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Developing Future Visions for Products and Applications based on 2,5-Furandicarboxylic acid – A Backcasting Approach

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Abstract

Plastics make up an integral part of everyday life, yet these materials have been under environmental scrutiny for some time, with the fossil origin of plastics, biodegradability, single-use applications, and plastic pollution being major areas of criticism. For these reasons, more sustainable solutions are being investigated. To address the issue of fossil resources, biomass-derived 2,5-furandicarboxylic acid (FDCA) is seen as a high potential platform chemical and even referred to as a "sleeping giant".

Nevertheless, FDCA-based products have not yet made it to the market on a commercial scale, and efforts in this area currently don't go much beyond R&D activities. The presented thesis uses two different approaches to identify the current state of research regarding FDCA and how the attributed potential of FDCA might be unfolded in the future, and what challenges and opportunities might be expected along the way.

Firstly, a literature review was conducted, limiting the vast body of literature by certain keywords and a selected time frame of publication. The further screened literature consisted of 100 papers, which were categorized thematically, and the content was analyzed. 61% of the included publications focused on the synthesis of FDCA, while the other side of the value chain, the research concerning applications for FDCA, was only subject to 23%. The remaining 16% were categorized as reviews. On the basis of the literature, 10 statements were formulated to briefly represent the current state of research.

Secondly, to expand the results of the literature and to identify future visions with regard to FDCA, a backcasting workshop was conducted with 42 experts from FDCA industry and research. The results show that academics and practitioners see great potential for FDCA-based products, particularly as a replacement for PET, but also emphasize the need to find niche applications for the promising substance. Economic aspects, such as costs, but also challenges in production and technology development are mentioned as the main barriers to FDCA market introduction. Interestingly, experts from FDCA synthesis and material development mainly refer to market applications for FDCA in their vision of the future. In turn, the future vision of FDCA application experts mainly covers developments in the areas of production, technology, and research, as well as increased environmental sustainability. To overcome these barriers, political regulations and the roles of society and consumers are considered to be the most important factors.

These results demonstrate the importance of cross-disciplinary collaboration among stakeholders and coordinated innovation and research activities along the entire value chain to develop a shared vision for the future of FDCA and, accordingly, to successfully bring FDCA-based products to the market.

Kurzfassung

Kunststoffe sind ein integraler Bestandteil des täglichen Lebens. Dennoch stehen diese Materialien seit einiger Zeit in der Kritik, wobei der fossile Ursprung der Kunststoffe, die biologische Abbaubarkeit, die Einwegverwendung und Umweltverschmutzung durch Kunststoffe die Hauptkritikpunkte sind. Daher wird nach nachhaltigeren Lösungen gesucht. Unter anderem wird dabei die aus Biomasse gewonnene 2,5 - Furandicarbonsäure (FDCA) als eine Plattformchemikalie mit großem Potenzial angesehen und sogar als „schlafender Riese“ bezeichnet. Dennoch haben es Produkte auf der Basis von FDCA noch nicht in kommerziellem Maßstab auf den Markt geschafft, und die Bemühungen in diesem Bereich gehen derzeit kaum über F&E-Aktivitäten hinaus. Die vorliegende Arbeit verwendet zwei verschiedene Ansätze, um den aktuellen Stand der Forschung zu FDCA zu ermitteln und zu untersuchen, wie sich das zugeschriebene Potenzial von FDCA in Zukunft entfalten könnte und welche Herausforderungen und Chancen auf dem Weg dorthin zu erwarten sind.

Zunächst wurde eine Literaturrecherche durchgeführt, bei der die umfangreiche Literatur durch bestimmte Schlagworte und einen ausgewählten Zeitraum der Veröffentlichung eingeschränkt wurde. Die weiter gesichtete Literatur umfasste 100 Arbeiten, die thematisch kategorisiert und inhaltlich ausgewertet wurden. 61 % der einbezogenen Veröffentlichungen befassten sich mit der Synthese von FDCA, während Anwendungen für FDCA nur Gegenstand von 23 % der Veröffentlichungen waren. Die restlichen 16 % setzten sich aus Reviews zusammen. Auf Basis der Literatur wurden 10 Aussagen formuliert, die den aktuellen Stand der Forschung kurz darstellen.

Um die Ergebnisse der Literatur zu erweitern und Zukunftsvisionen in Bezug auf FDCA zu identifizieren, wurde in einem zweiten Schritt ein Backcasting-Workshop mit 42 Experten aus der FDCA-Industrie und -Forschung durchgeführt.

Die Ergebnisse zeigen, dass Wissenschaftler und Praktiker ein großes Potenzial für Produkte auf Basis von FDCA sehen, insbesondere als Ersatz für PET, aber auch die Notwendigkeit betonen, Nischenanwendungen dafür zu finden. Als Haupthindernisse für die Markteinführung von FDCA werden wirtschaftliche Aspekte wie Kosten, aber auch Herausforderungen bei der Produktion und Technologieentwicklung genannt. Interessanterweise beziehen sich die Experten aus der FDCA-Synthese und Materialentwicklung in ihrer Zukunftsvision hauptsächlich auf Marktanwendungen für FDCA. Die Zukunftsvision der FDCA-Anwendungsexperten wiederum umfasst vor allem Entwicklungen in den Bereichen Produktion, Technologie und Forschung sowie eine verstärkte Umweltverträglichkeit. Um diese Hindernisse zu überwinden, werden politische Regelungen und die Rolle der Gesellschaft und der Verbraucher als die wichtigsten Faktoren angesehen.

Diese Ergebnisse zeigen, dass eine interdisziplinäre Zusammenarbeit zwischen den Akteuren und koordinierte Innovations- und Forschungsaktivitäten entlang der gesamten Wertschöpfungskette wichtig sind, um eine gemeinsame Vision für die Zukunft von FDCA zu entwickeln und dementsprechend FDCA-basierte Produkte erfolgreich auf den Markt zu bringen

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1 Introduction to market aspects of fossil-based and bio-based plastics

1.1 Fossil-based plastics and plastics derived from biomass

According to Andrady and Neal (2009), the use and application of polymers began very early in human history. Initially, man mainly used natural polymers, such as natural rubber, waxes, resins and horn. Over time, people increasingly experimented with rubber and plastics until the development of modern thermoplastics was initiated in the nineteenth century. Thereafter, intensive work continued on the invention of natural and synthetic polymers, such as vulcanized rubber (by Goodyear), polystyrene (PS), celluloid, polyvinyl chloride (PVC), and viscose. Since then, a myriad of new polymer compounds has been synthesized and the success of these materials has been substantial (Andrady and Neal, 2009).

Synthetic polymers are chains of a large number of monomers, typically obtained by polymerization (Ellen MacArthur Foundation, 2016). Plastics are then produced by adding various chemical additives, leading to a large group of different materials varying in composition (Andrady and Neal, 2009). Each plastic has characteristic properties that make it ideal for meeting different performance requirements of specific applications (PlasticsEurope, 2019). Therefore, these materials have become an integral part of many areas of daily life and can be found in all kinds of products, such as packaging, textiles, building and construction, electronic components, automotive and household applications (Andrady and Neal, 2009). In addition, these materials are often associated with quality of life, innovation and comfort, enabling many future technological and medical advances (Thompson et al., 2009). The success of plastics is also reflected in the enormous growth of its production in recent decades. In 1950, 2 million tons of plastic were produced worldwide, and since then, annual production has increased almost 200-fold, reaching 381 million tons in 2015 (Geyer et al., 2017). Today, demand for plastics far exceeds that for any other bulk material (such as steel, aluminum or cement) and has almost doubled since 2000 (International Energy Agency, 2018). According to the Ellen MacArthur Foundation (2016), almost 90% of the feedstock for these enormous production volumes is derived from fossil resources, which makes the plastic sector very dependent on these finite raw materials. Currently, about 4-8% of the world's oil production is employed in the manufacture of plastics, with one half being used as a material feedstock and the other half as fuel for the production process. Moreover, if the strong growth trend in plastics production continues, the plastics industry could already account for 20 percent of total global oil consumption by 2050 (Ellen MacArthur Foundation, 2016). This development can also be attributed to the shift in the packaging sector from reusable packaging to packaging designed for immediate disposal, which is also facilitated by the inexpensive nature of these materials (Barnes et al., 2009; Jambeck et al., 2015).

