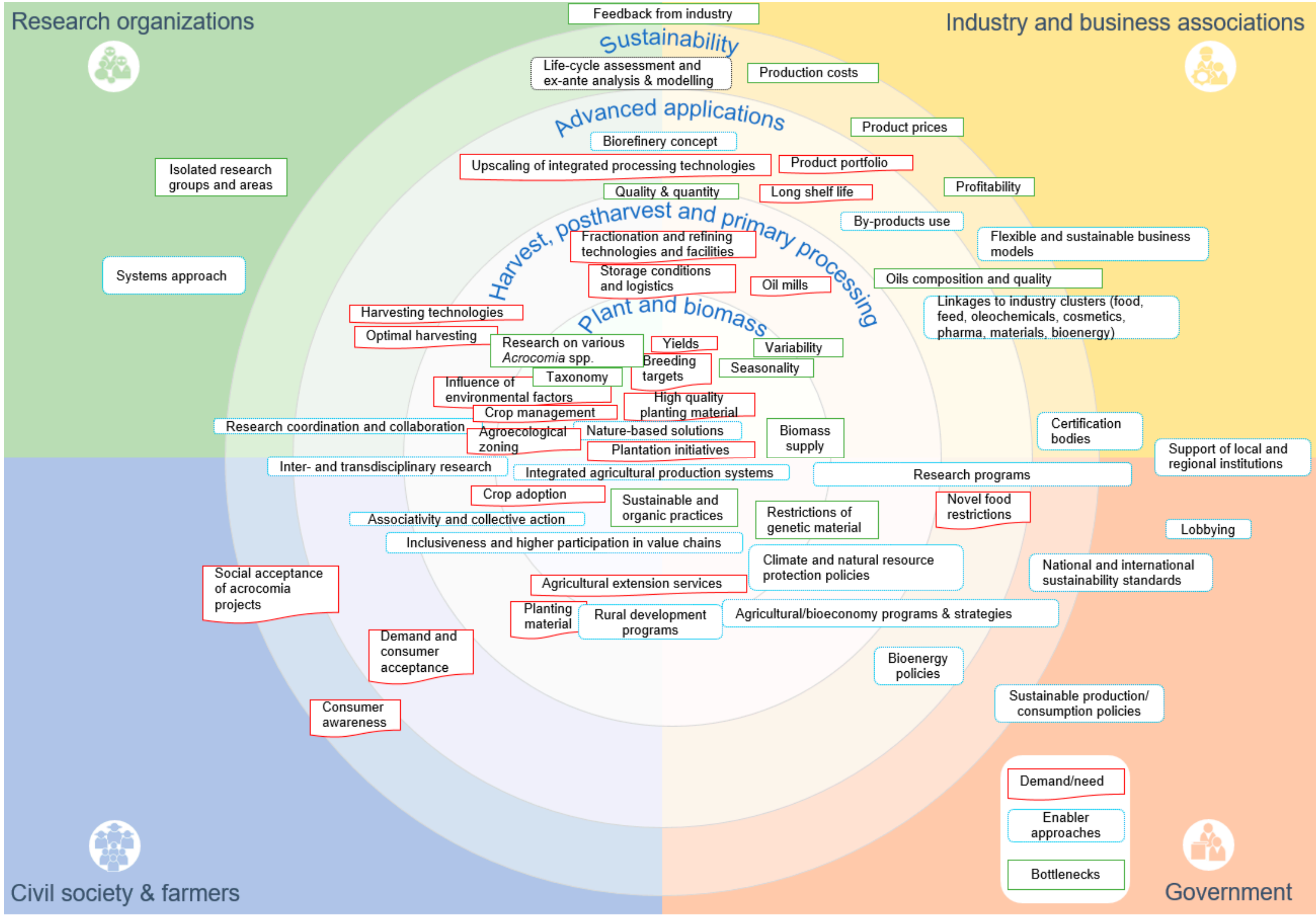

Figure 3. Priorities for the development of acrocomia value webs; results from four actor groups of the multi-actor workshop. The green, yellow, blue and orange squares represent the actor groups, i.e. research organizations, industry and business associations, civil society and farmers, and government, respectively, while the concentric circles represent value web areas.

- **Genetic characterization and plant breeding.** Knowledge of *A. aculeata* has been expanded by the genetic and biometric characterization of germplasm from natural populations in various regions of Brazil, progress in molecular biology information on the species, the study of its reproductive biology, and the establishment of germplasm banks [6,12,60–77]. This has allowed the identification of promising genetic material for selection. Various genetic parameters for selection have been studied, including morphological and physiological traits, with an emphasis on fruit and oil yield, but also on tree height, germination parameters, and water use efficiency [60,62,78–81].
  These advances are expected to lead to the development and supply of high-quality planting material and commercial varieties for plantations, as seeds and seedlings are currently derived from natural stands.
- **Technological processing pathways.** Applied research has advanced technical knowledge on plant properties (especially fruits, oils, and by-products), (pre-)processing pathways, and product performance, in a range of sectors embracing bioenergy (liquid and solid biofuels), human health, nutrition (including cosmetic applications), and animal feed, as well as materials and chemicals [6,10,17].
  As oils represent the main products from acrocomia fruits, this palm is foreseen as an alternative oil source with high ecological adaptability in unsuitable areas to cultivate African palm oil, thus possibly leading to reduce deforestation pressure on tropical forests [8,82]. The nutritional profile of acrocomia fruits indicates their potential as a source of minerals, carotenoids, tocopherols, and tocotrienols [10,83–86] . Differences between *A. totai* and *A. aculeata* fruits have been observed with regard to mineral composition and the contents of carotenoids in the mesocarp, protein, and carbohydrates [10,13,86,87].
- **Oil properties.** Profiles of acrocomia oils vary among species, populations, and regions. Acrocomia pulp oil is composed mainly of unsaturated fatty acids (oleic, 52.6–74.2%; palmitic, 13–27.1%; linoleic, 2.6–19.4%) and kernel oil is rich in saturated fatty acids (lauric, 26.8–45.4%; oleic, 18.7–39.3%; myristic, 7.6–13.5%; palmitic, 5.7–9.7%) [6,10]. In comparison to the red palm oil (RPO) from *E. guineensis*, acrocomia pulp oil has a higher content of oleic acid (RPO: 39.2%), similar values in linoleic acid (RPO: 10.1%) and a relatively lower concentration of palmitic acid (RPO: 44%) [88]. Lauric acid in acrocomia kernel oil has values close to those reported for palm kernel oil (PKO: 47.8%), higher concentration of oleic acid (PKO: 15.4%) and similar values of myristic acid (PKO: 16.3%) [88].
  Available information on composition *A. totai* fruits and products show small differences to *A. aculeata*. Oil's fatty acids profile of *A. aculeata* fruits are similar to those reported for *A. totai* [6,10,12,14,89].

