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Addressing Stakeholder Concerns Regarding the Effective Use of Bio-Based and Biodegradable Plastics

Carly A. Fletcher [1,*], Karolina Niemenoja [2], Rhiannon Hunt [1], Jill Adams [2], Alan Dempsey [1] and Craig E. Banks [1]

[1] Faculty of Science and Engineering, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, UK; rhiannon.hunt@mmu.ac.uk (R.H.); a.dempsey@mmu.ac.uk (A.D.); c.banks@mmu.ac.uk (C.E.B.)

[2] Prospex Institute, Victor Oudart Str. 7, 1030 Brussels, Belgium; karolina.niemenoja@prospex-institute.org (K.N.); jill.adams@prospex-institute.org (J.A.)

* Correspondence: carly.fletcher@mmu.ac.uk

Abstract: Bio-based and biodegradable materials have the potential to replace traditional petroleum-based plastics across a range of products and contribute to a more circular economy. However, the uptake of these materials will not succeed unless consumers, manufacturers, and regulators are convinced of their efficacy. Investigating performance and safety concerns put forward by academic and non-academic communities, this paper assesses whether these concerns are being adequately addressed by current policy and regulation. In addition, measures to overcome significant concerns are developed through a series of stakeholder engagement events, informed by the Prospex-CQI- and STIR methodology. Discussions across the stakeholder engagement events have highlighted several concerns that create barriers to market up-take of bio-based and biodegradable plastic products, including the continued confusion regarding terminology and resultant communication, difficulties in navigating the plethora of documents related to safety, the appropriateness of safety documents when applied to new products, and the overall suitability and sustainability of such materials as an alternative to traditional plastics. To overcome these concerns, a series of recommendations for research, policy, and practice are made with respect to the following key areas of concern: regulation and legislative instruments, material quality and performance, market penetration and availability, waste management infrastructure, sourcing and supply chain, communication and information provision, and material health and safety.

Keywords: bioplastic; bioeconomy; safety; efficacy; stakeholder engagement; CQI methodology; virtual workshops

Citation: Fletcher, C.A.; Niemenoja, K.; Hunt, R.; Adams, J.; Dempsey, A.; Banks, C.E. Addressing Stakeholder Concerns Regarding the Effective Use of Bio-Based and Biodegradable Plastics. *Resources* **2021**, *10*, 95. https://doi.org/10.3390/resources10100095

Academic Editors: Eleftherios I. Thalassinos, Noja Grațiela Georgiana and Mirela Cristea

Received: 13 August 2021
Accepted: 16 September 2021
Published: 23 September 2021

1. Introduction

Through the Bioeconomy Strategy, the European Union (EU) has acknowledged the importance of natural resource management as a way to reduce global dependance on non-renewable resources, address climate change, and strengthen industrial competitiveness [1]. The Bioeconomy Strategy, by delivering innovative solutions, contributes to the Green Deal, sustainable development, and the transition to the circular economy [2]. Highlighted within the bioeconomy action plan is the development and deployment of bio-based and biodegradable solutions [3]; this paper focuses on one suggested solution—the substitution of petroleum-based plastics with bio-based and biodegradable plastics (herein, BB-P/BD-P) [4].

By incorporating bio-based materials in place of petroleum products, plastic production can be decoupled from the use of finite resources [5]. As the feedstocks for BB-P tend to be organic materials (such as crops, organic wastes, and algae), they can be classified as renewable [6]. In comparison, traditional plastic production relies on non-renewable, petroleum-based feedstocks, which are associated with additional negative implications,

such as increased carbon emissions [5,6]. Indeed, Andrady and Neal [7] suggest that, as petroleum reserves decline, plastic innovation will increasingly utilize renewable biomass as a feedstock. Furthermore, the use of BD-P may contribute to a more circular economy by presenting opportunities with regards to waste management (e.g., composting and anaerobic digestion), potentially addressing issues of persistent plastic pollution and reducing the proliferation of microplastics in the environment [6].

The benefits of using BB-P/BD-P, especially those that can be composted, have been acknowledged internationally. For example, they are referenced within the Sustainable Development Goals (SDG) published by the United Nations, namely, SDG-12 that focuses on "Responsible Consumption and Production" [8]. Pioneers within the circular economy space, the Ellen MacArthur Foundation, also acknowledge the potential role of such materials within the 'New Plastics Economy' strategy and 'Plastics Pact' [9]. However, to date, the uptake of BB-P/BD-P products has been largely limited to packaging, healthcare, and agricultural applications [10]. In some cases, the use (and promotion) of BB-P/BD-P has been accused of 'green-washing' [11,12]. 'Green washing' refers to actions taken by companies that inaccurately convey superior characteristics of sustainability through misleading claims (e.g., "eco-friendly"), symbols (e.g., use of leaf imagery), or color (e.g., use of green) [12]. It is argued within the EU Bioeconomy Strategy that, to realize the potential of the bio-based (and biodegradable) sector, careful promotion of accurate information regarding the positive impacts is needed, as well as an equal footing regarding market and regulatory conditions vis-à-vis petroleum-based industries [1].

This paper seeks to identify and overcome barriers to uptake, specifically concerns related to a product efficacy. Here, efficacy is conceptualized as suitability for use and is based around three strands: technical performance, human health and safety, and environmental safety. This paper draws on academic literature, consumer awareness and expectations, industrial knowledge, and regulatory frameworks to investigate potential performance and safety concerns that may impact the uptake of BB-P/BD-P products. This paper is structured as follows. Section 2 provides contextual information, outlining the key concerns identified within academic and non-academic literature regarding the efficacy of BB-P/BD-P, highlighting existing policies and regulations that address these concerns. Section 3 details the methodology used to engage key stakeholders within the study, followed by Section 4, which presents the key topics of discussion from the four engagement events. Finally, Section 5 discusses the key concerns identified both in the literature and by the stakeholders and providing recommendations for further research, policy, and practice. A short conclusion is presented in Section 6.

2. Context

The use of plastics (of all types) is high on the political agenda, where the subject often touches upon a range of environmental, performance, and safety issues [13]. While most of these concerns are addressed within the policy landscape, consumer expectations and attitudes will likely have a long-term influence on market growth [13,14]. For example, consumers with pro-environmental values and purchasing behaviors may be predisposed to uptake BB-P/BD-P products. However, the purchase of such products may only materialize where these individuals are effectively informed about the environmental benefits of these materials and products. Furthermore, limited awareness of the environmental benefits of such products may limit these behaviors [14]. Conversely, overly optimistic consumer expectations about environmental performance, exacerbated through mis-information, could lead consumers to feel misled, risking negative long-term market repercussions [15]. The provision of accurate information and claims is especially crucial in the case of BB-P/BD-P, as improper handling and disposal can not only prevent the circularity of BB-P/BD-P from being realized but may also negatively impact on other material recycling loops. For example, as BB-P/BD-P are often visually indistinguishable from traditional plastics, their erroneous introduction into conventional recycling streams may render both types of materials non-recyclable. Thus, to promote and develop the market

for BB-P/BD-P products in the future, it will be imperative to identify (and address) issues related to environmental and safety concerns.

2.1. Concerns from the Academic Community

The increasing consideration of alternative plastics has been accompanied by a growing body of academic literature published over the last decade. Using the Scopus database (www.scopus.com; accessed 16 April 2021), relevant academic papers were identified using the umbrella term "bioplastic", nomenclature that commonly encompasses both bio-based and/or biodegradable plastics (this generic term also includes plastics that are biocompatible as well as those that are biodegradable but derived from petroleum feedstocks). Comparing studies published in 2020 with those in 2016 indicates that annual publications on the topic have almost doubled in the past four years and by a factor of five compared with 2011.

A prominent concern is the production and sourcing of BB-P/BD-P feedstocks. As noted by Acquavia et al. (2021) [6], most BB-P are produced from agricultural crop-based feedstocks. Due to the potential competition for arable land, fresh water, and food production, it could be argued that BB-P/BD-P have the potential to hamper the achievement of SDG-2 "Zero Hunger" and SDG-6 "Clean Water and Sanitation" [6], despite their positive contribution to SDG-12 "Responsible Production and Consumption". For example, by commandeering cropland for the production of feedstock, resultant increases in food prices may threaten the sustenance of poorer countries [16]. At the same time, limiting feedstocks to those grown sustainably and ethically could constrain the development and market growth of the bioeconomy by limiting availability and increasing prices [17]. Furthermore, Falcone and Imbert (2018) [18] have recognized that existing research (specifically that focused on social sustainability) has tended to focus on the worker stakeholder category (e.g., the "health and right of workers" is acknowledged as a commonly used indicator), whereas other consumer-based indicators such as community engagement are less frequently addressed. Acknowledging health and safety, as well as social acceptability concerns across a variety of stakeholder groups (especially consumers), is therefore key to resolving these complex and intertwined issues. Doing so will become increasingly pertinent for the development of effective public policies if they are to successfully encourage the uptake of BB-P/BD-P products [18].