The following figure (Figure 1) shows the proportions in which plastics are used in various industries and the proportion of total primary production accounted for by the various types of plastics. In addition to the versatile uses of plastics in a wide variety of end-use sectors, the different types of plastics are also very diverse. These include widely used resins and fibers, such as high-density polyethylene (HDPE), low-density polyethylene (PE) and linear low-density PE (LD, LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyurethane resins (PUR), but also polyester, polyamide, and acrylic (PP&A) fibers. Polyethylene makes up the largest group in total non-fiber plastics production (HDPE, LD and LDPE combined) (Geyer et al., 2017).

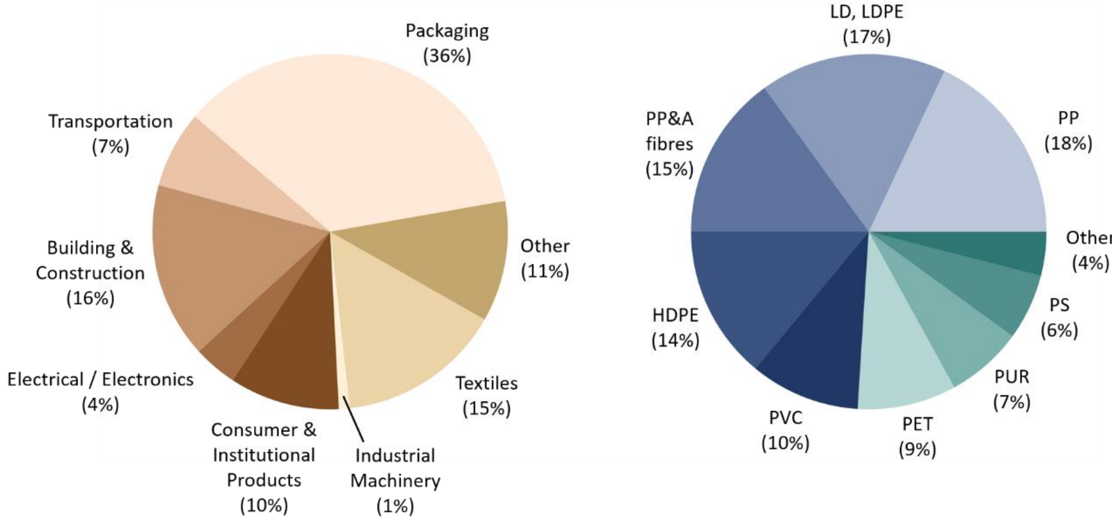

Figure 1: Shares of industrial use sectors in global primary plastics production in 2015 (left) and shares of polymer type in global primary plastics production in 2015 (right); Adapted from Geyer et al. (2017), "Production, use, and fate of all plastics ever made"

The data from Geyer et al. (2017) shows, that the packaging market is by far the largest end-user segment, accounting for more than one third of global plastics demand. This segment includes consumer packaging, such as PET beverage bottles, the packaging used in industry at large or in the business-to-business sector. In total, about 42% of all non-fiber plastics are used for this segment, which are mainly composed of PE, PP and PET (Geyer et al., 2017; International Energy Agency, 2018). Plastic packaging volumes are expected to continue to grow strongly, more than quadrupling to 318 million tons annually by 2050 (Ellen MacArthur Foundation, 2016). This is roughly equivalent to the total amount of plastics produced today.

These numbers illustrate the success of plastics, but they also provide a perspective on the future developments that will very likely accompany this mass production and the projected surge in consumption. This fact has also increasingly become the focus of public perception in recent years, which is mainly due to the increasing awareness towards the accumulation of waste in natural environments and the harmful effects for wildlife due to ingestion or entanglement in plastics (Thompson et al., 2009). But there are also concerns about chemical leaching from plastic products and the potential for plastics to transfer chemicals to wildlife and humans (Ellen MacArthur Foundation, 2016; Thompson et al., 2009)

To address these issues and to facilitate the transition from fossil resources to renewable feedstocks, interest in bioplastics is increasing because, unlike conventional plastics, they are associated with lower greenhouse gas (GHG) production (Coppola et al., 2021). However, the term "bioplastic" can be misleading, as these materials are often commonly referred to as being sustainable, environmentally friendly, and a better alternative to its fossil counterparts, but this is not necessarily the case. Figure 2 shows a classification of common types of plastics according to two properties that are significant in this respect: on the one hand, the biobased nature of the raw materials used and, on the other hand, biodegradability (European Bioplastics, 2015). Plastics that are widely referred to as bioplastic can be classified into three groups, highlighted in green and blue.

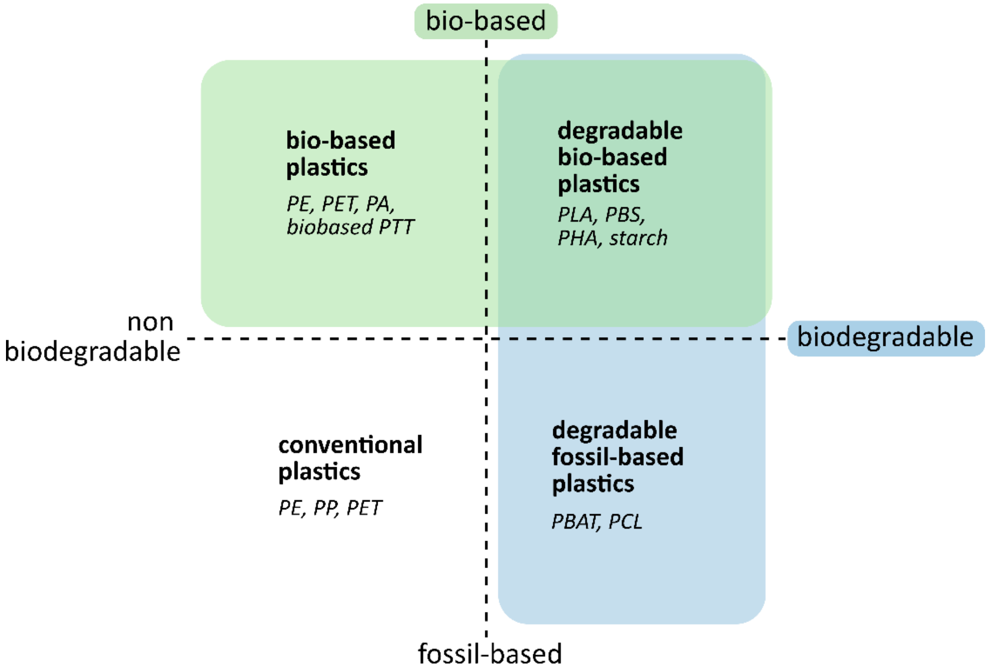

Figure 2: Classification of common types of plastic according to their feedstock and biodegradability; Adapted from European Bioplastics, 2015: "Fact sheet: What are bioplastics?"

The vast majority of the conventional plastics used today are made from fossil resources and are not biodegradable, such as PE, PP and PET (Geyer et al., 2017). Nevertheless, the fact sheet from European Bioplastics (2015) also includes a comparatively small group of biodegradable fossil-based plastics, such as polybutylene adipate terephthalate (PBAT) or polycaprolactone (PCL). These materials are mainly added to other biocompounds in combination with starch to improve application-specific properties (bottom right in blue, Figure 2). In contrast, however, there are plastics that are made from a biobased raw material but are not biodegradable (top left in green, Figure 2). PE and PET are again examples in this category, as they can also be produced from biobased raw materials. These plastics are also referred to as "drop-in" bioplastics, since adjustments only have to be made at the beginning of the value chain, while the properties of the products remain unchanged. The group of biobased, non-biodegradable materials also includes, for example, polyacrylic fibers (PA) and polytrimethylene terephthalate (PTT). These materials are used in a wide variety of applications where biodegradability is not a required property, e.g., in textiles, carpets or in automotive applications. The last group, that of bio-based and biodegradable plastics, includes naturally occurring biopolymers, such as polyhydroxyalkanoates (PHA) or starch, but also polyesters such as polylactic acid (PLA) (top right in green and blue, Figure 2). These materials have only been commercially available for a few years and until now have mainly been used for packaging. Nevertheless, there is an ongoing development that is taking place in this group, with the introduction of new bio-based monomers and compounds, as well as ongoing research for end-of-life solutions besides biodegradability, such as recycling (European Bioplastics, 2015).