Opportunities

- **Cultivation.** The suitability of acrocomia cultivation outside the tropical rainforest areas in agrosilvopastoral systems is seen as an opportunity for the diversification of land-use systems and the avoidance of direct and indirect land-use change, thus creating environmental and socio-economic benefits [8,15,16,27,82,90]. In addition, acrocomia could be a model crop for the provision of various environmental services and the ecological restoration of degraded pastures in extensive areas of Brazil, potentially contributing to biodiversity increment (as a native plant, acrocomia negative impacts on biodiversity can be lower in comparison to exotic species [8]), carbon sequestration, soil erosion prevention, and afforestation [25–27,31]. Acrocomia palms could, for example, be part of riparian or stream buffers and be cultivated on degraded lands [26,91]. Available knowledge on cultivation systems and plant spacing, plant nutrition and protection, as well as harvest and post-harvest, has contributed to advance the preparedness of acrocomia for cultivation [6]. However, there are still a number of research gaps related to site-specific crop management and cropping systems, as well as their performance evaluation, that need to be fulfilled in order to provide guidance for farmers.

- **High-value products and product variety.** High-value products from acrocomia fruits should be targeted as primary uses in order to maximize income opportunities for farmers. These include nutritional compounds and also multifunctional extracts for use in the food, feed, cosmetic, chemical, pharmaceutical, and agricultural sectors. Secondary uses could include energy recovery after the successive extraction processes, pursuing a cascading-use of biomass. For instance, oils from acrocomia can be used as feedstock for oleochemicals in food and non-food applications. Alternatively, by-products from the production of vegetable-oil-based energy carriers from acrocomia fruits (e.g., biodiesel and biojet fuel) could serve as raw materials for the extraction of valuable compounds.
- **Adaptation to local needs and enhancement of socio-economic regional development.** Different configurations of value chains and webs can be tailored to location-dependent characteristics of acrocomia fruits (i.e., acrocomia species and ecotypes), availability and distribution of biomass, targeted product portfolio (commodities/specialty products), existing and potential markets, and local needs and resources (e.g., available traditional and scientific knowledge) [8,27]. For example, decentralized, small-scale, and territorial biorefinery concepts, could bring advantages for adding value locally, increasing the participation of farmers in value-generation activities and contributing to socio-economic regional development in rural areas of Latin America.

Challenges and Demands

- **High genetic variability and the impact of environmental conditions**. High genetic variability among individual acrocomia palms and populations result in high variability in biomass productivity, fruit characteristics and composition, and oil profiles [6,65,70,73,92]. Moreover, a deeper understanding of the high phenotypic plasticity of acrocomia is required to determine the interactions between genotypes and environment [93–95]. Fruit yields show a strong response to crop management; however, there is high uncertainty for varying, marginal ecological conditions, and inter-seasonality productivity [8,15]. Systematic information on agroclimatic zones and fruit characteristics is needed to identify suitable growing areas [7,8,15,96,97]. This could contribute to estimating the response of different ecotypes of the palm species to non-biotic factors in different environments, and potentially identifying the location-specific properties of fruits and regionalized products. To address the issues mentioned above, and in order to contribute to genetic conservation strategies, a comprehensive knowledge of genetic resources is required, encompassing the numerous species of the *acrocomia* genus other than *A. aculeata* [11,15]. So far, most research efforts have focused on *A. aculeata* [6]. A comprehensive taxonomic classification of the genus is however necessary as a basis for species confirmation [6,11]. Germplasm collections are required from all domestic regions of the acrocomia species, following the blueprint of *A. aculeata* in Brazil [6], to develop highly productive and adapted planting material to different environmental conditions [15,82].
- **Plant breeding.** Applying advanced tools for reducing breeding cycles is key for the development of high-performing commercial cultivars [7,15]. Increased efforts are required to tailor plant breeding to locally available genetic resources and avert genetic vulnerability by mixing different genotypes and selecting open-pollinated and hybrid progenies, allowing for population improvement [6,82]. Given the potential multi-purpose applications of acrocomia fruit fractions, and the wide distribution of the genus, breeding programs require multi-objective and regional approaches that also integrate agronomic aspects (e.g., thornless plants, adaptability, short plants, inter-seasonality). Thus the prioritization of targeted products is of major importance,

which implies the consideration of context-dependent settings, fruit-specific features, and the needs of local stakeholders [15].

- **Cultivation systems.** The integration of palms on pasture lands implies the need of appropriate farm management planning for avoiding impacts from cattle on fruit yield. Cross-regional field trials in different locations of Latin America, using various acrocomia ecotypes, can deliver key performance data about integrated cultivation systems in pasture lands and with diverse annual crops. Ex-ante analysis considering place-based factors is crucial for the identification of suitable cultivation areas to avoid land use change impacts, and the definition of practices for guiding landscape and crop management [8]. In integration with farm economics modeling, these analyses can guide decision makers in the formulation of appropriate governance strategies to mitigate cultivation costs during crop establishment until reaching the productive cycle and ensure the inclusiveness of small-scale family farmers [28,32]. Further, a sustainability impact assessment is necessary for the identification of environmental and social hotspots and the formulation of improvement strategies. For this, data availability at farm-level can represent a constraint for high-resolution and spatial modeling, as first plantations are in the establishment phase. From an ecological viewpoint, there is a need to understand critical beneficial and antagonistic plant-soil-microbiome interactions driven by genotype, environment, and management (GxExM), relating to acrocomia growth performance including, but not limited to, nutrition, fruit quantity and quality, as well as potential risks associated to climate change (drought, heat) adaptation, pests and diseases [98–100].
- **Quality of raw materials/products.** The quality of acrocomia fruits, and other palm parts, is crucial for the processing and the standard characteristics of final products. In addition to the influence of genetic variability and environmental factors on the variability of acrocomia fruit composition (biomass heterogeneity), harvest time and techniques, as well as post-harvest operations (drying, storage, pre-processing), are determinants for the quality and integral processing of fruits. Thus, these processes require optimization with respect to the desired parameters for biomass conversion into target products, as well as the integration of experimental knowledge into upscalable protocols [15,16,27,82,101,102]. For instance, the mechanization of harvesting processes in mid- and large-scale plantations result in increased efficiency and quality. The design of processes for the extraction and supply of high-quality oil is required for further applications, particularly in the food, cosmetics, chemical, and pharmaceutical sectors. Energetic and resource efficiency during cultivation, pre-processing, main, and downstream processing, are key design principles, together with cost efficiency. Self-generated energy through the use of residual biomass acrocomia fractions as energy carriers is desirable.
- **Biorefinery approach.** So far, multiple technological pathways and applications have been developed using different fractions of acrocomia fruits (husk, pulp, endocarp, seed). These could be suitable for integrated processing approaches following the biorefinery concept [103,104] for the integral use of acrocomia fruits (see Figures 1 and 4), incorporating circularity [33,105], energy, and resource efficiency [104,106], as well as the cascading use of biomass [33,35,105]. Applying a biorefinery approach to the local processing of acrocomia fruits, with oils being the main platform, requires the prioritization (and possible combination) of the product portfolio. This includes the use of oils, oil refined fractions, and fruit by-products for human nutrition, energetic, and material (cosmetics, pharma, biobased chemicals) applications. Possible uses differ according to region and geographical distribution, biomass quality and availability, targeted market, technology access, and processing scales. For a holistic design of sustainable biorefineries tailored to the context, the application of multi-criteria, process optimization, and participatory approaches are essential [103,106–

108]. Additionally, it is necessary for the development of logistic systems and decentralized production structures, according to biomass availability and optimal processing scales, to ensure economic viability.