In addition to these social issues, concerns regarding technical performance and mechanical properties also plague the uptake of BB-P/BD-P [19,20]. Disadvantages listed within the literature include reduced mechanical, thermal, and barrier properties against oxygen, water, vapor, microbes, light, and high humidity [21–23]. This is especially an issue when the use of BB-P/BD-P is considered for high-risk applications, such as food packaging [19,21,23]. Challenges within this category are further exacerbated by the consumer expectation that these materials will perform to, not only an equal, but a higher standard compared to traditional plastics [18].

The solution to address these issues and improve the functional performance of these materials is often the inclusion of additives (e.g., [20,22,23]). However, concerns regarding the impact of non-polymeric components (e.g., dyes) and other fillers and additives on performance and overall safety when applied to BB-P/BD-P have been raised [10]. Here, it is worth noting that in addition to any potential impact on performance, there are also implications to consider regarding environmental performance, a characteristic which is often promoted as superior in BB-P/BD-P. For example, Ferreira-Filipe et al. (2021) note that the addition of acetyl tributyl citrate or polyethylene glycol to improve the technical performance of PLA (polylactic acid; bio-based plastic) can have unintended implications regarding biodegradability and ecotoxicity, particularly when discarded in the open environment [24]. Furthermore, the state in which a plastic material remains over time can influence how it interacts with the environment [25]—a point particularly relevant for BD-P, whose degradability within the environment may influence the rate at which additives and other components are released into the ecosystem.

In addition, the compatibility of additives developed for traditional plastics (whose suitability is determined through the use of standards and regulations developed for traditional materials) is also questioned when applied to BB-P/BD-P [10]. This could also be true in the development, optimization and commercialization of new BB-P/BD-P through the blending of different polymers [19]. While it would be incorrect to assume that all manufacturers of BB-P/BD-P only use additives created for traditional plastics, new BB-P/BD-P formulations often rely on the use of pre-existing additives to enhance technical properties (P. Moreau, Natureplast: Personal Communication). This can possibly be attributed to the experience–investment cycles, where experience in using a solution (i.e., pre-existing additives) leads to more investment in that solution which leads to more experience, and so on [26]. Alternatively, the economic reality means that some additives can be produced much more cheaply using existing production pathways [27]. As traditional plastics have been on the market for a much longer time, the production of additives for this market has had longer to develop, benefitting from economies of scale. More recently, there has been traction in the development of alternative additives that are either bio-based and/or biodegradable. However, due to limitations regarding marketability on the account of cost and availability, only a limited number of these products have been developed to pilot plant scale, and even less have reached the market [28]. One example that bucks the trend is the development and uptake of 'bioplasticizers' to replace phthalate-based plasticizers in the production of PVC (polyvinyl chloride; traditional thermoplastic) [28]. Indeed, De Paoli and Waldmen (2019) envision a ban on petrol-based plasticizers and exclusive use of bio-based alternatives in the near future [28]. Furthermore, these 'bioplasticizers', originally developed for use by traditional plastics (in this case, PVC), are now being used as additives in the development of new BB-P/BD-P formulations [29]. Of course, it is not the additives themselves that ignites concern (as the additives would have been tested to ensure technical performance and overall safety), but rather their interactivity with BB-P/BD-P materials and subsequent suitability, as the tests used above to confirm suitability have been historically developed for assessment in combination with traditional plastics [10]. Indeed, while the uptake of BB-P/BD-P is expected to significantly increase in the coming years, these new materials must play catch-up against well-established materials that have been continuously refined within an industry that has decades of research, development, and dominating market presence behind it [24].

Additionally, as these new materials tend to attract attention from a greater proportion of health and environmentally conscious consumers, BB-P/BD-P seem to be held to a higher standard, which creates superior expectations and thus intensifies concerns over safety [10]. Related to this, concerns regarding the multifarious nature of the mechanisms used to govern BB-P/BD-P have been highlighted [11]. It is argued that policies surrounding BB-P/BD-P, in their current state, are neither stringent enough nor enforceable [11]. The current fragmented sectoral approach has been argued to result in a lack of international cohesion [30]. A review completed by Philp et al. (2013), identified a considerable list of international standards concerning the biodegradation of plastics (both petroleum and bio-based), highlighting a number of challenges for comparative assessment across claims and materials [4]. Challenges include the influence of different test environments (e.g., is it anaerobic or aerobic, within compost, soil, fresh or marine water, etc.) and the use of varying terminology, such as 'ready' vs. 'inherent' vs. 'complete' biodegradation [4]. A further challenge is in effectively communicating the relationship between biodegradability and compostability in sustainability claims [31]. Whilst all products that are compostable are also biodegradable, the reverse is not true, as not all biodegradable materials will degrade under composting conditions [4]. Furthermore, under most certification schemes, composting conditions allude to industrial composting rather than home composting, thus creating a further level of complexity for cohesion and accurate communication. The presence of multiple, individual, and inconsistent strategies and guidelines can create barriers to the successful uptake of new innovations and the realization of their

full sustainability potential [11,30]. Furthermore, the lack of feedback mechanisms for consumers to raise their concerns to producers and manufacturers, and to access accurate information, may also create a further barrier to end-user uptake in the future [18].

2.2. Concerns from the Non-Academic Community

It may be argued that non-academic literature, such as news articles, web-based blogs from media outlets, industry publications, and environmental influencers, have a greater impact on how consumers perceive the effectiveness and safety of BB-P/BD-P products. A search of this grey literature was undertaken (using a Google news search, using key terms; "bioplastic" AND "performance" OR "safety") to identify instances where the safety of such products has been discussed within the last five years (2017–2021). A total of 12 articles were selected, all written in English and covering a wide geographical area, including Canada, Australia, China, and the EU. Review of these documents identified three common themes of concern.

The first common theme was the perceived consumer confusion regarding terminology. Multiple sources [32–40] noted a number of terms (e.g., bio-based, bioplastics, biodegradable, compostable, recyclable, recycled content, bio-derived, etc.) used in the promotion of these products. As these terms all relate to slightly different things and are not necessarily interchangeable, their use may, at the very least, cause confusion and, at worst, be potentially identified as a misleading case of "green washing" [33,35,39,40]. Furthermore, Goldsberry's article in Plastics Today, noted a lack of education on the topic, such that consumers cannot make well-informed sustainable decisions due to lack of knowledge about the products being offered to them [33]. While efforts over the past five years have tried to demystify the terminology used, e.g., [36,40], this issue continues to be discussed up to the present day, e.g., [32], thereby indicating that the disconnect between information providers and consumers persists.

The second commonality questioned the legitimacy of environmental credentials that often endorse BB-P/BD-P products [32,34,35,37–40], particularly those concerning anticipated and actual end-of-life management. In addition to confusion surrounding terms, such as 'biodegradable' and 'compostable', and the impact the confusion has on the practical behavior of consumers, these articles also highlight availability and accessibility of appropriate end-of-life infrastructure as a key factor in preventing the realization of environmental credentials associated with BB-P/BD-P [32,34,38,39]. To elaborate, where appropriate waste collection and management systems are not available, the products may end up in landfill where, in the absence of oxygen, the biodegradation of these products may lead to the production of methane exceeding that produced by traditional plastics [40]. Confusion may lead to ineffective end-of-life management, and again a disconnect between the provision of information and the consumer may exacerbate this issue further.

The final common theme is focused on products that come into contact with food (e.g., packaging) [41–43]. These articles highlight the potential risks and other unintended consequences of replacing petroleum-based products for use as Food Contact Materials (FCM). Of particular concern is the risk of allergens and other chemicals that may impact food safety and consumer protection. Indeed, Morrison's article for the Food Navigator website highlights that some BB-P/BD-P may contain up to 20,000 different chemicals. Furthermore, it is argued that many of these chemicals are unknown and untested for safety [41]. While these articles do acknowledge that the same risks are likely present for traditional petroleum-based products, it is argued that a lack of research (specifically focused on BB-P/BD-P) makes knowing the true human health impacts of substituting petroleum-based products with these materials unclear [41–43]. Furthermore, food waste is a considerable environmental issue, resulting in a waste of natural resources, additional carbon emissions, and the generation of significant quantities of waste that local authorities must then manage. If BB-P/BD-P food packaging does not effectively protect food and keep it fresh, then further food waste may be generated, countering any environmental benefits gained by making the switch to BB-P/BD-Ps.