Part of this development is polyethylene furanoate (PEF), a novel polymer that, according to Coppola et al. (2021), is anticipated to enter the commercial market by 2023. It is seen as a promising alternative to the widely used fossil-based PET due to its superior barrier properties and can be produced from ethylene glycol and 2,5-furandicarboxylic acid (FDCA) (Coppola et al., 2021). PEF also has advantages over PET from an environmental point of view, as it enables a reduction in non-renewable energy demand from 51% to 43% and GHG emissions from 55% to 45% (Eerhart et al., 2012). In addition, a first step towards the implementation of a PEF recycling stream was taken in 2017, in which the "European PET Bottle Platform" has awarded an interim approval for the recyclability of PEF in the European bottle recycling market (BASF, 2017; EPBP, 2017).

1.2 2,5-Furandicarboxylic acid: a renewable candidate for bioplastics?

FDCA is the key monomer in PEF production and belongs to the furan family (Sousa et al., 2016) . It contains two carboxyl groups in opposite positions on a central aromatic ring (Figure 3).

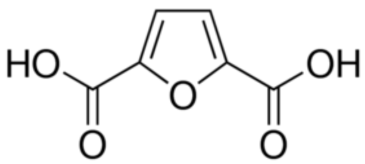

Figure 3: Structural formula of 2,5-furandicarboxylic acid

This structural similarity to terephthalic acid (TPA) makes it a suitable substitute for fossil-based TPA, a predominant compound in polymer and resin production, with a potential market size of several 100 M€ (Wojcieszak and Itabaiana, 2019), although the corresponding reference time span of this value is unknown. In particular, its suitability for generating PEF has earned it the title of “sleeping giant” (Sousa et al., 2015; Tong et al., 2010). According to Wojcieszak and Itabaiana (2019), however, FDCA is also seen as a promising building block for a variety of other downstream products and applications. It is a suitable monomer to produce polyesters, polyamides, polyurethanes, thermosets, and plasticizers. This variety of possible materials results in a broad range of applications, for example in plastic bottles, packaging, fibers, textiles, resins, and films (Wojcieszak and Itabaiana, 2019).

FDCA can be produced from biomass-based carbohydrates, e.g., fructose and glucose, by various routes, generally involving chemical, biological and electrochemical methods (Nam et al., 2018; Yuan et al., 2020). The most common route for synthesizing FDCA from biomass is through the catalytic oxidation of 5-hydroxymethylfurfural (HMF), having commercial potential due to good HMF conversion and FDCA yield. However, there are still various challenges related to product recovery, catalyst recycling, system integration, and production costs (Sajid et al., 2018). Moreover, HMF is of inherent instability and commercially available only in small capacities and at a high price (Dessbesell et al., 2019). Another challenge lies in the feedstocks used, as the main sources of starting sugars for FDCA synthesis are derived from starch-containing food crops, such as corn, and thus could compete with the food chain (Eerhart et al., 2012). Therefore, other routes for FDCA synthesis are being investigated, for example, the synthesis from lignocellulosic biomass (Zhang, J. et al., 2015).

FDCA is seen as a key nearmarket platform chemical and has already been identified as one of the top twelve high potential biobased products by the US Department of Energy in 2004 (Bozell and Petersen, 2010). In 2011, the Dutch company Avantium took an important step towards industrialization of FDCA with a pilot plant producing 40 tons per year (Sajid et al., 2018). Moreover, the commissioning of a flagship plant with a production capacity of 5 kilotons per year is planned for 2023 (Avantium, 2021a). Nevertheless, despite the many advances in FDCA research and promising applications, there is still no relevant market share for this molecule (Sajid et al., 2018).

In FDCA research, efforts in product development have been scattered in individual scientific activities throughout Europe and collaboration between academia and industry has been very limited. Moreover, almost all studies that have been conducted so far are limited to the laboratory scale. To overcome these obstacles, the entire value chain of 2,5-furandicarboxylic acid and derivatives needs to be considered, thus improving collaboration between relevant stakeholders in FDCA research and industry. This can provide important opportunities for overcoming scientific, technological, and industrial limitations (COST Association AISBL, 2019).

2 Research Objective

The goal of the presented thesis is to identify current barriers and challenges that hinder the commercialization of FDCA-based products and to highlight potential future applications. In this regard, an attempt is made to describe possible future visions for FDCA-based products and ways to achieve them. The research questions can therefore be stated as:

- Which economical, technological and sustainability related barriers and incentives are there for the commercialization of FDCA and FDCA based products?
- What would stakeholders along the value chain rate as the most desired future with FDCA-based applications, and what milestones do they believe have to be achieved to reach that future?

To find answers to the research questions, a two-step approach with the combination of a screening of the current literature and a workshop with stakeholders of the technology is applied.

3 Methods

3.1 Literature Review

The systematic literature review is the first part of this thesis and is intended to shed light on the current state of scientific knowledge on FDCA production and products. This includes on the one hand the identification of resources used to produce FDCA and on the other hand application fields for this molecule. Additionally, relevant aspects from the literature that describe the current market situation and sustainability aspects of FDCA and FDCA based products were derived from the literature for subsequent use in the stakeholder workshop.

In the first step, a defined body of literature was generated. An attempt was made to use well-chosen search terms to compile FDCA literature that has a specific focus on economic or sustainability issues, in order to cover market related aspects. For this purpose, the following search terms were applied in the multidisciplinary database Scopus (search query on the 27th of April 2020), based on the search terms used by Wenger et al. (2020), who conducted a similar literature review on lignin:

TITLE ("2,5-furandicarboxylic acid“ OR "furan-2,5-dicarboxylic acid" OR "2,5-furan-dicarboxylic acid" OR "2,5-dicarboxyfuran" OR "fdca" OR "dehydromucic acid") AND TITLE-ABS KEY ("sustainab*" OR "application" OR "market" OR "economic*" OR "financ*" OR "te chno-economic" OR "value-add*" OR "value add*" OR "added value" "cost" OR "price" OR "money" OR "innov*" OR "valori*" OR "decision" OR "busi ness" OR "revenue" OR "environment*" OR "green" OR "social" OR "life-cycle" OR "life cycle" OR "LCA"))

The resulting articles and reviews were limited to the period from 2015 to 2020, although papers from an earlier period were also considered if they were found to be particularly relevant. The resulting collection of articles was examined for the distribution of their topics covered, resources used, products manufactured and key drivers and barriers for the market situation of FDCA-based products. To this end, a list of keywords was compiled with the aim of capturing as many aspects of economic and environmental sustainability as possible (see Table 1). The results from the literature were processed using Microsoft Excel.

Table 1: List of key words for screening the selected literature

Target issue	Search term
Economic aspects, market related aspects	value, billion, market, demand, cost, price/prize, econom*, commercial, industr*, cheap, expensive, innov*, financ*, applic*, business, scale
Sustainability aspects	environment*, sustainab*, green, degrad*, fossil, bio*, recycl*, eco, petro*, renewable, reus*, energy
Challenges and opportunities in general	Benefi*, advantag*, potential, challenge, opportunit*, better, success, promising, important, platform, key, driver, barrier, alternative, replac*

3.2 Backcasting Workshop

The second part of this work consisted of a stakeholder workshop in which the backcasting approach was applied. Backcasting originated in the energy sector, where it was introduced as an alternative planning method for supply and demand of electricity (Lovins, 1976). The predominant forecasting methods at the time attempted to make predictions about the future based on current observations, whereas backcasting begins with a predefined future from which it is attempted to derive ways to achieve it (Grêt-Regamey and Brunner, 2011). According to Robinson et al. (2011), the approach has been expanded to include a more general analysis of alternative desired futures, particularly those that focus on sustainability and can be applied at national and local scales. In addition, within backcasting, the focus has shifted away from scenarios created by researchers to achieve externally defined goals towards participatory approaches, considering the preferred futures of stakeholders (Robinson et al., 2011). According to Quist and Vergragt (2006), the participatory nature of backcasting analyses can address the complex processes required for sustainable developments and changes in current production and consumption systems. Due to the inherent uncertainty of the future and the ambiguity of stakeholders with their different value sets and mental frames, industrial transformations are processes that require the combination of technological, cultural, social, institutional, and organizational changes. Such changes also affect many stakeholders when they diffuse into society and can involve complex processes of social change over the long term (Quist and Vergragt, 2006).