Conventional and generic technologies for oil extraction and simple by-product valorization (e.g., grinding press cakes for animal feed) are commercially available and operative, as in the case of acrocomia oil mills in Paraguay [23,27]. Various biodiesel production pathways have been tested, aiming at the efficient conversion of oils with high acidity level. Advanced technologies for oil extraction, oil pre-treatment, and the conversion of specific acrocomia fruit fractions (including oils and by-products) into intermediate and final products are at lab-testing level, some of these with registered patents [109]. However, biorefinery models that integrate advanced technologies remain undeveloped and only biorefinery-related concepts for biodiesel, solid biofuels, and biojet fuel production, have been partially analyzed [110–112].

3.2.2. Industry and Business Associations

Industry and business associations play an important role in value webs for the supply of biobased products and services. These can contribute to direct value generation from cultivation to the production of final goods, as well as in the provision of supporting services and inputs to sustain the operation of the value web. Enterprises can benefit from technological developments from research organizations and trigger continuous innovation [33]. A sustainability orientation of start-ups and companies in acrocomia value webs is essential to avoid potential market failures and negative externalities. The development of regional clusters based on acrocomia that integrate new and established companies requires support from the public sector, and close interaction with research organizations and stakeholders including farmers and the local community. The following points highlight key aspects related to the private sector for the development of acrocomia value webs, according to the perspectives of participants in the workshop.

Advances

- **Plantations.** Ensuring an acrocomia biomass supply for the creation of value chains and webs requires the establishment of plantations. Advances in the domestication of *A. aculeata* have led to the establishment of first acrocomia plantations and seedlings supply in Brazil (state of Minas Gerais) led by start-ups and university spin-offs (ca. 1750 ha reported until 2021, projections to reach 4,000 ha by 2023, around 55,000 ha by 2025 and 80,000 ha by 2030 [6,7,31,113–115]). In Paraguay, emerging initiatives to promote acrocomia cultivation are being led by community-based organizations with the support of international development organizations using *A. totai* [6]. Similarly, initial plantations of *Acrocomia* spp., are being promoted in Costa Rica [6,116] (possibly *A. aculeata* due to the natural occurrence of this species in Central America [11]). These initiatives are based on varying cultivation systems and business models (sole cropping, silvopastoral, agrosilvicultural and agrosilvopastoral) with palm densities ranging from 192 to 400 palms per hectare and also integrate wild fruit collection as biomass supply strategy [6,23,27,31,115]. Plantation projects differ in their growing schemes (outgrower schemes with smallholder farmers, large-scale plantations) and set a baseline to provide information and orientation in the adoption of this crop [27].

  Estimations of acrocomia yields are based on wild plants (mostly *A. aculeata*) and exhibit high variability, ranging from 13.7 to 57 kg fruits per palm, up to 100 kg [6,19,90,117,118]. Projected annual yields in a plantation of 400 *A. aculeata* palms ha^{-1} result in 23 tons of fruit dry matter ha^{-1}, 2.9 tons of pulp oil ha^{-1} (5.7 tons in a high-yield scenario) and 0.5 tons of kernel oil ha^{-1} (1 ton in a high-yield scenario) [6,19]. Considering that the average palm oil yield from African oil palm is 3.3 tons oil ha^{-1} $year^{-1}$ [119], estimated acrocomia productivity and its wider adaptability indicate the potential of this palm as an alternative oil source [7]. In a scenario of 80,000 ha of *A.*

aculeata (projected for 2030 in Brazil) with a plant density of 400 palms per hectare, 232,000 tons of pulp oil and 40,000 tons of kernel oil could be supplied annually (around 0.3% of palm oil and 0.5% of palm kernel oil produced globally in 2020 [120]). A high-yield scenario (46 tons fruit ha^{-1} [6,19]) under the same conditions could result in up to 456,000 tons of pulp oil and 80,000 tons of kernel oil.

- **Fruit processing.** The industrial processing of acrocomia fruits is currently undertaken on a small scale in Paraguay and Brazil, where oils are extracted from fruits collected from natural populations and commercialized locally for the cosmetic industry (e.g., soap manufacturing) and diverse food applications including products other than oil, such as pulp flour [11,23]. Interestingly, all fruit fractions are currently used as animal feed, energy carriers, and fertilizers, as is the case in Paraguay. In this country, the industrial use of *A. totai* fruits has been in place since the 1950's [13] with processed volumes of biomass declining during the last decades. In Paraguay, the estimated supply of acrocomia fruits from natural *A. totai* populations for oil extraction ranged from 50,000 to 100,000 tons between 2010 and 2016 [23,121]. The estimated volume of kernel oil (main product) produced in Paraguay during this period fluctuated between 3,000 and 6,000 tons, and annual exports varied from 700 to 2,500 tons [23,97,121,122].

Opportunities

- **Local markets.** Domestic markets for novel acrocomia-based products have high potential to incentivize the development of value webs, as market and consumer acceptance already exist. As such, acrocomia could support self-sufficiency at local level through regional value chains.
- **Sustainable vegetable oils for bioenergy, non-premium and premium products.** Oils are considered the main products from acrocomia and drivers for market entry [27]. Industrial sectors that use inputs derived from vegetable oils for food and non-food application are key to creating demand for acrocomia-based products [27]. From an energetic-use perspective, biodiesel and jet biofuel are the applications with highest potential as complementary and future substitutes for fossil fuels [27]. In fact, bioenergy is one of the drivers of increasing acrocomia research in Brazil. However, high volumes, competitive prices, and continuous supply are critical aspects for this sector [123]. Moreover, diversifying markets in biodiesel production systems is fundamental [123]. The non-energetic applications of acrocomia oils at an industrial level could include companies that use vegetable oils as their main input but are looking for alternative oils motivated by sustainability concerns [27]. Examples include transnational food companies with large product portfolios highly dependent on a small number of biobased inputs, where any alternative oils must meet similar requirements to those used currently in terms of volumes, continuous supply, price, and quality. On the other hand, companies that primarily focus on particular characteristics of oils and derived products for 'premium' applications are of high interest for acrocomia value webs targeting specialty products. This segment includes companies from the cosmetic and organic food sector with a relatively niche market who place more emphasis on specific oil properties and quality aspects. The higher value and prices of oils in e.g., cosmetic and pharmaceutical sectors, can determine their final market in these industries contrary to bioenergy [16,123].
- **Resource efficiency and cross-sectoral approaches for a sustainable value web.** Rather than a value web specializing in a single oil type, multiple products should be considered. The valorization of by-products as a resource efficiency strategy leads to value webs with manifold intermediate or final products for various sectors. Cross-sectorial approaches and linkages with geographically proximal markets are thus crucial for the success of acrocomia-based biorefineries with a multi-product business model based on diversification and flexibility as business strategies. Moreover, value streams from carbon sequestration by acrocomia palms and the provision of

ecosystem services should be integrated when defining business models and value web strategies. A sustainability orientation at the core of novel acrocomia value webs can represent a differentiation strategy in a world market needing to shift from 'business-as-usual' and increasingly tending towards sustainable practices and suppliers. Creating ecological, social, and economic value, necessitates the development of governance strategies towards social inclusion, fair trade, the reduction of structural barriers, the higher participation of farmers in value-adding activities, and the avoidance of negative impacts on the environment. The certification of sustainability standards and the regional designation of origin are two possible mechanisms to differentiate acrocomia-based products on the (international) market [124].