2.3. Relevant Mechanisms across the Policy Landscape

Despite their sustainability credentials, BB-P/BD-P remain subject to existing regulations. These regulations are optimized for existing materials on the market developed over many years. Additionally, as many BB-P/BD-P are new, innovative materials, legislation may lag or not be applicable/relevant, further hampering their uptake. As the trade of products is often based within a globally interrelated economy, robust and comparable methods are key to ensuring performance and safety [44]. The EU has been identified as one of the main international regulators: widely regarded as having some of the strictest public health and environmental safety regulations in the world [45]. Within the EU, safety is ensured through the interconnected use of directives, regulations, standardization, and protocols. While directives and regulations provide targets and overall objectives, standardization documents act in a complementary and practical role outlining rules or guidelines, providing definitions, or specifying methodological approaches [46]. Standards also ensure compatibility across network externalities, reduce (often negative) environmental impacts and can overcome information asymmetry between producers and consumers [47].

Within Europe, all products, regardless of type or function, must be shown to conform with the General Product Safety Directive (2001/95/EC) [48]. This means that they do not present any risks to human health/safety under normal or reasonably foreseen conditions. Safety issues tend to arise when increasing product complexity, competition-induced time and/or cost pressures, reduced understanding of new technologies (particularly concerning unknown features and impacts), and the use of products in unanticipated ways [49]. As such, producers are expected to take reasonable care to ensure the safety and performance of their product. For example, to show compliance with Directive 2001/95/EC, any product placed on the consumer market must fulfil certain requirements (laid out in laws, regulations, and standards) to identify all possible hazards related to the product across its lifecycle, making efforts to eliminate risks. Where a product fulfils these criteria, the CE (or European Conformity) mark is used as a declaration of conformity [48,49].

For products with a specific function or target consumer group, adherence with specific safety regulations is also required. For example, any product that encounters food must adhere with FCM Regulations, ensuring that all relevant materials (and subsequent products) are manufactured using Good Manufacturing Practices [50], and under normal conditions/usage, do not transfer their constituents to the food contained in quantities that (1) could endanger human health, (2) bring about unacceptable changes in composition, or (3) causes organoleptic characteristics (flavor, color, texture, etc.) to deteriorate [51,52]. While these directives, and associated standards and protocols, are applicable to a broad range of products, they have been developed (over a significant period) with respect to traditional materials. In contrast, those related to BB-P/BD-P are much more limited, and with respect to BB-P have been developed a lot more recently.

The first standardized test methodology for the biodegradability of plastics was published by the American standardization organization, ASTM, in 1999. Prior to this, several standards on the biodegradation of organic compounds had been published by the International Standard Organization (ISO) [31]. With the recognition that compostable plastics could contribute to the circular economy, current standards (e.g., ISO 14851 and ASTM 6400) have focused on aerobic degradation tests in (industrial) composting conditions [31]. The EU has also published a range of biodegradability standards that are specific to packaging materials, focusing on compostability and anaerobic digestion (e.g., EN 13432). These standards tie into existing labelling and certification schemes (such as the Seedling logo; https://www.european-bioplastics.org/bioplastics/standards/labels/; accessed on 25 April 2021, OK Compost label; https://www.tuv-at.be/green-marks/certifications/ok-compost-seedling/; accessed on 25 April 2021, and BPI compostable certification; https://www.bpiworld.org/Certification; accessed on 25 April 2021) to aid communication

between businesses and end-users. Of course, these labels only indicate the potential biodegradability/compostability of products and materials, and do not guarantee their ultimate destination or the availability of local waste management infrastructure.

While policy mechanisms to ensure product safety (applicable to most generic product categories) and to test biodegradability (of certain materials) have been available for decades, they have generally been developed (over many years) with traditional materials in mind. Whereas policy mechanism related specifically to bio-based materials are much newer. In fact, the release of Mandates M429 [53] and M430 [54] in 2008 launched the exploration and development of bio-based product standards by the European standards organization, European Committee for Standardization (CEN). In response to these mandates, CEN established the Bio-based Products working group (CEN/BT/WG 209), which in turn produced the CEN report "Bio-based products" [55]. Outputs from this report identified a wide range of stakeholders, analyzed the appropriateness of existing (non-specific) standards, and developed a programme of deliverables. Key recommendations were to publish the findings of the standards analysis and to develop standards specifically for bio-based products [55]. Subsequently, Technical Committee 411 (TC-411) was formed in 2011, and over a seven-year period developed ten standards specific for bio-based products [56]. As is the norm for CEN technical committees, the TC-411 was disbanded after fulfilling its original purpose to "develop standards for bio-based products covering horizontal aspects". The ten standards were concerned with: terminology (EN 16575), methods to determine bio-based content (EN 16766, EN 16785, EN 16640, EN 17351), environmental sustainability (EN 16751), application of Life Cycle Assessment (EN 16760), and the means of communication between businesses (EN 16848) and to the end-user (EN 16935).

This review of the literature (both academic and grey) suggests a number of perceived and actual barriers that may restrict market uptake of BB-P/BD-P in the future. Notable barriers include concerns regarding technical performance, continued consumer confusion regarding terminology, allegations of green washing, and an uncoordinated policy landscape. While is it interesting that existing policies, regulations, and standards have been promoted to counteract some of these barriers, there seems to be a disconnect between what the policy landscape attempts to address and the impact of actual implementation at the industry and consumer level. Furthermore, as these policy mechanisms introduced to address current barriers are often adapted from existing documents (that were developed for different scenarios/materials), this raises the question over appropriateness when applied to BB-P/BD-P. Considering the ongoing discussions regarding the efficacy of BB-P/BD-P products and acknowledging the vital (and often overlooked) role stakeholder groups have in resolving complex and intertwined issues, this paper reports on a series of stakeholder engagement events that were held to further explore existing concerns. The discussions held also sought to identify potential means to overcome or eradicate such barriers, underpinning key recommendations for research, policy, and (industrial) practice.

3. Methodology

Stakeholder engagement events (e.g., consultations and workshops) allow groups of key actors to address a domain-specific issue through innovation, creative problem solving, and knowledge sharing [57]. Due to the ongoing COVID-19 pandemic, the following four stakeholder engagement events were held virtually on the online telecommunication platform, Zoom (Zoom Video Communications, Inc. San Jose, California, United States), between December 2020 and May 2021.

Event 1 (Consultation) was held on 8 December 2020, with the aim of collecting initial thoughts on the status of the existing policy landscape and the potential direction for further engagement events. Event 2 (Workshop) was held on 17 February 2021 and engaged stakeholders from the front-end of the value chain (producers, manufacturers, industry associations) to identify concerns, challenges, and opportunities regarding the efficacy of

BB-P/BD-P products. Event 3 (Workshop) was held on 18 February 2021 and engaged stakeholders further down the value chain (industry associations, end-users, consumer associations, and end of life/recycling associations) to identify the information required for consumers to make informed decisions in response to safety and efficacy concerns. It is noted that different stakeholders from industry associations (and for the purpose of these stakeholder events this category also included individuals from academic and research institutions) were present at both Events 2 and 3, as the registered individuals represented viewpoints from up- and down-stream of the value chain, respectively. Finally, Event 4 (Workshop) was held on 19 May 2021 and brought together stakeholders from across the full value chain to collect opinions from across the product life cycle as well as attendees' reactions to previous discussions. In all four events, a range of participatory activities including, presentations, Q&A sessions, breakout room discussions, plenary debates, and online whiteboards, such as Mural (Tactivos, Inc. San Francisco, California, United States) etc., were used to facilitate in-depth discussions and to collect ideas and information. All stakeholder events were prepared and facilitated by professional facilitators/moderators.

To identify and engage key stakeholders in a comprehensive and representative manner, the Prospex-CQI methodology was employed. The Prospex-CQI methodology is part of the STakeholder Integrated Research (STIR) approach (Figure 1) to stakeholder engagement in large-scale research projects developed by Gramberger et al. [58]. The Prospex-CQI methodology first defines a set of *Criteria* including categories of relevant stakeholder groups; it then sets minimum *Quotas* across the categories to ensure representativeness. Finally, *Individuals* are identified with respect to the category quotas and invited to participate. This structured approach encourages a conscious selection of stakeholders which avoids the choice being based on convenience rather than need. Personal data (e.g., names and contact details) were treated in accordance with GDPR.

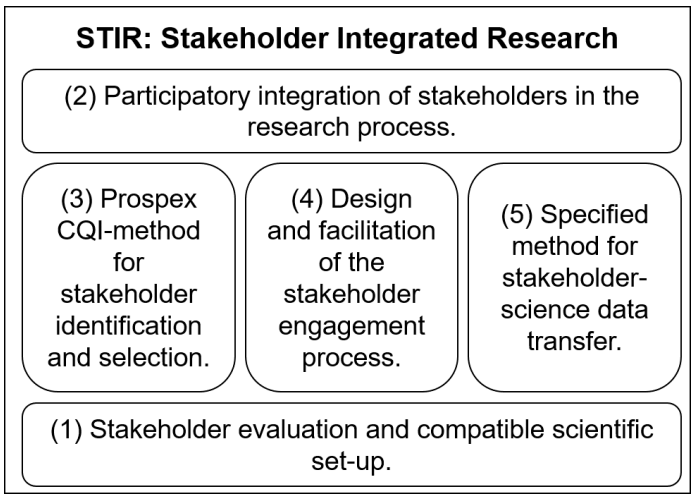

Figure 1. Stakeholder Integrated Research (STIR) approach. Reproduced from Gramberger et al. (2015).