The backcasting approach was decided to be a suitable method to answer the question of how FDCA products could be brought to the market since it allows the involvement of a wide range of stakeholders, not only to identify the problems, but to find solutions and to develop visions for the future as well. This approach considers the supply chain as an interconnected production system and allows economic and social components to be included (Quist and Vergragt, 2006). Robinson et al. (2011) defined the essence of the backcasting approach to futures studies as "the articulation of desired futures, and the analysis of how they might be achieved". This definition was used as the guiding principle in the backcasting approach chosen for this thesis. The method was implemented in an online workshop with 42 researchers and industry representatives participating in the COST Action Fur4Sustain.

To incorporate the backcasting approach in a time-limited online workshop, the methodological framework as described in Quist and Vergragt (2006) and applied by Partidario and Vergragt (2002) was adapted to this setting. To be able to maintain the crucial participatory, interactive element of backcasting in this situation, the interactive presentation software Mentimeter was chosen. Mentimeter is a tool that can be used to create presentations that allow audience engagement in an online setting. The interactive element consists of questions and polls that can be answered in real time during the presentation by the participants via their own smartphones or computers (Mentimeter, 2021). The biggest advantages of this tool compared to traditional survey or interview methods are seen in the better comparability of the context for each participant since it is carried out in a mutual workshop and in the fact that all answers are immediately visible in the presentation. This in turn can stimulate new thought processes and increase social learning among participants, which takes into account the inherent value of participatory processes as tools for social change (Robinson et al., 2011).

In a first step, the value chain of FDCA and the respective affiliation of the participants to particular elements of this chain was considered. Therefore, at the beginning of the workshop, the 42 participants were asked to assign themselves along an illustrated value chain of FDCA products according to their professional background (Figure 4).

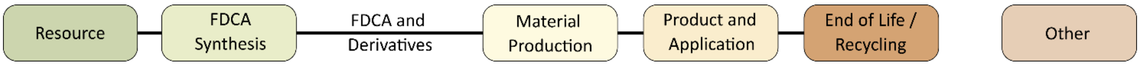

Figure 4: Value chain of FDCA-based products

Subsequently, an attempt was made to summarize the current situation of FDCA-based products. For this purpose, ten general statements on the potentials, challenges and sustainability aspects related to FDCA were derived from the literature review conducted earlier (see 3.1). These statements were presented to the workshop participants, and they were asked to express their agreement or disagreement with the respective statements, assigning scores between 1 (I strongly disagree with the statement) and 5 (I strongly agree with the statement). The slides used during the online workshop are supplied in the Appendix (see Figure 16).

The next steps in the workshop followed the scheme shown in Figure 5. After assessing the participants' level of dis-/agreement with the general statements about FDCA, the opportunity to supply open-ended responses was provided to address aspects that were not covered by these general statements but were necessary to describe the current situation with FDCA-based products (item 1 in Figure 5). The results of the first step were visible to all participants in the presentation. In case new ideas arose as a result, the possibility of submitting several answers was pointed out.

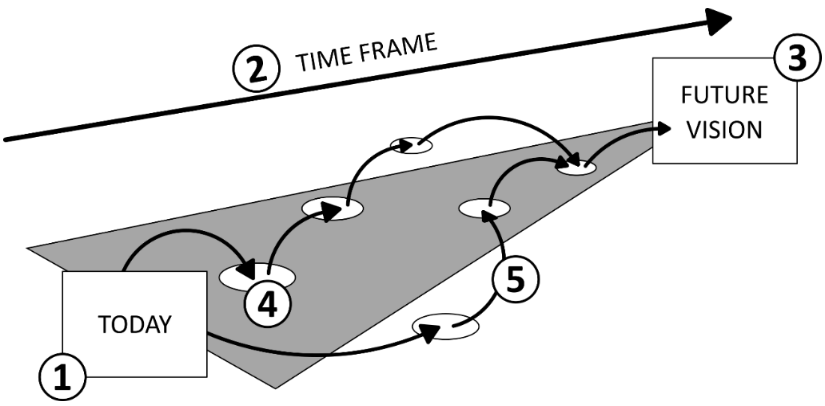

Figure 5: Illustration of the Backcasting process applied in the stakeholder workshop (adapted from Grêt-Regamey and Brunner (2011))

The second step was to define the time frame for the future vision (item 2 in Figure 5). For this purpose, the time frame was set from 2023, which is the end of the COST Action, to 2060, and participants were asked to set their target year for the following definition of the desired future. The mean value was calculated from all the answers given and defined as the collective target date for the desired future visions.

The third step was to define the future vision for FDCA-based products (item 3 in Figure 5). The participants were asked to focus on their personal visions, detached from the current challenges that still exist in relation to this topic. The collected answers were again shown on the presentation visible for all participants and multiple answers per person were allowed. The last two steps related to finding ways to connect the current situation with the desired visions of the future. To this end, the first step was to define milestones that must be reached in order to achieve the desired future vision (item 4 in Figure 5). The final step in the workshop then related to defining appropriate measures for achieving these milestones and, in the further course, the desired vision for the future (item 5 in Figure 5).

For the elaboration of the results, the responses of the workshop participants were thematically categorized by hand using Microsoft Excel. To examine dependencies between professional backgrounds and future visions, a Chi-squared test (as first described by Pearson, 1900) was conducted on the supplied answers (tested with alpha=0.05) in R (RStudio Version 1.1.456), to determine dependencies.

4 Results

4.1 Results of the Literature Review

4.1.1 Thematical composition of the selected FDCA literature

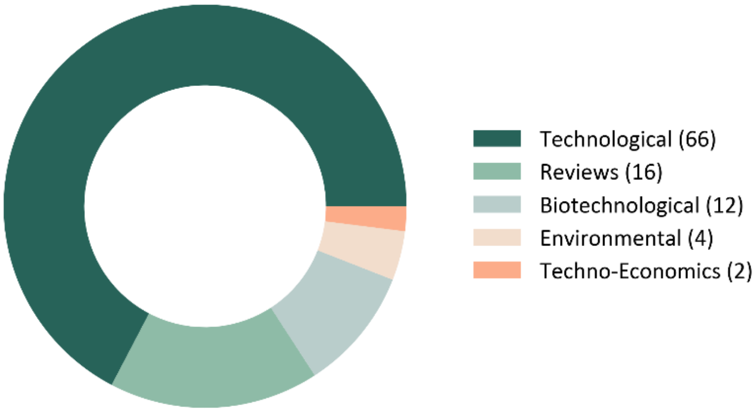

Figure 6: Composition of the examined literature according to scientific focus (n=100 research papers)

Figure 6 shows the distribution of the selected literature according to its research focus (Figure 6, for a detailed list see also Table 6 in the Appendix). By far the largest part of the literature collection consists of papers with a technological focus, i.e., they concentrate on the synthesis of FDCA from various feedstocks or on the production of products from FDCA (66 papers). A smaller part of the literature consists of review papers (16), and about the same number of papers (12) have a biotechnological focus and investigate the enzymatic production of FDCA or products from FDCA. A very small number of papers (4) deal explicitly with environmental issues in relation to the production of FDCA. In addition, only 2 papers were found that address techno-economic issues in relation to FDCA.