Challenges and Demands

- **Cultivation inputs and supporting services.** Emerging plantations rely on the use of genetic resources from natural stands with high genetic variability. Indeed, the lack of commercial varieties tailored to final applications and desired characteristics is a bottleneck to cultivation. Long-term efforts on plant breeding and close, continuous interaction with actors from the market are necessary to ensure the quality of biomass and derived products. Developments are required for providing supporting services, such as seedling production, cost-efficient planting material provision, and capacity building for technical assistance on crop management, including phytosanitary aspects and harvesting [16]. Technical support on the sustainable management of integrated agricultural systems and low-input farming systems is key. In addition, guidance on sustainable and multi-product business models for acrocomia growers and inclusive strategies (financing, value governance strategies) are extremely important for the integral sustainability of primary producers. Accordingly, knowledge and innovation transfer from research to the agricultural market is paramount.
- **Quality, market acceptance and competitiveness.** In existing acrocomia value chains for oil production, biomass purchasing prices are low and fruit quality is neither controlled nor fully incentivized. This results in the low quality of final products and the loss of opportunity and competitiveness on the market. In addition, international market prices for competing products, such as African palm oil, put high pressure on the price of acrocomia oil, in turn leading to the reduction of costs. The establishment of processing facilities is a key aspect for advancing acrocomia cultivation. The simultaneous market acceptance of products and an aligned agenda that intertwines biomass requirements, (pre-) processing features, and market needs, are also necessary.
- **Processing technology implementation.** Advanced integrated technologies are required to broaden value-adding possibilities in the processing of acrocomia fruits beyond oil extraction, e.g., by biorefining oils and residual fruit fractions. Accelerating technology development and transfer to established and new processing facilities and industrial clusters is necessary in parallel to cultivation activities to develop a market for acrocomia. In this regard, existing acrocomia low-tech processors that operate mainly at small-scale are important industrial actors to pull the demand for acrocomia fruits. Utilized conventional processes (e.g. mechanical oil extraction and fruit fractions' separation processes) can be upgraded towards more efficient up-, mid and down-stream processes, higher quality control, and novel products.

3.2.3. Government

National and regional public organizations play an important role in funding research, creating an enabling environment, and establishing governance mechanisms to ensure the sustainable deployment of acrocomia value webs, including their social-ecological embeddedness. Public entities can contribute to strengthening the demand for acrocomia-based products and support cultivation activities and emerging industrial clusters. Governments are key to preventing negative externalities and addressing potential market failures. They are also influential in setting conditions that enable the open participation of local communities in decision-making processes and issues related to natural resource management and biodiversity conservation, land use, rural development, and social well-being. The following points summarize key aspects identified by the workshop participants that require public sector action for the development of acrocomia value webs.

Advances and Opportunities

- **Biodiversity for local bioeconomy systems and value webs.** The sustainable use and protection of biodiversity as part of the bioeconomy have gained importance at national level in a number of Latin American countries as a pathway towards social-ecological transformation. Various strategic programs have been developed to strengthen national innovation systems, considering the socio-economic relevance of agriculture, the importance of a multi-sectorial perspective, and the abundance of natural wealth. This has contributed to scientific progress on biodiversity, building on traditional knowledge and the local use of natural resources to develop knowledge-based and sustainable bioeconomies. This is the case for acrocomia in Brazil, where publicly funded research has led to a strong scientific network in specific regions. Consequently, today *A. aculeata* is a semi-domesticated plant with multiple explored uses, with first plantations in the process of being established by entrepreneurs (i.e. commercial players). This can serve as a model for other countries with a natural occurrence of acrocomia species [27]. International funding mechanisms have a significant role to play in supporting plantation initiatives, as has been reported in Paraguay, Brazil, and Costa Rica [6,23,31,116].

Challenges and Demands

- **Market regulation.** Further enabling mechanisms from the public sector for the development of acrocomia value webs could be aimed at incentivizing the demand for products in national markets through the promotion of consumption of products from local biodiversity, and establishing appropriate regulatory frameworks for novel products. For instance, current international restrictions on novel foods create hurdles for the market introduction of food products from acrocomia. In addition, the provision of technical assistance for smallholder growers of acrocomia palms requires governance strategies with the participation of public agricultural entities.
- **Regulatory frameworks, policies, and governance.** The development of regulatory frameworks at regional, national, and international level, to ensure sustainable acrocomia deployment at cultivation, processing, and trade stages, requires the attention of actors from both academic and public sectors. This includes the design of policies and arrangements to regulate the expansion of acrocomia planting areas to avoid potential land-use-change impacts, land tenure issues, adverse effects on food security through the replacement of established food crops, biodiversity loss, and depletion of abiotic resources. Here, private-public partnerships in the form of national or international roundtables or multi-stakeholder initiatives are needed, with a strong contribution from acrocomia value-web stakeholders. Out of these, regulatory trade frameworks at international level for cross-border value chains may be developed [124]. Additionally, institutional arrangements should be implemented to foster the

inclusion of smallholders in value chains and webs and promote their economic viability. Examples include the 'pro-macauba' law (Law No. 19.485/2011—Pró-Macaúba) [125], the 'Minimum Price Guarantee Policy for Sociobiodiversity Products' (PGPM-Bio) [126], the 'Social fuel stamp' (Selo Biocombustível Social) [127], and the National Program for Smallholders Strengthening (PRONAF) [128] in Brazil.

3.2.4. Farmers and Civil Society

Farmers and civil society are two key stakeholders in the supply of biomass, the consumption of biobased products, the election of political agendas that foster the local bioeconomy, and the acceptance of biomass-based value webs. In addition, non-governmental organizations can contribute to capacity building and promoting collective action to promote the adoption of novel livelihood options among smallholders. This section describes some aspects of high relevance elucidated during the multi-actor workshop that are related to farmers and civil society in the establishment of acrocomia value webs.