For this research, the criteria set ensured representation both geographically across the EU as well as across the value chain, with categories including manufacturers and producers, industry associations, end-users and consumer associations, end-of-life and waste management, academia, and research associations. To facilitate a rounded discussion, creating equal gender balance was also considered key. In this first stage, over 200 potential stakeholders were identified. These were individuals who were identified as conforming with one or more of the criteria. At this point, these individuals had not been contacted. From this initial stakeholder mapping, relevant participants were contacted using publicly available information (such as email addresses) and invited to register for one

of the stakeholder events. Of course, registration was completely voluntary. Where stakeholders declined to register, another stakeholder fulfilling the same criteria was then invited. The stakeholders that were contacted, and the order in which they were approached, was dependent on their background, demography (gender, age, location) and how they aligned with the criteria/quotas. This ensured that those who registered provided a mix of opinions and experiences. In addition, this avoided occurrences where multiple stakeholders who represented the same background/experience were present at the workshop.

Table 1 presents a breakdown of the stakeholders that registered to participate across the four events, categorized by position on the value chain. Of course, while these stakeholders registered with the intention of participating, engagement was entirely voluntary and thus a certain level of drop out was expected (e.g., due to scheduling conflicts, unforeseen circumstances, etc.). To try and overcome this and reduce the dropout rate, additional information and reminders were sent out prior to the events.

For all the events, a target number of 10–20 participants was set. The lower limit was set to allow in-depth discussions and a range of opinions and experiences. The upper limit was set to avoid too many voices within the room, relax any time restrictions per participant (to allow adequate time for all participants to provide their opinion), and stop dominant opinions overruling quieter voices. Furthermore, the workshop format and content were continuously adapted with the registration numbers in mind to allow for meaningful and interactive discussions and allowed each participant the opportunity to express their own views, thus contributing to a wider discussion. The difference between registered participants and actual attendees (shown in brackets) is further discussed in Section 5.1: *Limitations.*

Table 1. Number of registered (and actual) participants at each stakeholder engagement event. Breakdown of representation across the value chain and gender balance also shown. ("n/a"—stakeholders were not actively recruited for an event).

Stakeholder Engagement Event	Total Number of Participants	Manufacturers/Producers	* Industry Association	Retail	End-user/Consumer	End of Life	Gender Balance Male: Female
Event 1 (Consultation)	11 (6)	2 (1)	7 (3)	n/a	1 (1)	1 (1)	65:35 (65:35)
Event 2 (Workshop)	18 (10)	11 (4)	7 (6)	n/a	n/a	n/a	50:50 (40:60)
Event 3 (Workshop)	9 (5)	n/a	3 (2)	1 (0)	1 (1)	4 (2)	20:80 (40:60)
Event 4 (Workshop)	18 (5)	7 (2)	8 (2)	2 (1)	n/a	1 (0)	45:55 (40:60)

* Includes stakeholders from a range of industrial associations as well as academic and research institutions.

4. Results

The key points of discussion recorded during the four stakeholder events were first transcribed and then, using thematic analysis, categorized into seven sub-themes: regulation and legislative instruments, material quality and performance, market penetration and availability, waste management infrastructure, sourcing and supply chain, communication and information provision, and material health and safety. Details of the discussions held in each of the four sessions can be found in Table 2.

Table 2. Key discussion points made by stakeholders across four engagement events. Overall focus of each event and coverage of the seven themes is shown, as well as discussion points made in each engagement event, supported by stakeholder quotations.

Stakeholder Engagement Event	**Event 1 (Consultation)**	**Event 2 (Workshop)**	**Event 3 (Workshop)**	**Event 4 (workshop)**
Focus	Status of the existing policy landscape.	Identify concerns, challenges, and opportunities regarding BB-P/BD-P efficacy from **industry point of view**	Identify concerns, challenges, and opportunities regarding BB-P/BD-P efficacy from **consumer point of view**	Reflect on previous discussions. Collect opinions across the **full value chain**.
Regulation and Legislative Instruments	√			√
Material Quality and Performance		√	√	
Market Penetration and Availability		√	√	
Waste Management Infrastructure		√	√	√
Sourcing and Supply Chain		√	√	√
Communication and Information Provision		√	√	√
Material Health and Safety				√
Stakeholder engagement event	**Event 1 (Consultation)**			
Regulation and Legislative Instruments	The range of existing standards, regulations, and directives applicable to BB-P/BD-P were highlighted *"Bio-based and biodegradable plastics already need to adhere to a range of standards, regulations, and directives"* Potential difficulties for companies to navigate and understand all documents was also noted. *"There is no point in reinventing the wheel. There is a plethora of documents out there that concern the production, use and disposal of biobased and biodegradable plastics. The issue concerns how companies' access and understand them."*			
Stakeholder engagement event	**Event 2 (Workshop)**			
Regulation and Legislative Instruments	It was suggested that companies new to the industry are often unfamiliar with the applicable documents, unsure which are relevant for them, and struggle with unfamiliar/complex language. *"The language used in the existing standards is often difficult to understand for new users"* It was also noted that paywalls (to access documents) can create additional (and sometime unnecessary) financial burdens. *"Standards are copyrighted and you have to pay for full access of them. A bit more information about what's included in the standards document should be made available, before you then actually go ahead and buy the standard yourself."* Increased support and positive policies from intra-national and national governments were suggested.			

	"What we need to bring biobased materials on a high level is the positive support from Brussels as well as the national authorities. We can sell our products by our own, but support is required."
Material Quality and Performance	The exploration of "safety by design" prinicples was suggested. (The safety by design principle aims to address, overcome, or eliminate any risks to safety in the design phase [59]) *"I am very interested in the safety by design principle. The safety by design principle is the start of everything. It is a nice principle, but we have to work on it and bring meat to this principle."*
Market Penetration and Availability	The concept of appropriate alternatives was introduced. *"The value of biodegradability and bio-based materials is always connected to the application into the material that you are producing. So, it should always be seen in the context of where those materials make most sense with the sustainability values."* It was suggested that producers work with retailers to ensure competitive price points. *"I think that one of the main hurdles for consumers might be price. It is not in all applications that you see the actual cost of the material, but this is definitely an issue."*
Waste Management Infrastructure	It was argued that current waste management infrastructure is inconsistent arcoss different countries. *"Then another very important point is that we get access to end-of-life options, such as mechanical recycling and composting infrastructure. In some countries we do have this, but there are still many countries where we don't. That is very important, because if you bring products to the market, it is of key importance that you have an end-of-life solution for that. You cannot just throw it away or incinerate it, so access to end-of-life options is key."* *"The role of these materials with biodegradable and biobased materials has to be inextricably linked to the end of life through biowaste treatment. And the reason why Italy is biggest market, I think in Europe but possibly in the world at the moment outside of China, is because it collects more food waste than anybody else. Two thirds of all food waste in the EU is collected in Italy. If you're going to treat food waste, you need materials which mimics food waste, safe food waste treatment, and this is the role of biodegradable and biobased materials. The reason why we don't have big markets elsewhere in Europe is because we simply don't have ubiquitous collections of food waste. That's coming in 2024 across the whole EU, and I think that will be the main driver for our industry."* *"I agree that we need more acceptability for compostable packaging by the waste industry."*
Sourcing and Supply Chain	It was suggested that a clearer understanding about the benefits and limitations of BB-P/BD-P in the context of sustainability is needed. *"We do need a better understanding of the benefits and limitations of bioplastics for downstream users, in particular consumers."* Arguments were made for the importance of considering environmental impacts across the whole lifecycle. *"It is very important that life cycle environmental impacts are being taken into account in decision-making, when it comes to promoting and advancing these kinds of new materials. Also, the industry should be encouraged to go towards that direction. Our lifecycle approach means that the viewpoint should be from the product design for the use and for the recycling onto the next life stages."*