4.1.2 Resources for and products from FDCA

A closer look at the feedstocks used for FDCA production shows a clear focus on HMF as the starting material (Figure 7). Most of those papers dealing with the synthesis of FDCA explore the improvement of catalysts for the conversion of HMF to FDCA (e.g. Chen et al., 2017; Gao et al., 2019; Schade et al., 2019). In comparison, only a very small number of papers attempted the synthesis of FDCA from furoic acids, namely from 2-furancarboxylic acid (2-FCA) by Nocito et al. (2019), or from 5-bromofuroic acid (Nocito et al., 2019; Shen et al., 2018; Shen et al., 2019; Zhang et al., 2018; Zhang, S. et al., 2017). Ban et al. (2019) propose 5-methylfurfural (MF) as a feedstock for FDCA production to replace some of the relatively expensive and chemically unstable HMF. Those papers that produce FDCA from fructose, glucose, starch or sucrose mostly choose a one-pot synthesis, which again works via the HMF route. In some cases, this is an attempt to circumvent pure HMF and use crude HMF as a starting material (see also Table 7 in the Appendix).

Figure 7: Frequencies with which certain starting materials are used to produce FDCA in the selected literature.

A closer examination of the technological, biotechnological, techno-economic, and environmental papers shows an imbalance in the frequencies of the published papers when assigned to their respective position along the value chain. The focus of the literature collection is clearly on the production of FDCA from various resources, with 61 papers. In comparison, only 23 papers deal with the manufacture of products from FDCA (see also Table 6 in the Appendix).

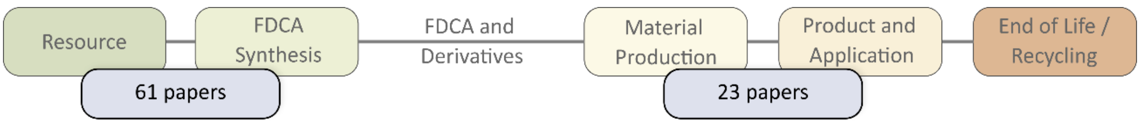

Figure 8: Number of papers, assigned to the respective stage in the value chain

Focusing on the applications for FDCA mentioned in the literature, it is noticeable that the possibility of replacing TPA and producing PEF is consistently mentioned as a specific potential application (in 76 out of 84 papers). In addition, more general applications of FDCA in the production of polymers, fine chemicals, pharmaceuticals and agrochemicals (e.g. Ardemani et al., 2015), and also for polyamides, polyesters and bio-based epoxy resins (e.g. Gong et al., 2017) are mentioned throughout. Another remarkable aspect is that no publication deals with end-of-life aspects of FDCA products.

Figure 9 shows the products and applications that are manufactured in the 23 papers that are on the product development side of the FDCA value chain. As far as the frequencies are concerned, it is noticeable that only 2 papers deal with the production of PEF, while the remaining 21 account for the many different products shown in the figure below (see also Table 8 in the Appendix).

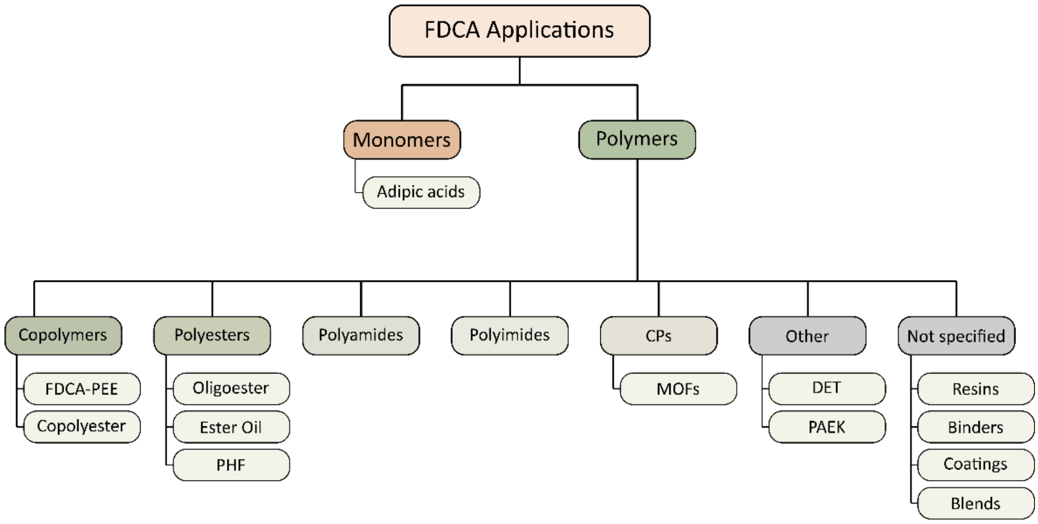

Figure 9: FDCA Applications identified from the literature

In one work, FDCA is used for the production of adipic acid (AA), which in turn can be used as a key monomer to produce nylon 66 and polyurethane (Wei et al., 2019). Moreover, the production of a wide range of different polymers is investigated in the selected literature. Guidotti et al. (2019) produced multiblock copolyesters for bio-based and compostable films in sustainable flexible packaging and Sousa et al. (2016) produced FDCA derived polyetheresters (PEE) for films and microspheres. A wide range of other materials was produced. This included e.g. heat resistant epoxy resins for the application in chemical industry and coating, but also with a potential for utilization in aerospace, new energy and information applications (Miao et al., 2017). Additionally, oligoesters for applications as macromolecules and ester oil for lubricants were produced using FDCA (Cruz-Izquierdo et al., 2015; Fan et al., 2020). Poulopoulou et al. (2020) prepared various polyester blends, including PEF, aiming at expanding the thermo-physical properties of bio-based polymers. Two papers actually dealt with the production of PEF from FDCA, for applications in packaging, bottles and films (Banella et al., 2019; Joshi et al., 2018), another two works are concerned with improving PET, either in attempting to produce bio-based PET (Ogunjobi et al., 2019) or in producing copolyesters for the modification of PET (Sun et al., 2018). Zhang et al. (2019) produced poly(hexylene 2,5-furandicarboxylate) (PHF), which is described as a biomass-based polyester with high performance. Other specific applications of FDCA-based polyesters include polyester binders for polyurethane coatings (García González et al., 2018) and polyester coatings for coil applications (Lomelí-Rodríguez et al., 2018). In addition, some high-performance materials for various engineering applications are also presented. For example, FDCA has been used in the fabrication of coordination polymers (CPs) and metal-organic frameworks (MOFs), both materials that find applications in gas storage and separation, nonlinear optics, catalysis, luminescence, drug delivery, sensing and detection, nanomagnets, heat transformation applications and fluorescence (Dreischarf et al., 2017; Ma et al., 2016; You et al., 2020; Zhao et al., 2017). Similar applications were mentioned for the polyimides prepared in the work of Ma et al. (2018), such as optoelectronic devices, gas separation, smart materials and composite materials.

Polyamides, such as those produced in the work of Cao et al. (2017) and Jiang et al. (2015), are also suitable materials for the utilization in high performance applications, such as heat resistant polyamides for electronic components, in marine, automotive industry, oil industry, electronics, machinery, domestic appliances, medical devices and personal care applications. Furthermore, the poly (aryl ether ketone) (PAEK) produced by Bao et al. (2019) can be used as industrial materials in aerospace, electronics, automotive and other fields.

4.1.3 Defining the present situation regarding FDCA from the literature

After screening the selected literature, statements S01-S10 (see Table 2) were formulated to reflect the general scientific consensus on the current situation of FDCA. The compact formulation was chosen to facilitate the presentation of the statements in the backcasting workshop.

Table 2: General statements on the potential, challenges and sustainability aspects of FDCA-based products

Category	**Nr.**	**Statement**
Potential of FDCA products	1	FDCA is a product with a high added value. There is a great potential in the utilization of FDCA.
	2	Currently, the market for FDCA is limited.
	3	FDCA is a promising material and can be an alternative to other materials.
	4	There are bright market prospects and an increasing demand for PEF.
Challenges in the production of FDCA and FDCA products	5	There are still some difficulties in the production of FDCA from biomass.
	6	HMF is at the moment the primary starting material for the production of FDCA.
	7	It's a technical challenge to further process FDCA into value-added products.
Sustainability aspects of FDCA products	8	Environmental concerns related to mineral oil are a major driver for the interest in producing FDCA from biomass.
	9	FDCA is a sustainable, environmentally friendly product.
	10	FDCA has the potential to reduce the dependence on fossil fuels.