The adoption of acrocomia agroforestry systems by smallholders in Latin America is seen as a potential inclusive strategy for the cultivation of this crop and alternative income source [16,27,82]. Higher participation in value-adding activities beyond on-farm work could create more livelihood options and job opportunities in rural areas [82]. Here, collective action groups, such as farmer-based organizations, have an important role to play as platforms and networks for connection with other actors from the value web and promotion of smallholder-based agricultural development. This includes consultancy services, the delivery of technical assistance, training, and the representation of individual farmers in pricing and negotiation activities. Of all factors influencing the adoption of acrocomia, the 4-to-5-year period from planting until first harvest represents a major challenge. Therefore, strategies to enable access to inputs (e.g., planting resources) and to compensate for production costs during crop establishment are extremely important [8,15]. They include agroforestry systems (e.g., intercropping with other crops or integration into livestock production systems) and financial support mechanisms for the establishment of plantations. This is essential to ensure farmers' short- and long-term profitability, address opportunity costs, and increase farmer acceptance. Market development and consumer acceptance of, and willingness to buy, acrocomia-based products are necessary to avoid crop non-adoption and failure of acrocomia cultivation programs. Thus, innovative business models require the integration of a mixed portfolio of price-competitive products with a positive sustainability perception on local and international markets, and products that increase farmers' self-sufficiency (food, animal feed, fertilizers, energy, materials, etc.). The cultivation of native plants like acrocomia can contribute to fulfill local needs and traditional services, while potentially reducing the dependency on external planting material and technologies [8]. The use of decision support tools is recommended to estimate productivity land use scenarios for acrocomia cultivation [28,32]. Strategies such as the establishment of model farms based on acrocomia can help to explore adoption scenarios, raise interest, and encourage farmers and stakeholders to introduce the crop.

3.3. Developing Sustainable Acrocomia Value Webs, a Challenge beyond the Introduction of a Novel Crop: R&D Roadmap

The development of biobased value webs as multifunctional, multi-actor, and social-ecological systems [129–131] requires a systems approach to research and innovation [132,133]. The introduction of novel crops, such as acrocomia and their derived production systems, is part of the transition towards a sustainable bioeconomy, for which integrative, participatory, long-term, and precautious thinking is a prerequisite [4,8,132,134–137]. Incorporating sustainability aspects, understanding interlinkages in the value web, and designing solutions suitable to context conditions are fundamental steps from early stages of research and development (R&D). This involves intertwined and interactive processes that combine multiple factors (ecological, biological, policy, economic, social etc.) and diverse stakeholder objectives [132,138]. Such interaction, and multidimensionality, was evidenced in the dialogue between academic and non-academic actors, confirming the nexus of research and development stages. In fact, such novel industrial crops are subject to the 'chicken-and-egg' dilemma between cultivation and commercialization, which also stresses the relevance of a systems perspective on crop management, post-harvest, processing and product development [138,139]. The systems approach is also underlined by acrocomia's multipurpose characteristic in terms of products (i.e., food, feed, fuel, and materials) [6]. A systems approach can facilitate a 'nexus and resilience thinking' [33,129] and contribute to addressing the complexity of novel multi-purpose crops and derived value webs, as well as to understanding interdependences of a production system with biophysical, social, technical, and ecological elements [129,140]. The systems, components, and systems' boundaries need to be defined, and the interactions, desirable, and undesirable system outcomes, need to be analyzed. Based on the workshop results, we define the system as an acrocomia value web oriented towards sustainability, and composed of biomass production, processing, and alternative uses, as depicted in Figure 4.

This would allow the understanding of interlinkages between different biomass use pathways, value chains, and products. Moreover, it integrates stakeholder interactions as well as ecological, social, and economic relationships [34,130,131]. The conceptualized acrocomia value web is considered a territorially embedded social-ecological system, additionally suggesting the need for territorial approaches to the governance of these systems [129,130,132,141]. Context-dependent factors and territorial settings (e.g., biophysical, socioeconomic, stakeholders' norms, and values) require active consideration in the design and development of acrocomia value webs as there are no 'one-size-fits-all' solutions [5,108,132,142–144].

3.3.1. Fostering Multi-Actor Collaboration in the Acrocomia Value Web

Stakeholder involvement, multi-actor collaboration, and a partnership approach to research and innovation have been highlighted as fundamental aspects in the context of agricultural and bioeconomy development [35,36,132,133,145–147]. The establishment of a bioeconomy requires collaboration not only between research organizations, but also between government agencies, enterprises, farmers, civil society, and education and training providers [148,149]. The complexity of challenges identified in the multi-actor workshop indicates the importance of collaboration to overcome them. Figures 4 and 5 depict such a multi-actor collaboration approach to the acrocomia value web development.

The analysis of the acrocomia research landscape indicates low connectedness between the diverse research networks, a large number of key actors mainly affiliated to Brazilian research organizations, and, to some extent, a lack of integration and inter- and transdisciplinary approaches. This evidences the limited interaction between research networks working on different key areas of acrocomia value web development and the existence of 'knowledge islands' both geographically and thematically. This could be due to the relatively young but evolving status of acrocomia research [6,109]. A collaborative approach is required to integrate research topics and strengthen the interaction between research networks, fostering interdisciplinarity rather than building on individual perspectives and envisioning sustainable, knowledge-based acrocomia value webs. Thus, it is key to couple fundamental and applied research from the characterization of genetic resources to cultivation (biomass development, see Figure 5), and from upstream to downstream value-adding processes and products (value web development, see Figure 5), as well as the mobilization of the knowledge base for innovation [132]. Moreover, other research areas beyond the productive viewpoint should be integrated, such as biological and ecological (botany, taxonomy, plant ecology, distribution, conservation), as well as social (cultural aspects, ethnobotany) perspectives. In addition, a transdisciplinary approach can contribute to fostering participation, understanding context conditions for acrocomia value web development, co-creating solutions, and transferring knowledge. While multi- and interdisciplinarity refers to collaboration between different disciplines to solve a problem from the perspective of each discipline, a transdisciplinary innovation approach is based on the integration of knowledge from various disciplines and practitioners [150]. It is embedded in a practical context, aims to solve a complex problem, and entails all actors learning from each other [150,151].

The multi-actor workshop contributed to the fostering of collaborations between experts from different disciplinary fields and regions, but also with actors from the industrial sector. This contributes to overcoming bottlenecks such as disciplinary silos and limited collaboration [152]. Partnerships approaches to research and innovation [132,133] can enable the establishment of 'innovation systems on acrocomia' [153,154]. The increase in scientific research on acrocomia, specifically *A. aculeata*, has been driven by the public sector's interest in the palm as an alternative bioenergy source [6] given the potentiality of acrocomia for biodiesel production [11], for which it is crucial to ensure an abundant biomass base by means of cultivation. A regionally concentrated knowledge base on acrocomia in the state of Minas Gerais (Brazil), public-private endeavors (e.g., the 'Macauba Research Network'—REMAPE [15,155], which integrates research organizations and investors such as Embrapa and Petrobras), and emerging entrepreneurial initiatives have favored an enabling environment for the semi-domestication and early-stage introduction of *A. aculeata* [6,8]. A suitable regulatory framework and incentives for the production of acrocomia-based products (e.g., the National Program for the Production and Use of Biodiesel (PNPB) in Brazil and related blending mandates [156]) can reduce uncertainties and foster crop adoption and processing initiatives [149]. Financing the value web development requires public-private partnerships and the support of multilateral organizations, development agencies, and the third sector [149].

Innovation systems concepts applied in the context of the bioeconomy, such as 'National Innovation Systems' [35] and 'multiple helix models of innovation' (triple, quadruple, and quintuple) [157], serve as a blueprint for the development of sustainability-oriented acrocomia value webs. The 'quintuple helix' innovation model, for example, adds the fifth helix of 'natural environment of society' to the previous 'university-industry-government-civil society' constellation, with the aim of directing innovation towards social-ecological transformation [157,158]. This innovation model can contribute to put environmental protection at the core of knowledge production activities. In addition, it could serve to the imperative of incorporating stakeholders' multiple value perspectives, conditions and needs (e.g., conservation strategies, ecological boundaries, smallholder farmer inclusiveness, provision of livelihood options, and intrinsic value of native plants for local communities in terms of food, feed, and energy self-sufficiency) for responsible and inclusive research and innovation on acrocomia [36,108,143,144,159–161].