Communication and Information Provision	Arguments were made for more (and clearer) communication to break down and simplify the facts about BB-P/BD-P products, both in terms of provenance and use/disposal. *"We need many of the waste processing technologies to improve before we can communicate this to end users and consumers (e.g., whilst a PLA yoghurt pot can technically be chemically recycled back into monomers, the collection, sorting and processing infrastructure is not yet available)."*
Stakeholder engagement event	**Event 3 (Workshop)**
Material Quality and Performance	The performance levels of innovative materials were discussed as a key concern. *"We need a good performance of these innovations. The first developments were quite weak. For instance, the supermarket plastic bags were initially not so resistant"* It was argued that some of these issues are inherent to the material itself and that the use of additives, such as inks and dyes (commonly used in traditional plastic products), may require further consideration. *"Different additives are needed, for instance inks or dyes, on the packaging or labelling. I think we should consider the safety aspects. Because as we need to use different chemicals, we need to be sure that they are they are not creating any problems. Because these additives are developed and tested with conventional plastics, not bio-based plastics, we don't know the behaviour or the degradation itself."* *"To ensure that it actually biodegrades and just doesn't break down in small pieces or small microplastics in the environment. Most of the risk of these microplastics is not only the physical particles of microplastics. Most of the chemical problems begin because parts of the microplastics contain these additives. So, all the ingredients of the bioplastics. The bioplastics itself can be safe and it can degrade in a safe way, but we need to test the degradation in real conditions: not just with plastics, but with the additives, glues and components that are needed to create it, and which can be different from conventional additives."*
Market Penetration and Availability	It was felt that the current low levels of product availability and information resticted informed decision making. It was argued that retailers and manufacturers need to provide more offers and/or alternatives, focusing on competitive price points. *"We need to have enough offers and different alternatives to choose from. For instance in supermarkets, I need to have enough things to choose from, otherwise I cannot make an informed choice."* The growth and visbility of organic products as a potential framework was highlighted. *"I think it is very important that these bio-based products are properly displayed in shops. For example, if you are in shop right now it is easier to find organic products and it would be really good if that would be the same case for bio-based products."* The concept of appropriate alternatives in conjunction with third party certification was highlighted. *"There are also issues with biodegradability itself, because we need to make sure that the composting processes do have processes for bio-based and bio-degradable plastics, and that the composting time is long enough to ensure that we don't end up with microplastics. In terms of safety, it is important that the end-of-life processes are ensured. I also support the argument that we should have third-party certification. Especially when talking about bio-based content,*

	this is important to ensure that we actually have 100 per cent recyclable products and that it is not a false claim." *"A trustworthy chain of custody and 3rd party certification is important, because we have claims that products are bio-based but you have some very loose accounting methods that allow the counting of biobased characteristic that is not fully in the physical product, in the physical polymer. So, we have this mass balance method chain of custody, but more generally for plastics, and the same lines could be applicable for bio-based products."*
Waste Management Infrastructure	The need to consider existing and future waste management system was highlighted as a key concern. *"a proper sorting or recycling system. If I make the effort to buy recyclable plastic bags, for example, I need to be sure that I can put them in the organic container. If we are talking about bio-based products, they are disturbing the recycling processes nowadays, because the facilities are not ready to sort them. If the end of life is the same for conventional and bioplastics, we are not doing anything good."* Suggested direct, simple, and practical information regarding the optimal waste management option, such as explicit instructions on which bin (or waste stream) should be used. *"Just to echo comments from before, is it home composting, can it go in my organic waste bin or composting or anaerobic digestion? I want the communications that go with those problems to be really clear."* *"I want it to be really clearly labelled, I want to make sure that it is more sustainable than its fossil fuel-based alternatives in terms of life cycle and impact on the environment."* *"Very clear information that enables me to make that kind of decisions, and then again having the option for what to do with it when I no longer need it."*
Sourcing and Supply Chain	Potential conflicts regarding feedstock sourcing (specifically with reference to developing nations) were highlighted, as well as potential issues of genetically modified (GMO) crops. *"We need to ensure that these materials stem from sustainable sources, we are not competing with primary, so we are not using potatoes for a packaging when people don't have enough for eating, for instance."* *"When we are creating new products on the market, for developing countries it can be a problem if we are using as bio-based products some of the raw materials or primary materials like potatoes, maize, or something like that. In the long term it is a problem if we are using these materials for creating bio-based products, because we are decreasing the amount of food that stays in developing countries. So, we should only allow for secondary materials, or residual or waste streams to be used."* *"Can we also raise the issue of using genetically modified crops for producing bioplastics? GMO is a possible option, but I don't think it is good for the humans and the environment to use GMO modified crops."*
Communication and Information Provision	In-depth discussion regarding communication, specifically related to how information is conveyed to the end-user. Covering claims of sustainability, notification of content, and correct methods of use/disposal. Reliability and clarity of information provided was discussed as a key concern.

	"I would need reliable information. For instance, everything is biodegradable nowadays, so I think we would need a certificate or some sort of external assessment. For me personally, it is only biodegradable if it is compostable, because we need it to adapt to the recycling process." *"I agree with the previous comment that informing consumers is important, but today there is confusion regarding what is bio-based and what is bio-degradable. It is very important to make these claims clear to the consumers, so that bio-based products do not end up in the organic waste bin if they are not biodegradable."* *"To have very clear labelling and be able to first of all find those products and then be able to select them and actually know what I am purchasing when I am actually in the supermarket or in cafes or restaurants. More labelling and clear communication for the consumers"* Discussed the potential issue around mixed-messages regarding the avoidance of plastic use and zero-waste ambitions. *"We should also ensure that any products made out of these bioplastics are more beneficial than products made of traditional plastics. Obviously, conventional plastics have very developed recycling systems. By replacing something that has a very established recycling scheme, are we actually making it worse by doing that?"* *"what will be important will be the prevention, and we see that for example the use of single use plastics should still be banned, even if it is bio-based. So, changes in the perception may be interesting, but just because something is biodegradable it does not mean we should promote single-used items. For instance, if you go to a shop or you buy your meal, it is maybe bio-based, but it is not actually biodegradable, and the change of perception may in this sense undermine the objective of limiting the use of single use plastics."* Argued that any information presented for BB-P/BD-P products should not give the impression that "biodegradability" gives the consumer the license to dispose of these products outside of the recommended environment (e.g., littering in the open environment). *"Bioplastics should never give the impression that because they are biodegradable, they can be thrown away. It should be very clearly indicated in the labelling and in the communication strategy, that these should not be thrown away into the environment."* It was suggested that sustainability criteria should be applied to the entire value chain and life cycle of the product. *"One important point is the sustainability of the whole value chain of the biobased plastics, meaning the sustainability of the production, making sure that there's no competition for food or making sure that if we produce them from waste, what about the competition for example with the paper waste industry? I think we can sum it up as the whole sustainability criteria behind the biobased plastics and in the life cycle assessment in general."*
Stakeholder engagement event	**Event 4 (Workshop)**
Regulation and Legislative Instruments	It was suggested that simplicity is key when developing and implementing norms and/or certifictaion schemes. *"Any norm or EU certification has to explain to the people what the real advantage of using certain materials is, and how they should be handled. In my opinion, everything has to be created to simplify the life of the of the people."*

	It was also argued that better leadership from European governments is required, specifically in terms of labelling and explanations. *"Because on the market today, there is a very big confusion; people write on any packaging, compostable, sustainable, and so on, and nobody really understands what is going on. And this confusion has come about, because there is not very clear input from the European government in terms of labelling and explanations… Because very few know what industrially compostable, compostable, biodegradable mean. It is not just about the expert community, but we have to create something that makes it clear to everybody."*
Material Quality and Performance	It was argued that producers should take responsibility to ensure the sustainability of their product. *"Maybe I'm generalising here, but I suspect from most consumers point of view, let's say they unwrap their food, and they have a pack in their hand. And actually, they just want to know what to do with it. I suspect most people don't want to read about how much biobased content there is or how sustainable the package is. Probably a lot of those a lot people would just like to leave that that sort of decision to the people putting the packaging on the market, and you would like to think that they've made the right choices further back in the chain, and that actually they wouldn't be putting things on the market that are clearly unsustainable. There will be a small percentage of consumers who are interested in all the details, but I think generally the messaging needs to be simple. And again, it applies to conventional packaging, you just need a message on the pack, whatever it is, that tells you what to do with it. And I think from the consumers point of view, it should just be simple."*
Waste Management Infrastructure	Raised the issue of microplastics. Highlighted the similarities in the generation of microplastics when BB-P/BD-P and traditional plastics were compared, especially when products are wrongly discarded within the environment. *"Often, the questions we receive are about microplastics. I think that is one of the hottest topics at the moment."*
Sourcing and Supply Chain	Raised the issue concerning unknown variables that may impact the supply of materials (either feedstock or compounded materials), especially in relation to the limited capacity within the EU (outside research and development) to produce and process such materials itself compared with the amount required to fulfil the EU's ambitions for use. *"The supply of the new material. Because as I as far as I understood, Europe has just limited that capacity to introduce new polymers, and we are just buying all the material from Asia, which is every day coming up with a new offer, as well as from the United States and Canada. Europe is at the moment just doing research, but we don't have the pipeline and supply chain needed in order to deliver us enough material to make the project a reality. So it's just research, which is not fulfilling the industrial demand."*
Communication and Information Provision	Discussed the impact of approriate and reliable information provided to consumers. *"Not just those scientific facts, but also this appropriate or inappropriate information about biobased and biodegradable products in the market that that can lead to not enough knowledge for the consumer, which can also lead to lack of safety of the product."* It was suggested that simplicity is key when concerning consumer information.