4.2 Results of the Stakeholder Workshop

4.2.1 Defining the present situation from the experts point of view

Agreement with the statements S01-S10 was consistently high (see Figure 10), with a median score of 4 for statements S01-S03, S05, S06, and S08-S10. Only statements S04 and S07 resulted in a median score of 3, which indicates neutral sentiment.

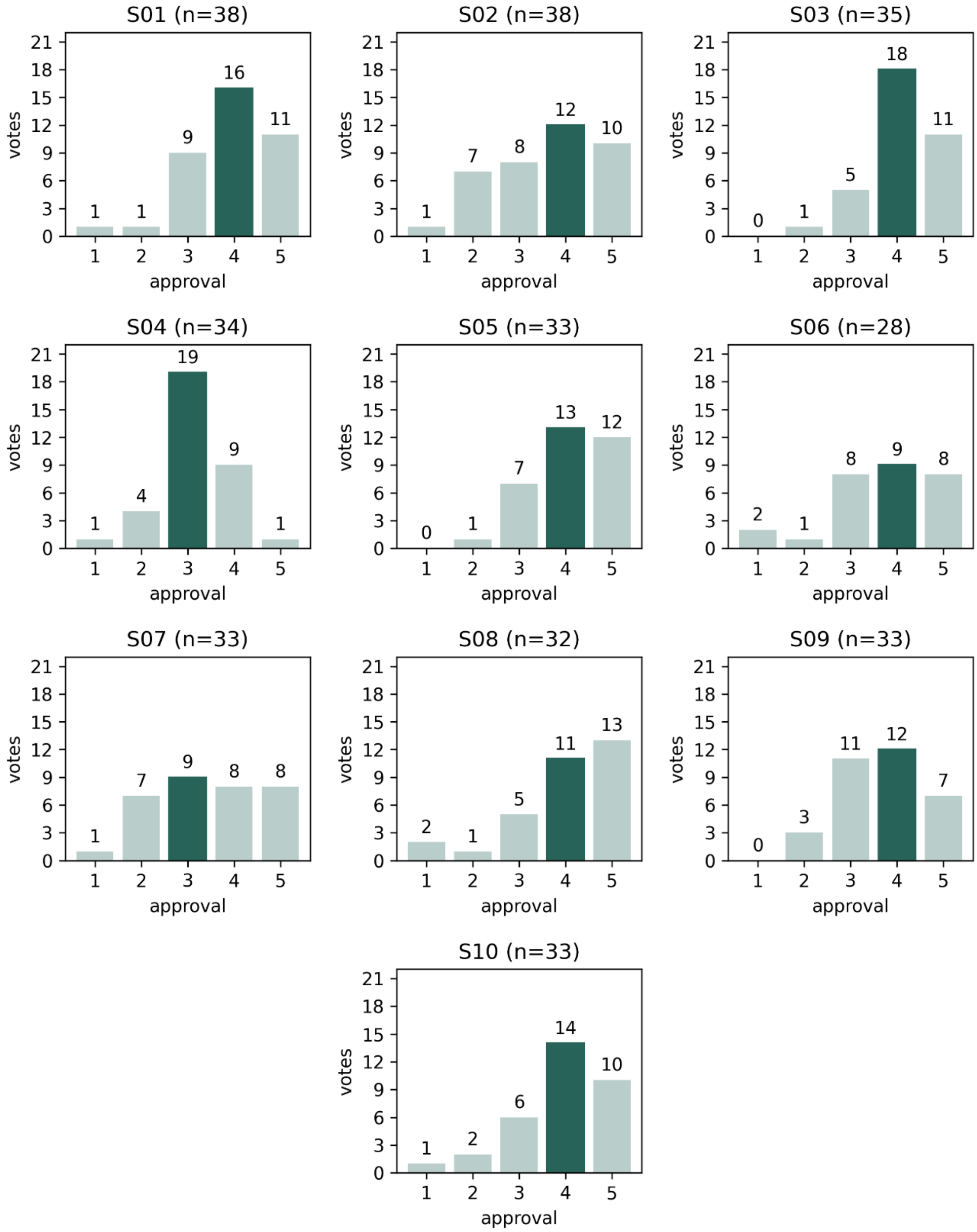

Figure 10: Workshop participants' responses to presented statements on the current situation regarding FDCA (See also Table 9). The level of agreement is shown on the x-axis, the number of participants showing the respective level of agreement is shown on the y-axis. The dark green bar indicates the median.

In summary, this means that the workshop participants consider FDCA to be a product with a high added value and with great potential in its utilization (S01). Although the market for FDCA is currently seen to be limited (S02), this molecule is considered to be a promising material that can be an alternative to other materials (S03). Currently, there are still some difficulties in producing FDCA from biomass (S05), and the primary starting material is HMF (S06). FDCA is seen by the workshop participants as a sustainable and environmentally friendly product (S09), with environmental concerns related to mineral oil being a primary reason for the interest in producing FDCA from biomass (S08). FDCA is also seen as having the potential to reduce dependence on fossil fuels (S10). There is average agreement with the statement that demand for PEF is increasing and that bright market prospects can therefore be expected (S04). In addition, the technical barriers to the manufacture of products from FDCA are not considered to be particularly high (S07).

The answers of the practitioners given in the open section of the workshop regarding the current situation of FDCA are supplied in Table 10 in the Appendix. By a wide margin, economic considerations, in particular the price of FDCA, were seen as the biggest obstacle to market introduction (Figure 11, blue bar). It was highlighted by the participants that FDCA is currently not yet market competitive with respect to oil prices and that FDCA is only available in limited quantities.

Some factors were also mentioned regarding environmental aspects (green bar). All statements in this area related to the end of life of FDCA products, such as biodegradability and difficulties in processing FDCA products together with already established materials in the existing recycling stream.

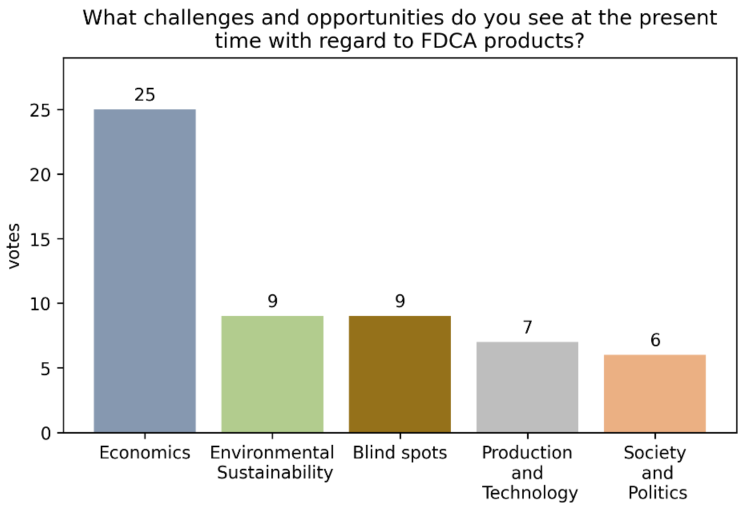

Figure 11: Responses on challenges and opportunities with regard to FDCA products, according to thematic clusters represented by the colored bars (n=30 participants)

In addition, the participants pointed out important fields that do not seem to be the focus of attention so far (brown bar). For example, it was mentioned that the emphasis on FDCA alone is too strong and that it would make sense to investigate other FDCA derivatives and furans as well. Similarly, the strong focus on PEF as an end-use application was also critically noted and it was pointed out that suitable niche applications for FDCA also need to be explored.

A small part of the answers referred to production and technology. Regarding the production of FDCA, mainly by-products from the synthesis and purity of the final product, but also thermal stability of furans were mentioned as relevant aspects (Figure 11, grey bar). Also, the advantages of FDCA over TPA were highlighted based on its favorable atom economy, and the compatibility with PET infrastructures was pointed out.

Only a few responses were categorized under Society and Politics, and thus seem to be less prominent in the current situation from the viewpoint of the participants (orange bar). These answers were mainly related to the need for a shift in thinking in general. This includes, on the one hand, consumers, and their acceptance of the products on the market but also politicians who set the regulatory framework.