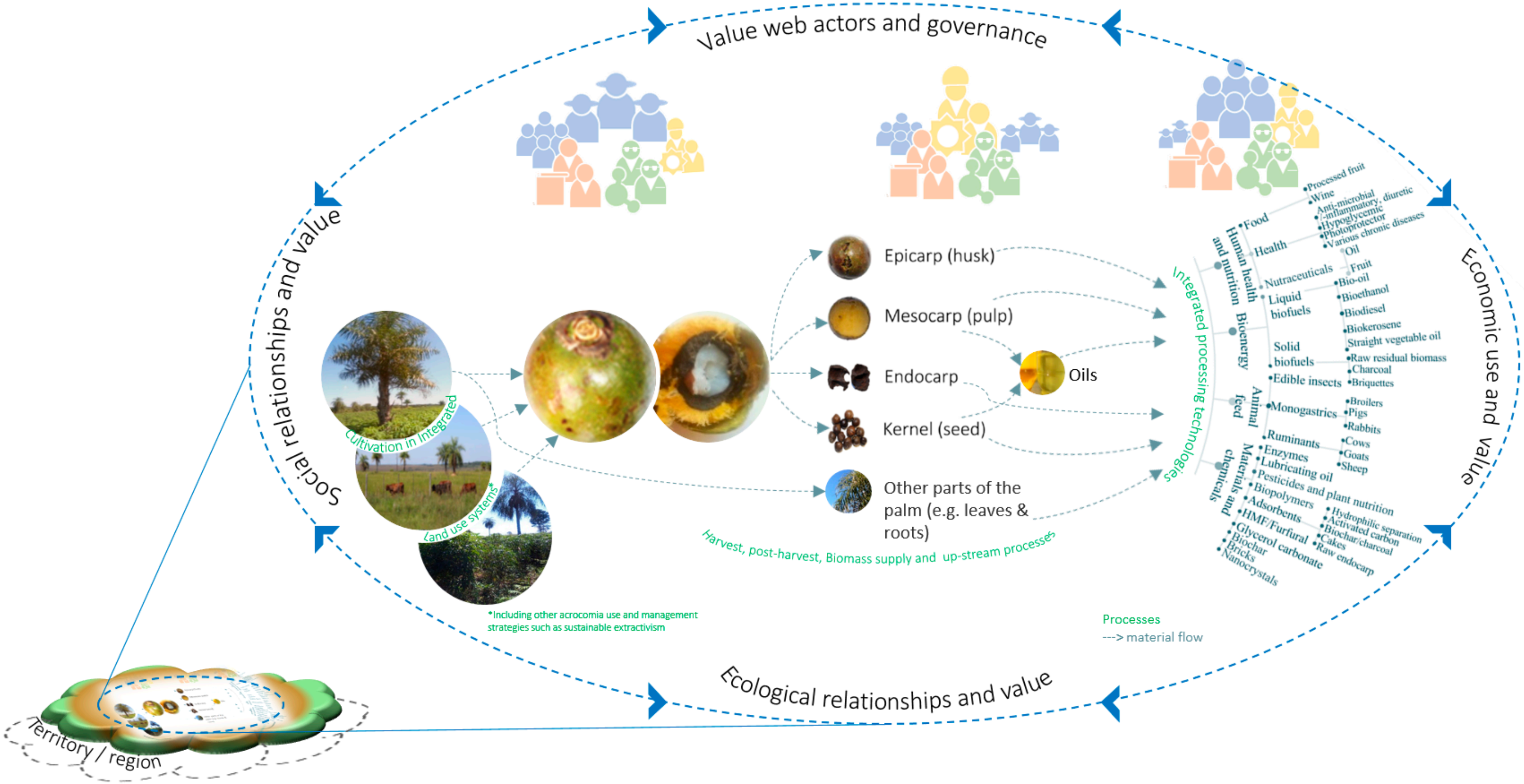

Figure 4. Conceptual acrocomia value web, territorially embedded. It displays: (1) the actors — farmers ; civil society: ; industry and business associations: ; government: ; research organizations: — involved and their relative importance (icon size) along the value web; (2) the material flows, from biomass production, through processing to a range of investigated applications using oils, fruit fractions and by-products; and (3) context factors that influence and interrelate with the value web system. The dotted boundary lines represent the openness of the system in terms of flows (material, information, funding, knowledge), relationships with external systems (biophysical, social, economic), and actors. Adapted from [6,130].