	"All this activity has to be simplified for the end user or the market. Because today there is quite a lot of confusion about the packaging; what is compostable, recyclable and so on." *"This is creating a lot of confusion, and it is not clear for people how bioplastics and all the new materials coming to the market can be used and recollected and how they can be managed"*
Material Health and Safety	A key issue concerned the role of standardization. Here, the discussion centered around the EU standard for composting (EN 13432) and the apparent lack of emphasis on the importance of safety regarding the application of the subsequent compost to soil. *"Conforming to the European EN 13432 standard about the producing of compost, and the safety for the end of life of this compostable plastic when it becomes compost, and then returns to the nature to fertilise the soil. The importance for the soil and the circular thinking when it comes to producing bio-based and compostable plastics; to offer to consumers a new product that are in circular economy that can compost."* Noted that appropriate information is required to ensure safety in the market, where novel and newly developed materials should be checked to meet all relevant requirements. Did not consider it appropriate to treat BB-P/BD-P with more caution than traditional plastics and that raising such concerns publicly around the former (and out of proportion when considering the latter) could imply to consumers that BB-P/BD-Ps are more hazardous. *"I understand that bio plastics are new and people want to know about them. And I guess it's a little bit like building a house; when you build the latest house, it has to be built to the latest specifications and probably has more safety features built in et cetera. But sometimes we perhaps just need to go back and look at the existing houses and just check that they are still up to scratch and still meet all the requirements. There are aspects within conventional materials that could potentially be the same as the bioplastic materials, but they are not highlighted, in a way. […] I think the bar is very, very high for bioplastics, whereas maybe conventional materials… I accept that they're well known and they've been used for many years, but maybe there are things that might not be as good as everyone believes."*

To provide an overview, when asked, "what would encourage you to use more BB-P/BD-P products?", participants across the three workshops presented a range of responses. These included a clearer understanding about the benefits and limitations of BB-P/BD-P in the context of sustainability, as well as increased (and positive) support from intra-national (e.g., the EU) and national governments. Other responses included enhanced access to suitable end-of-life options, the exploration of "safety by design" principles, and competitive price points. Strong arguments for the importance of considering environmental impacts across the whole lifecycle were also raised, where the lifecycle approach means that all perspectives are considered, e.g., product design, material selection, consumer use, and end-of-life management. Several participants argued for more (and clearer) communication to break down and simplify the facts about BB-P/BD-P products, both in terms of provenance and use/disposal. Summaries of these discussions held across each theme are presented below.

4.1. Regulation and Legislative Instruments

During Event 1, participants highlighted that the production and marketing of BB-P/BD-P products must adhere to a range of existing standards, regulations, and directives. It was also noted that the plethora of such documents can create difficulties for new companies to navigate and understand their obligations. This was reiterated by participants within Event 2, who suggested that companies new to the BB-P/BD-P industry are often

unfamiliar with the applicable documents, unsure which documents exist/are applicable to them, and struggle with the unfamiliar/complex language common to these documents. Furthermore, particularly with respect to standardization documents, companies are often met with paywalls, where payment is required to access a full version of a document. As well as adding to the mystery, paywalls may create an additional (and potentially unnecessary) financial burden if a company pays to access a document that they then realize is not relevant for their product. Finally, the participants across all workshops emphasized the importance of considering the full value chain, as different stages of the value chain are responsible for making sure specific regulations and directives are adhered to.

4.2. Material Quality and Performance

With respect to performance issues, the participants noted that some first-generation products had gained a reputation for being of poor quality, and that even recent innovations may have performance issues. It was argued that some of these issues are inherent to the material itself, for example, where the inclusion of BD-P impacts the lifespan of the material (i.e., the time before it starts to degrade). If used in food packaging, this may reduce the shelf-life of the food item. Of course, any material or product used for food packaging must be shown to conform with 'Food Contact Material' regulations and tested in light of established norms. However, as many of these tests to show conformity have been developed for traditional plastics they may not be optimized for BB-P/BD-P, which may unfairly discriminate against these materials and place additional pressure on producers of BB-P/BD-P to demonstrate the efficacy and safety of their products. In lieu of a level playing field and consistency within the industry, testing regimes that are specific to BB-P/BD-P are needed, or at the very least, systematic evaluation of existing testing protocols to determine appropriateness and applicability when used to test BB-P/BD-P. Additionally, the use of additives, such as inks and dyes (commonly used in traditional plastic products) may require further consideration and/or testing to ensure that they are not negatively interacting with the BB-P/BD-P material. As these additives have often been tested (and pass quality checks) using protocols and standards developed for traditional plastics, the implications, and indeed behaviors, of using them in BB-P/BD-P is unknown. Plainly put, the participants want BB-P/BD-P products to be as good as the incumbent products they are replacing, fit for purpose, and, overall, safe. This can sit in a wider discussion about reducing the over-use of certain chemicals and substances (that may be harmful) in all products.

4.3. Market Penetration and Availability

When discussing the (poor) availability of alternative BB-P/BD-P products, and the information required to make an informed decision, the participants felt that there was a need for supermarkets and other outlets to provide more offerings and alternatives, alongside suitable communication campaigns and attractive (not overly expensive) price points. A comparison is made with organic products (including non-food items such as cotton products) that are currently very easy to find and distinguish within shops. Furthermore, the participants highlighted the concept of appropriate alternatives, where BB-P/BD-P products are only introduced where there is a need, and where they can be shown to be more sustainable than the incumbent traditional product they would be replacing. To do so, the participants suggest the use of third-party certification that considers the entire life cycle of the product as well as the incumbent product that is being replaced and the local situation.

4.4. Waste Management Infrastructure

Subsequently, the local situation also plays an important part with respect to current and future waste systems. Here, the participants highlighted the fact that many traditional plastics have well-established waste management and recycling systems. In addition, they

argued that by replacing traditional materials with BB-P/BD-P products (which may not have suitable systems currently available to ensure the preferred waste management option is carried out), waste management providers may have to resort to less sustainable options, such as landfill or incineration. Again, communication plays an essential role here, with participants noting that they would feel more comfortable in using BB-P/BD-P if they were confident about it being disposed of responsibly. Here, the participants suggested direct, simple, and practical information regarding the optimal waste management option, such as explicit instructions on which bin (or waste stream) should be used. Another issue raised by the participants (in Event 4) was that of microplastics, which is already a matter of current debate and concern with respect to traditional plastics. Here, stakeholders were keen to highlight the similarities in the generation of microplastics when BB-P/BD-P and traditional plastics are compared, especially when products are wrongly discarded within the environment. To elaborate, even when considering BD-P, specific industrial conditions are often required to ensure full break down of these materials; as such, in the wrong (or inefficient) environment, biodegradability may not proceed past the disintegration phase, akin to traditional non-biodegradable plastics.

4.5. Sourcing and Supply Chain

Furthermore, the participants highlighted potential conflicts regarding feedstock sourcing (specifically with reference to developing nations), where the issue of genetically modified (GMO) crops was brought up. Here, the participants were keen to make sure that any assessment of sustainability included references to feedstock sourcing and the production of BB-P/BD-P and encourage the use of sustainable sources. As feedstock sourcing can conflict with food security, either by using food crops or the land required to grow them. Participants concluded that developers of BB-P/BD-P should therefore endeavor to use second and third generation feedstocks, such as residual (crop) and municipal waste streams, wherever possible. Another line of concern (raised in Event 4) relates to the unknown variables that may impact the supply of materials (either feedstock or compounded materials), especially in relation to the limited capacity within the EU (outside research and development) to produce and process such materials itself compared with the amount required to fulfil the EU's ambitions for use.

4.6. Communication and Information Provision

The discussion concerning communication, specifically related to how information is conveyed to the end-user, was continued, in-depth, by participants across the three workshops. Here, the discussion not only covered claims of sustainability and notification of content (e.g., with respect to BB-P) but also how the consumers should use and correctly dispose of the products once discarded. Some of the key concerns brought up in these discussions also included performance levels of innovative materials, reliability and clarity of information provided, availability of alternatives (and the information needed to make an informed choice), and consideration of existing and future waste management systems. The potential issue around mixed-messages regarding the avoidance of plastic use and zero-waste ambitions was also discussed. Here, the participants acknowledged that plastic avoidance is not always possible, so it is important that when plastic materials are required as part of our everyday lives, they should be recyclable or biodegradable (preferably compostable). However, the promotion of BB-P/BD-P products should not come at the expense of established circularity messages such as reducing consumption, reusing products, not using single-use products, etc. Furthermore, any information presented for BB-P/BD-P products should not give the impression that "biodegradability" gives the consumer the license to dispose of these products outside of the recommended environment (e.g., littering in the open environment). To overcome some of these issues, the participants suggested applying sustainability criteria to the entire value chain and

life cycle of the product. In addition, very clear, simple, and direct communication between producers, end-users and waste manager was suggested across the workshop sessions.