4.2.2 Visions for a future with FDCA-based products

In the next step, a time frame for the ideal future vision with FDCA-based products was determined by the workshop participants. The mean value was calculated from all the answers, resulting in a target date of 2033 (see Table 11 in the Appendix).

Figure 12 shows very clearly that participants' responses regarding their desired future vision relate strongly to applications for FDCA (Figure 12, yellow bar). In general, most statements were related to PEF, and very specific ideas of what this future could look like became clear. The vision was expressed that PEF would be commercially available in 2033, with different market shares being mentioned. For example, a complete replacement of TPA by FDCA, or only a partial replacement of 20-50% was considered desirable by the different participants. Again, some participants pointed out other possible applications than bottles and food packaging for FDCA, such as high-performance engineering bio-based plastics, textile fibers made of 100% PEF or a FDCA share of 10% in polymers for coating. Moreover, in the future FDCA-based materials could just be one among many other materials, and only used where needed.

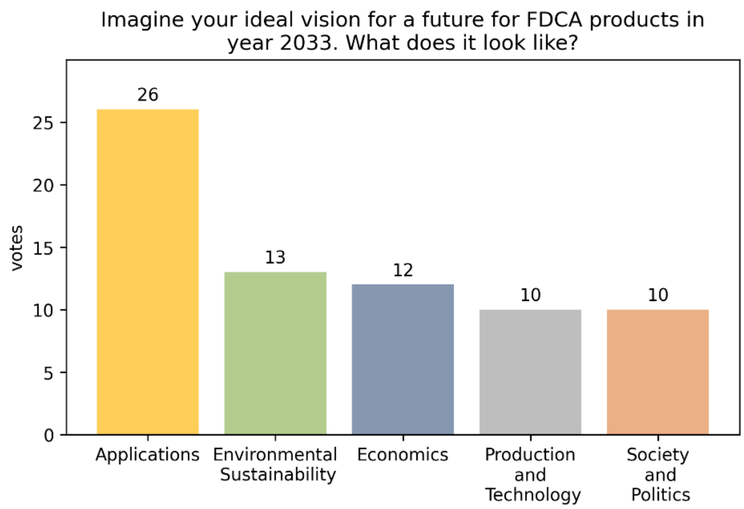

Figure 12: Responses to the question about the idea of an ideal future vision, according to thematic clusters represented by the bars (n=26 participants)

Environmental sustainability also plays a prominent role in the participants' visions of the future (green bar). Part of the future vision was that the planet earth would generally be on a cleaner path by the target date, e.g., using wind and solar power or carbon capture and utilization technologies. In addition, a general decrease in consumption per capita was also mentioned as an important part of the future. Moreover, recycling was predicted to be subjected to a change process, with technical feasibility and sustainable end-of-life scenarios for FDCA products.

Furthermore, some answers were given with a more economic focus (blue bar). For example, the vision of a circular economy was expressed, in which FDCA plays an important role and a higher bio-based share is generally found in commercial products. A more economical production of FDCA products was defined as a clear target vision, for example through better availability of cheaper feedstocks and scale up. In addition, in the desired future vision, FDCA should be available at a reasonable price in conformity with the market, and thus also achieve a certain market share. A vision was described that by the end of the timeframe several facilities in Europe will produce FDCA for different applications and that this molecule will replace its fossil counterpart if the final product is more sustainable. A global production of FDCA of 200 kt per year, of which 100 kt will be used for PEF and the rest for other applications, was also defined as a clear vision.

Some relevant aspects regarding production and technology were also mentioned (grey bar). The vision that the principles of green chemistry should also be realized in furan development, rather than focusing only on "green" materials, was very clear. In general, improvements in furan product development were mentioned as an important component of the future vision, together with further pilot and demonstration plants and additional funding for further research and process optimization. Furthermore, production of FDCA from non-food resources was mentioned as an important component of the desired situation in the future.

In the vision of the future, as well as in the present, the role of society and politics seems to be on the sidelines (Figure 12, orange bar). Still, some important aspects were mentioned by the participants that are part of the desired vision of the future. These include, on the one hand, the consumer side, where a significant amount of education and awareness about sustainable materials has happened, and, on the other hand, the policy side, which is concerned with regulation. This could be implemented in the future through a joint approach at the European level, by promoting the production of FDCA-based products, for example, through the financing of sustainable materials and carbon taxes.

4.2.3 Milestones on the path to the future vision

In the next step, the participants of the backcasting workshop were asked which milestones, from their point of view, must be reached to achieve the desired future vision (Figure 13). Corresponding to the participants description of the present situation, the primary obstacles mentioned to achieve the desired future vision with FDCA were related to economics (Figure 13, blue bar). In this context, the availability of FDCA on a commercial scale and at a competitive price, e.g., less than 10€/kg, was mentioned above all, but also feedstocks available at low cost and a clear scale up in production were mentioned. This includes the need to increase the number of FDCA producers in general and the role of investments from the European Union for the establishment of larger production facilities for FDCA.

Again, the replacement of TPA by FDCA was seen as another important milestone, but also the need to further diversify the product portfolio of FDCA and thus to be a real alternative to other polymers besides PET.

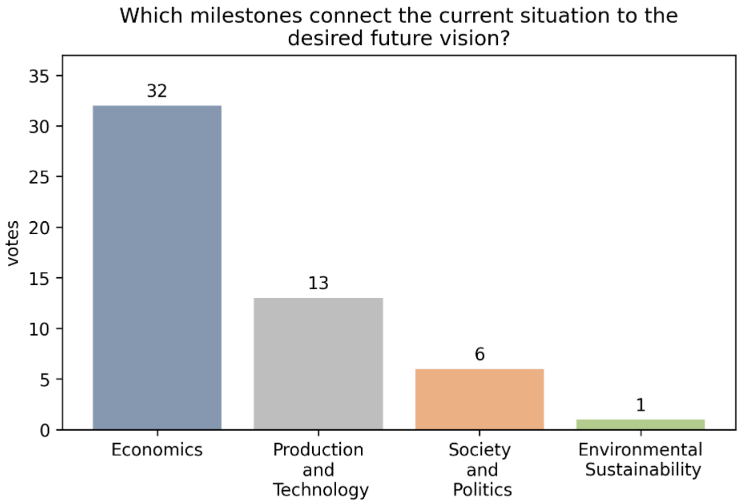

Figure 13: Responses to the question about the milestones to be reached until the future vision is achieved, according to thematic clusters represented by the bars (n=22 participants)

Milestones in the area of production and technology make up the second largest pillar for achieving the vision of the future (Figure 13, grey bar). Here, the participants primarily mentioned aspects such as purity or meeting technical standards of products, but also further process development. On the one hand, the achievement of a fully developed sugar to furan technology was mentioned, but also the utilization of lignocellulosic biomass for FDCA production. As a further important component of these milestones, the participants saw a necessary shift in the field of research, away from purely academic work, towards a more applied research, involving industry, manufacturers, and end users.

Again, a small part of the answers referred to the role of society and politics (Figure 13, orange bar). Still, the participants saw regulations, e.g., plastic bans, as important milestones in this area to promote bio-based products. The role of society was seen as important in the sense that public opinion could influence political decisions.

A brief statement concerned the safety of furan-based products. Thus, these materials should be safe for humans and the environment, but most importantly, they should not be hazardous after decomposition in the environment.

In the last step of the workshop, the participants were asked about measures that would be suitable to reach the milestones mentioned above and thus gradually achieve the vision of the future (Figure 14). A clear shift is evident here, as the role of society and politics was now considered to be the most important component (Figure 14, orange bar). Many participants emphasized that a change in behavior of society in general will be necessary, which could be achieved, for example, through more education and information. On the political side, legislation was seen as an important part of achieving the milestones, as it could increase investment in furan production and financial resources for further research and FDCA and FDCA derivatives. Consumers were also considered to play an important role, above all, the necessary willingness to pay more for bio-based products was emphasized.