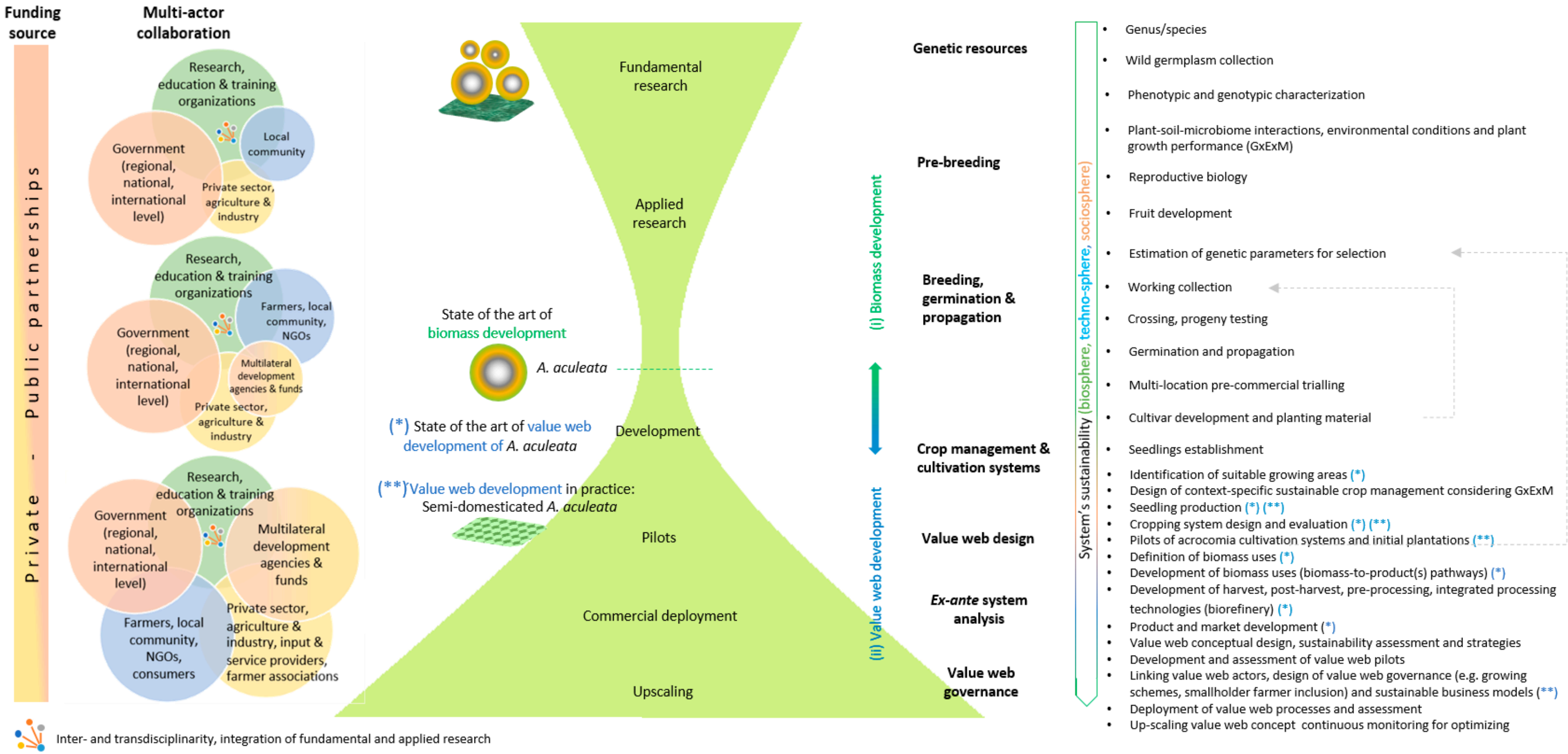

Figure 5. Sustainability-oriented R&D acrocomia roadmap integrating (i) biomass development and (ii) value web development, along with multi-actor collaboration (green, yellow, blue and orange circles represent the actor groups, i.e. research organizations, industry and business associations, civil society and farmers, and government, respectively) and financial support (yellow and orange represent private and public funding respectively). The funnel shape indicates the development process and the availability of funding. The knowledge base has boosted the biomass development level of acrocomia for its introduction as a novel crop. Simultaneous research activities are contributing to advance the value web development (*), while practitioners contribute to the demonstration and upscaling of acrocomia value webs (**). Initial plantations and the early-stage establishment of value web relationships are led by entrepreneurial initiatives in Brazil (*A. aculeata*). Similarly, cultivation of *A. totai* is being promoted in Paraguay, despite the lack of a solid knowledge base on biomass development. Existing value webs based on wild-growing acrocomia palms (e.g., in Paraguay and Brazil) should be integrated into the R&D roadmap to achieve their transition to cultivation systems, the implementation of sustainable management plans of wild populations, and upgrading strategies along the value web. Adapted from [6,134].

3.3.2. Considerations on Biomass Development and Upscaling to Ensure the Resource Base

The development of novel perennial crops with a sustainability orientation is especially challenging considering the long R&D processes, potential failures in breeding, market uncertainty, and sustainability expectations [134]. In such cases, long-term planning and continuous financing of research-based programs involving public, private, and third sectors, are required throughout the innovation pipeline, as illustrated in Figure 5 [134]. Public funding is extremely important to cover the high costs at early stages of research and crop establishment [134]. Given the value that acrocomia can represent for society and nature if produced sustainably, prioritization and resource allocation at regional, national, and international levels are necessary to advance knowledge, mitigate risks, and avoid potential failures. The increase in scientific research on acrocomia, specifically *A. aculeata*, has been driven by the public sector's interest in the palm as an alternative bioenergy source [6] given the potentiality of acrocomia for biodiesel production [11], for which it is crucial to ensure an abundant biomass base by means of cultivation. So far, public-funded fundamental and applied research has bolstered preparedness of *A. aculeata* for cultivation [6,27]. This species has been extensively studied, resulting in accumulated knowledge mainly on its specific biology, genetic and phenotypic characterization, germination, and propagation [6]. This has triggered the establishment of initial plantations of *A. aculeata* in Brazil by private actors, backed by scientific research and supported by multilateral funds for value web development and climate-oriented initiatives [6], indicating that –in Brazil– the species is transitioning from wild exploitation to a semi-domesticated status and initial cultivation. In addition, cultivation of acrocomia by smallholder farmers is being promoted in Paraguay and Costa Rica, led by local and international organizations from the public, private, and third (e.g., NGOs, farmer-based organizations) sectors, as well as research institutions [23,27,116]. Planting material for plantation establishment is currently being sourced from natural high-performing acrocomia populations in the form of seeds to be germinated according to the germination protocol [52] in Brazil, or plantlets that are then taken to tree nurseries in Paraguay. These can be seen as strategies in the transition towards domestication; the latter corresponds to the most advanced phase in the palm management spectrum [162,163] and highlighted as a research goal in the Brazilian bioeconomy [149]. Other acrocomia management strategies to be integrated into R&D include the sustainable use and management of natural stands of acrocomia palms by farmers for different purposes (i.e., subsistence at community level, small-scale processing, and marketing) through e.g., non-timber forest products (NTFPs), and integration in agroforestry cultivation [27,162–168].

Value-generation activities for acrocomia-based products and upscaling will be influenced by progress on domestication, quality of planting material, sustainable and diversified cultivation systems, and adequate harvest and postharvest practices [15]. Ongoing research and innovation on the development of high-quality planting material addressing multiple objectives (yield stability, adaptability, water and nutrient efficiency, biomass properties and uses) have the potential to boost the cultivation of *A. aculeata*, possibly serving as a model for other acrocomia species of interest in other regions of Latin America [6,27]. In this way, rather than specializing on a few acrocomia cultivars in Latin American regions, territorially embedded production systems based on local acrocomia species/ecotypes that grow in specific biogeographic regions and are genetically diverse provide a strategy for crop adaptability, low-input and resilient cropping systems, physiological suitability, genetic variation and biodiversity conservation, and fulfillment of local needs [8,11,15,96,97]. Breeding activities and planting material should be tailored to site-specific conditions and factors, products, and crop management needs.

The exchange of information and identification of (farmer, market, landscape) needs [138] necessitates connecting stakeholders, working on biomass production R&D with those focused on conversion technologies and applications. In addition to advances in planting material, other areas that require further attention include the upscaling of cost-effective seedling production, agronomic aspects, crop management, and integrated cropping systems (i.e., agroforestry), thus tailoring agricultural production systems to biophysical context and sustainability conditions. For instance, suitable management strategies of agroforestry systems are key for ensuring high biomass yields, land and biodiversity restoration, and a heterogeneous agricultural landscape, supported by adequate contractual arrangements [45]. Farmer training on cultivation, crop management, and harvest and post-harvest methods, can promote the transfer of knowledge to ensure sustainable agricultural practices and high-quality fruits in terms of processing and product requirements [82,149]. With the goal of avoiding direct and indirect land-use change impacts, integrating acrocomia palms into pastures for livestock is considered a promising strategy that can contribute to both landscape restoration and the sustainability of animal production systems, two of the Brazilian bioeconomy priorities [149]. The determination of agricultural areas for the sustainable expansion of acrocomia is necessary to avoid negative impacts on land use [8,149].