4.7. Material Health and Safety

When asked "In the context of the whole value chain, what do you think the key issues are regarding the uptake of BB-P/BD-P products?", participants from Event 4 provided a range of responses. A key issue concerned the role of standardization. Here, the discussion centered around the EU standard for composting (EN 13432), and the apparent lack of emphasis on the importance of safety regarding the application of the subsequent compost to soil. The participants also noted that appropriate information is required to ensure safety in the market, where novel and newly developed materials should be checked to meet all relevant requirements. Whilst safety is a concern, the stakeholders did not consider it appropriate to treat BB-P/BD-P with more caution than traditional plastics and that raising such concerns publicly around the former (and out of proportion when considering the latter) could imply to consumers that BB-P/BD-Ps are more hazardous. Terminology and semantics can therefore play an important role in how these materials are viewed and approached.

5. Discussion

To summarize the discussions held across the four stakeholder events, market uptake of BB-P/BD-P products may be restricted by the following:

- Continued confusion regarding the meaning of terms, such as biodegradability/compostability, and the communication of these qualities and characteristics throughout the value chain.
- Difficulties for inexperienced companies in navigating, comprehending and interpreting the plethora of documents related to the safety of BB-P/BD-P with respect to their company/product.
- Applicability and appropriateness of existing safety documents for new BB-P/BD-P products.
- Overall appropriateness of using BB-P/BD-P as a sustainable alternative to traditional petroleum-based plastics.

These discussions must also be taken in the context of the arguments made previously in Section 2. Figure 2 summarizes the concerns reported in the academic and grey literature, identifies which policy instruments should (theoretically) address them, and then presents additional recommendations based on the discussion held during the stakeholder events.

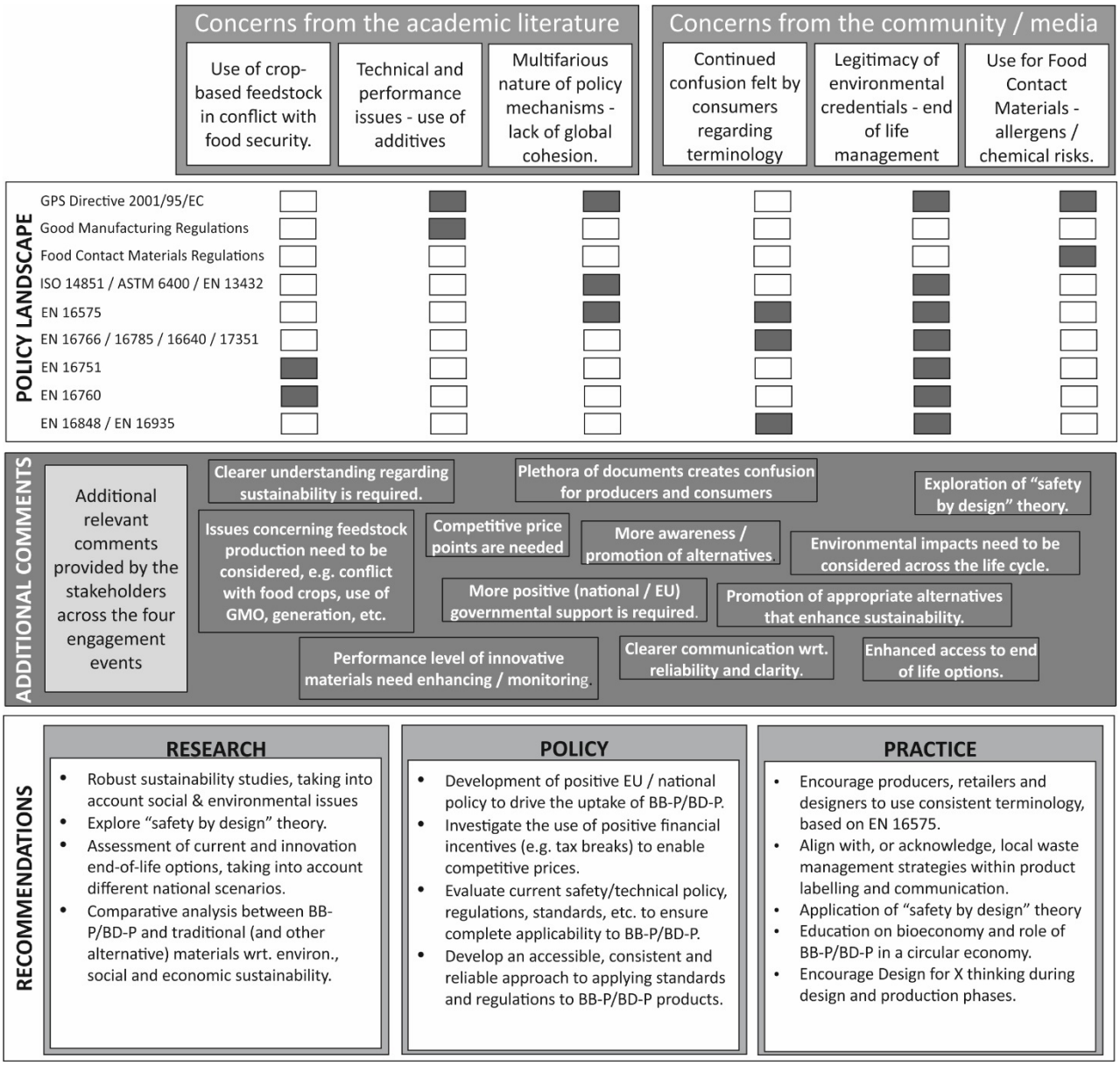

Figure 2. Overview of the key concerns raised within the academic literature, community platforms, and by stakeholders regarding the efficacy of bio-based and biodegradable plastics. Coverage within the existing EU policy landscape is indicated and summaries of recommendations for research, policy, and practice are provided.

When compared with two recently published reports, CS3 white paper on "Science to enable sustainable plastics" [60] and the "EU Biorefinery Outlook to 2030" report [61], there is clear alignment across the recommendations made from this study and those contained within these reports. While similarities are apparent, the current research complements these existing reports by bringing a unique stakeholder viewpoint that considers the whole product life cycle. Recommendations for research, policy, and practice are discussed in more detail below, highlighting synergies with [60,61].

5.1. Recommendations for Research

In the development of new sustainable plastics (including those classified as BB-P/BD-P), being able to assess the products sustainability is as important as technical performance, where future materials should be designed to minimize toxicity and environmental impacts. To facilitate assessments, the development and implementation of rigor-

ous sustainability metrics are required [60]. Indeed, Platt et al. [61] suggests that the development of assessment methodologies and the identification of thresholds/limits should be built upon the work completed by Technical Committee 411 (TC-411) to ensure rigor and standardization across the sector.

Furthermore, any consideration of sustainability must take into account the entire life cycle, where assessment should be integrated (along with techno-economic assessments) at appropriate stages of technology translation [60]. This aligns with the stakeholder consensus within this research that (1) any sustainability claims should be grounded on tangible and reportable evidence, and (2) factors across the entire life cycle of a product should be taken into account. Furthermore, the stakeholders agreed that the work completed by TC-411 provides a foundation on which future progress can be based. Here, it is recommended that any sustainability assessment undertaken should focus on specific end-of-life options (e.g., recyclability, biodegradability, compostability), and more importantly, consideration should be given regarding the implications of end-of-life options to consumer behavior (both intended and realized).

Another key point stressed by the stakeholders was that the uptake of BB-P/BD-P should not be considered paramount, nor should it compete with other sustainability strategies (e.g., reducing consumption and production). Instead, their use should be encouraged in certain situations, such as a genuine need for a product, where existing (and well established) end-of-life processing routes are available, and where existing reusable solutions are not an option.

5.2. Recommendations for Policy

Overall, research is required to understand, develop, and promote the uptake of materials with desirable properties in the context of end-of-life options that utilize alternative feedstocks that are scalable, abundant, and sustainable and can reduce sector-level GHG emissions [60]. In order to do this, there is a need for policy and practice alignment. For example, the Outlook to 2030 report [61] presents a range of policy recommendations, such as sector targets for GHG reduction ambitions, bans/restrictions on the sale of selected non-recycled petroleum-based products, the establishment of voluntary producer-level commitments, public procurement standards, and the taxation of petroleum-derived resources.

As indicated by Figure 2, concerns related to the efficacy of BB-P/BD-P raised within this study (across the academic literature and community platforms) have existing coverage within the current EU policy landscape. However, that raises questions about how well these policies and regulations are adopted. Here, concerns have been raised regarding the applicability and/or accessibility of existing documents that allow companies to easily adopt measures to adhere with policies and regulations. To overcome this, the evaluation of current safety and technical policies (and associated documents such as standards) is needed to ensure that such documents are fully applicable and entirely appropriate for scenarios that utilize BB-P/BD-P. Furthermore, the development of an accessible, consistent, and reliable approach for companies to identify, apply, and conform with safety and technical documents is needed. Again, this was a key theme throughout the stakeholder engagement events, where the accessibility and interpretation of standards and policies was highlighted as a potential barrier to the uptake and utilization of BB-P/BD-P by SMEs.

5.3. Recommendations for Practice

An area that has already received a significant amount of attention, both within academic research and across the policy landscape, is the standardization of terminology. Not only was the act of standardizing terminology considered important, but so too is the establishment of mechanisms to encourage (and eventually enforce) the consistent use of correct terms. By creating a consistent and coherent vocabulary across the many stakeholders of the value chain, some of the issues concerning confusion may be addressed.

While the current regulatory framework provides the tools to (theoretically) ensure consistent and clear communication, it could be argued that compliance is key. Clear communication through sustainability reports, labels, and certificates will enable consumers to make an informed choice and thereby support market growth [18]. This may also be aided by the inclusion of bioeconomy and sustainability themes within education, where the next generation of consumers have sustainability embedded as standard from a young age, compared with the current generation who may need to adopt new behaviors in lieu of established societal norms.

Overall, communication activities should be based on robust and rigorous sustainability studies that consider social and environmental issues across the entire life cycle (such as those mentioned in Section 5.1*: Recommendations for Research*). Sustainability studies should cover product design and manufacture, where safety, technical performance, and potential end-of-life treatment are considered as part of these processes. The stakeholders across the four engagement events made it clear that considerations (and ultimately decisions) regarding the introduction, use, and final end-of-life route of BB-P/BD-P products should not be conducted within separate silos, but instead should adopt a systems perspective and transdisciplinary approach. For example, designers and producers of BB-P/BD-P products could consider the exploration and uptake of "Design for X" (e.g., where X = safety, recyclability, compostability, or disassembly, etc.) approaches. In the same vein, there is also a call to develop enhanced support for SMEs to better facilitate compliance with relevant standards, as well as actions to combat the lack of visibility, transparency, and consistency regarding communication and information provided for BB-P/BD-P [61].

5.4. Limitations

This study employed an initial literature review to identify efficacy concerns that may limit uptake of BB-P/BD-P products. The results of this research are therefore closely aligned with the defined search terms. This limitation was exacerbated by publisher paywalls as only the studies that were open access or available through institutional portals were included. Apart from extending the search and access to full texts, this research could be advanced by considering the policy environment beyond the EU (in reference to the limited capacity within the EU to cultivate and process BB-P/BD-P) as well as collecting primary data (e.g., through surveys) to establish the extent of consumer/end-user concerns and expectations regarding the use and/or efficacy of BB-P/BD-P products.

Furthermore, the use of stakeholder engagement events (such as consultations and workshops) to collect information and inform the discussion has inherent and contextual limitations. A number of challenges associated with stakeholder engagement such as the increased demand on time and resources, biased representation of stakeholder groups, and tokenistic engagement may lead to a number of dis-benefits such as reinforcing power imbalances, creating/exacerbating misunderstandings, and delaying decision making [62]. To address these potential issues, this study employed the Prospex-CQI methodology to identify and recruit participants. As reported in Table 1, this process was successful in gaining registrations from across the value chain, providing a representative spectrum (i.e., regarding area of expertise, gender, location, etc.) of participants. This mitigates the dis-benefits listed above by ensuring participants with a range of perspectives and experiences were included.

Table 1 also highlighted that the number of registrations across all four events was higher than the number of participants in attendance. This difference was higher than expected for this type of event (where some drop-out is the norm, and thus expected) and is attributed to the virtual/on-line nature of the workshop. Indeed, this phenomenon has been noted across other events, for example, Raby and Madden [63] found the behavior and engagement of academic conference delegates changing with the move to online virtual events. Comparable to the experiences within this study, Raby and Madden (2021) [63] document that, out of the 950 pre-registrations in their study, just over half attended

the conference. Due to the lack of appropriate data, Raby and Madden acknowledge that it is not possible to determine the cause for this difference [63]; however, one possible influence may be the effect of video-call fatigue, colloquially known as "Zoom fatigue". Video-call fatigue is a modern, post-COVID-19 issue that is described by Wiederhold [64] as the "tiredness, anxiety, or worry resulting from overusing virtual videoconferencing platforms". Bailenson [65] argues that video-call fatigue is caused by excessive amounts of up-close eye gaze (a behavior normally restricted to close relationships), increased cognitive load (users need to work harder to send/receive nonverbal signals), increased self-evaluation (continuous visual feedback, akin to staring in a mirror), and physical mobility constraints (exacerbate by the camera's field view). The difference between registered and actual participants may also be caused by a lack of perceived incentive. Pre-COVID-19, events such as these would have not been virtual, and so the potential inclusion of travel, accommodation, and in-person networking/social engagements (both during and before/after the event) may have presented more incentive for the registered participants to attend.

6. Conclusions

This paper set out to explore the question: what concerns related to the efficacy of BB-P/BD-P create barriers to uptake and how do we address them? Through a literature review and several stakeholder engagement events, key areas of concern were highlighted, including regulation and legislative instruments, material quality and performance, market penetration and availability, waste management infrastructure, sourcing and supply chain, communication and information provision, and material health and safety.

This study also presents a novel perspective, compared to the existing literature, by engaging with stakeholders across the value chain. Indeed, this study has highlighted the important role stakeholder engagement plays in supporting the understanding of dynamic and multi-faceted issues, whilst promoting collaboration to produce solutions. Here, the Prospex-CQI methodology was used to identify and engage with a range of stakeholders from across the value chain. By creating a fulfilment criterion, the methodology enabled the participants included to be representative of both the industry, and of society in general. This meant that opinions gathered throughout the four stakeholder events came from different perspectives and levels of expertise, providing new insights and building upon existing literature and understanding.

The research also highlighted other areas requiring further investigation, beyond the scope of this study, which may be useful for guiding future research on the topic. For example, the fundamental question underpinning this paper could be asked during the development of new and existing policy instruments (such as safety directives and regulations), i.e., 'Are there any caveats required or challenges that need to be addressed for products made from BB-P/BD-P that would not necessarily be an issue for traditional materials?'. In addition, it may be necessary to consider the application of existing non-material-specific testing protocols and standards to evaluate and test BB-P/BD-P materials and products, considering the impact that the presence of BB-P/BD-P may have on their accuracy and appropriateness. For example, 'Might the performance of traditional fillers, additives and adhesives be impacted by the presence of BB-P/BD-P materials?'. Further to this, there is a need to evaluate BB-P/BD-P in relation to the current industry context, including existing waste management infrastructure. Therefore, both the potential (technical) circularity and the contextual (realized) circularity of BB-P/BD-P should be investigated and correlated.

A further consideration that may be required is the disparate use of certification schemes and logos in the communication of BB-P/BD-P products. This plays into a greater concern regarding the reported confusion felt by companies and consumers regarding the vocabulary used to describe BB-P/BD-P products. Under the current system, national and company-level certification schemes and logos are used to infer information regarding

bio-based content, compostability, and degradability, which in turn may lead to confusion and limited uptake by the end-user. Development of a harmonized, international certification scheme (and accompanying logo) that differentiates between different end-of-life scenarios could ultimately help to alleviate these issues.

By addressing these further research areas identified, the BB-P/BD-P industry will be better supported in its advancement and market penetration, whilst avoiding many of the pitfalls experienced by existing material industries.

Author Contributions: Conceptualization, C.A.F., R.H. and A.D.; Data curation, C.A.F. and K.N.; Funding acquisition, A.D. and C.E.B.; Investigation, C.A.F., K.N., R.H., J.A. and A.D.; Methodology, C.A.F., K.N. and J.A.; Project administration, C.A.F. and A.D.; Visualization, C.A.F.; Writing—original draft, C.A.F. and K.N.; Writing—review & editing, C.A.F., K.N., R.H., J.A., A.D. and C.E.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was completed as part of the BIO-PLASTICS EUROPE project, funded by the Horizon 2020 Framework Programme of the European Union, Grant Agreement N° 860407.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Science and Engineering Research Ethics and Governance Committee of Manchester Metropolitan University (Reference number 17215, approved 15 January 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available in accordance with participant confidentiality and the Chatham House rule.

Acknowledgments: The authors would like to thank the participants that took part in the stakeholder events for their honest and open discussions.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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