Data and experience from both initial acrocomia plantations and the analysis of existing and emerging value webs can contribute to the adaption of related processes and governance to local conditions (i.e., adaptive research) [142]. For this, close contact between research organizations and actors involved in acrocomia cultivation, such as private businesses, the public sector, farmer-based organizations, and pro-rural development NGOs, is fundamental. Positive hopes and expectations of acrocomia require scientific validation to prevent both crop failure (due to low performance) and the failure of promotion programs. Scientific evidence can help guide investment and policy decisions regarding acrocomia cultivation. Prior to mass-scale cultivation, it is necessary to test the suitability and performance of acrocomia under the biophysical conditions of different bio-geographic regions, taking into account its eco-physiological requirements and aiming to develop more sustainable agricultural systems. Evidence-based and precautious (ex-ante) approaches are required to avoid undesired ecological impacts in biodiverse tropical and subtropical ecosystems [8]. In addition, integrated sustainability assessments of acrocomia production systems are required to elucidate benefits and impacts in order to compare these with other multifunctional crops and identify strategies for sustainable intensification systems. In this way, farmers can be informed of diversification advantages, productivity, management requirements, and the costs of acrocomia cultivation, based on scientific evidence and accumulated experience from on-going cultivation initiatives.

In addition to fair prices for the biomass, farmer involvement in value-adding activities in the acrocomia value web (i.e., pre-processing of fruits) and eventual compensation for ecosystem services can contribute to diversification strategies at farm level [169]. Therefore, programs that promote the adoption of the crop should extend their scope to the industrial processing and marketing of acrocomia-based products [169]. Moreover, it is recommended that value web governance strategies involve a plurality of actors, including government, multilateral organizations, businesses, farmers, the third sector, and civil society (i.e., local community). Such governance strategies should include institutional arrangements to ensure inclusiveness, transparency, cooperation, and sustainability [149]. For acrocomia value webs to be inclusive, structural barriers to the participation of smallholder farmers in value added-stages must be avoided [170]. Combined government, market, and third-sector (civil society, NGOs) governance strategies, should be considered to address failures in aspects including input supply, technology access, and extension services [15,30].

3.3.3. Considerations on Processing, Product Development and Markets

To date, acrocomia is unfamiliar to many industries despite its multipurpose potential, foreseen productivity, and sustainability advantages. Its commercialization is mainly hindered by: the uncertainty and limited development of plantations in productive phase as well as the lack of detailed information on ecophysiological requirements and environmental influence on plant performance; information on cropping systems and sustainable cultivation practices; high performing planting material and seedling production; yield and biomass composition predictability; standardization of efficient harvesting and post-harvesting processes to ensure high quality biomass; biorefinery development, product, market, and value chain development, and the sustainable and inclusive business models that ensure economic viability (considering that the productive cycle starts after five years from plantation establishment); environmental feasibility; and social benefits [6,8,16,23,27,82,96].

The acrocomia R&D agenda's top priorities center on the involvement of industry partners from various sectors. Key to the development of acrocomia value webs with a biorefinery approach is the aim of making use of the complete fruits. Accordingly, integrating knowledge and efforts from diverse research networks specializing on specific applications is necessary to analyze the advantages and trade-offs between alternative uses of oils and other fruit fractions. Despite the prospect of acrocomia as a bioenergy crop, the increasing interest in non-energetic acrocomia products has resulted in research networks dedicated to applications for the human health and nutrition sectors, as well as animal nutrition, biobased chemicals, and diverse materials [6]. In fact, existing acrocomia value chains have primarily focused on non-energetic uses of fruits and oils for cosmetic and food applications, possibly due to the low processing technology required, the market existence, higher oil prices for cosmetic and pharmaceutical applications [16], and the adaptability to operate with a limited quantity and quality of biomass sourced from natural plants. Technological advances on biomass production, fruit handling and (pre-) processing and knowledge on properties of acrocomia products could contribute to upgrade existing value chains.

Advancing integrated processing technologies and applications of fruits and individual fractions is crucial to promote industrial demand for acrocomia in a way that addresses the chicken-egg dilemma between cultivation and commercialization from an early stage of development. Key steps towards the deployment of acrocomia value webs include the development of biorefinery concepts based on the most promising biomass-to-product(s) pathways, considering biomass availability and quality, sustainability aspects, market, and local needs. Consequently, the conceptual design and development of integrated pilot processing plants would allow a higher technology readiness level to be reached, applying accumulated knowledge and the principles of cascading use of biomass [6]. Complementary, sustainable business models along value-adding processes are fundamental to ensure innovation uptake, environmental feasibility, social desirability, and techno-economic viability. Sustainability and techno-economic assessment of biomass production and supply, processing, and products, is essential to continuously monitor the system's performance.

Technology targets for the design of integrated processing systems such as small-scale and decentralized biorefineries should consider the context factors and reflect market needs. The tailoring of applications of oils, oil derivatives, and biobased products from acrocomia fruits will help ensure market acceptability. Existing small-scale value chains and local markets for acrocomia-based products (e.g., oil extraction for soap production and food applications, pulp flour for baking, use of by-products as animal feed, energy, and fertilizer) could benefit from these upgrading strategies and promote their demand, favoring the implementation of short, local, and circular acrocomia value webs. Therefore, the definition of a biorefinery's product portfolio requires the incorporation of local industry players and consumers. In this way, potential biorefinery facilities could be set in close proximity to the market.

4. Conclusions

The analysis and characterization of research networks that have contributed to the advancement of scientific knowledge on acrocomia, and the empirical evidence collected during the multi-actor workshop, indicate the importance of a collaborative, systems approach to research and innovation in the development of acrocomia value webs. This suggests that interventions need to be interconnected and formulated for the whole acrocomia value web system, considering the existing nexus between biomass resources, processing technologies and products, actors and governance, and context (ecological, social, socioeconomic, institutional and technological). Presently, *A. aculeata* is at the transition from applied research to development driven by science, public-sector interest, and entrepreneurs. There are still key R&D activities required before acrocomia can be commercially deployed through value webs, and these require broad collaboration between research organizations, the public and private sector, farmers, and civil society. We contributed to this endeavor by enabling multi-actor collaboration and engaging academic and non-academic stakeholders in an inter- and transdisciplinary dialogue around acrocomia. This collaborative space helped stimulate stakeholder involvement, knowledge sharing, formulation of research questions, and the defining of interdependencies. The identification of research networks and the realization of the multi-actor workshop resulted in a R&D roadmap that serves as a basis for further collaboration. This could lead to the establishment of regional and national innovation systems with a broad range of stakeholders. The development of acrocomia value webs should be oriented towards a sustainable vision shared by all stakeholders involved that lays down the principles necessary to avoid failure of this promising crop. These principles should include the imperatives of biodiversity and climate protection, social inclusiveness, carbon neutrality, and human wellbeing. Active consideration of context specificities, the incorporation of sustainability criteria, and multidimensional assessment, are key aspects in the design and development of the value web to ensure its integral sustainability. Here, the involvement of stakeholders, the fostering of collaboration, and a systems approach to R&D, are fundamental. From a methodological perspective, we contributed to advancing the practicability of the biomass-based value web framework. Involving actors through participatory methods and integrating the research dimension in the analysis can foster the development of knowledge- and biomass-based value webs.

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