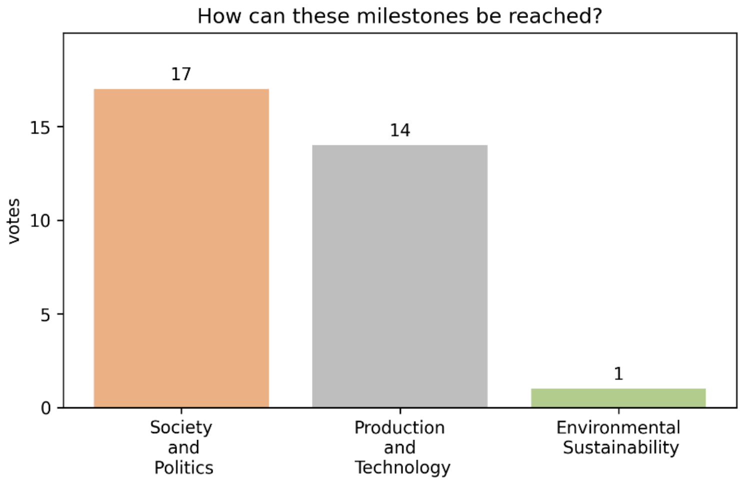

Figure 14: Responses to the question on measures to reach the milestones, according to thematic clusters represented by the bars (n=19 participants)

A sizable number of the proposed measures were aimed at the area of production and technology (Figure 14, grey bar). In particular, the need to explore alternative production methods for FDCA products was highlighted by participants, especially enzymatic routes and biotechnology. In general, sugar to furan technology should be improved, with several producers engaged in dedicated research. In this context, the need for better mutual understanding regarding the respective work of different professions involved in furan product research was also emphasized. One participant pointed out that compounding and microstructure are essential in materials processing, and awareness of this is needed among molecule manufacturers.

A participant also mentioned pressure from climate change, which, as an external factor can support driving action to achieve the milestones toward a future with FDCA-based products.

4.2.4 Perceptions of the future depending on participants' professional backgrounds

Figure 15 shows the total distribution of the participants according to their professional expertise, as they categorized themselves at the beginning of the workshop. All answers given are supplied in Table 11 in the Appendix.

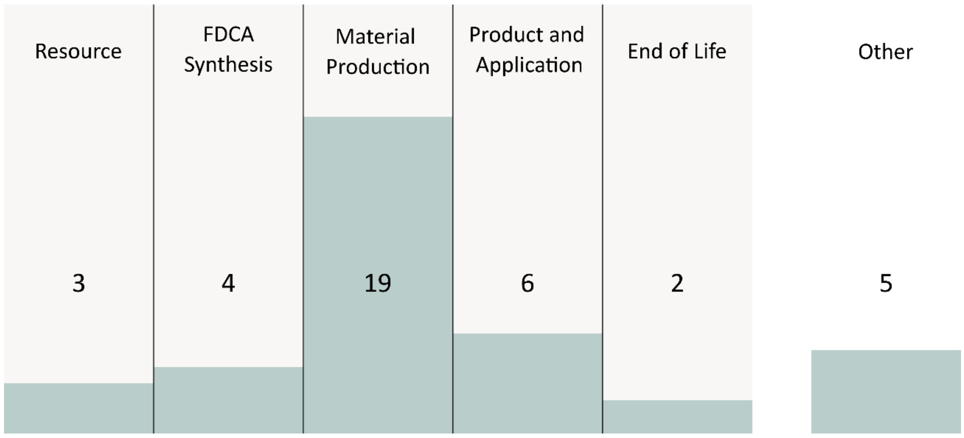

Figure 15: Assignment of workshop participants according to their professional backgrounds

The following cross-table (Table 3) shows the distribution of the given answers with regard to the self-assigned professional background.

Table 3: Cross-table of professional background and thematic category of the given answers, including totals

		Future Vision					
		App.	Env. Sus.	Eco.	Prod. Tec.	Soc. Pol.	Σ
Professional Background	Res.	0	6	1	0	0	**7**
	Syn.	3	0	1	0	0	**4**
	Mat. Prod.	12	2	5	2	4	**25**
	Prod. App.	8	5	3	7	6	**29**
	EoL	0	0	1	0	0	**1**
	Other	1	0	1	1	0	**3**
	Σ	**24**	**13**	**12**	**10**	**10**	69

What is particularly noticeable in this table is, that people involved with resources pay the most attention to environmental sustainability in their vision of the future.

This table also shows that some cells are filled with only a few responses or none at all. In order to meet the test requirements for the Pearson chi-squared test (expected frequencies > 5), aggregations were made for the fields "Professional Background" and "Future Vision", respectively. For this reason, the "Resources," "End-of-Life," and "Other" categories were omitted altogether because there were too few responses to meet the requirements. As shown in Table 4, the categories "FDCA Synthesis" and "Material Production" were then combined, while the "Product and Application" category was retained. For the response categories, "Environmental Sustainability" was combined with "Production and Technology" and the "Economics" category was combined with "Society and Politics", whereas the "Applications" category was retained. This results in the following cross-table with observed frequencies for the Pearson chi-squared test, which was conducted in R:

Table 4: Cross-table for the Pearson chi-squared test; observed frequencies with aggregated professional backgrounds and aggregated categories of the given answers, including totals

		Future Vision			
		Applications	Environmental Sustainability, Production and Technology	Economics, Society and Politics	Σ
Professional Background	FDCA Synthesis, Material Production	15	4	10	**29**
	Product and Application	8	12	9	**29**
	Σ	**23**	**16**	**19**	**58**

This results in the following values for the expected frequencies:

Table 5: Expected frequencies calculated from the cross-table with aggregated categories

		Future Vision			
		Applications	Environmental Sustainability, Production and Technology	Economics, Society and Politics	Σ
Professional Background	FDCA Synthesis, Material Production	11,5	8	9,5	**29**
	Product and Application	11,5	8	9,5	**29**
	Σ	**23**	**16**	**19**	**58**

The conducted Pearson chi-squared test shows that the participants' imagined ideal future vision for FDCA products in 2033 is significantly dependent on their professional background ($p=0.045$).

While individuals engaged in synthesis and material production in the field of FDCA refer in their future vision mainly to market applications of FDCA, individuals engaged in FDCA products and applications refer in their future visions for FDCA mainly to developments in production, technology, research, and development, and increased environmental friendliness. The categories of economics, society and politics, on the other hand, occur with equal frequency in the visions of the future of both professional groups.

5 Discussion

5.1 Technical aspects

The first part of the presented thesis gathers the state of the current scientific literature on FDCA. Dividing the resulting literature into two groups, namely that of FDCA production and that of FDCA-based products and comparing how many papers can be assigned to each category, a clear overbalance in the synthesis of FDCA becomes apparent, while the development of possible applications of the substance is less prominent. One possible explanation for this finding could be, that there is simply a greater need for research in FDCA synthesis. The assumption is also consistent with the outcome of the workshop, where participants strongly agreed with the statement "There are still some difficulties in the production of FDCA from biomass" (S05), while the statement "It's a technical challenge to further process FDCA into value-added products" (S07) was received neutrally.

Most of the included papers which deal with FDCA synthesis use some form of HMF as starting material; either by creating it as an intermediate from a bio-based feedstock like starch or glucose, or by purchasing pure industrial HMF. Again, this result is supported by the responses of workshop participants who strongly agreed with the statement that HMF is currently the primary starting material for FDCA production (S06). This is particularly noteworthy, since the production of HMF is described as cost- and resource-intensive and not sustainable (in e.g. Schade et al., 2019) and even the oxidation of HMF into FDCA leaves room for improved sustainability according to Mei et al. (2015). Additionally, Motagamwala et al. (2018) note that in order to be economically feasible, FDCA synthesis from HMF has to be carried out at high HMF concentrations. A fact, that is also noted by Hameed et al. (2020) who state, that most of the reported studies with high FDCA yield in the aerobic oxidation of HMF have been performed with diluted HMF, which is not realistic for the practical production of FDCA on an industrial scale. According to Liu et al. (2020), the direct utilization of carbohydrates-derived crude HMF as feedstock could be an intriguing alternative from an economic perspective, because the costly and difficult HMF separation/purification procedure could be circumvented. Unfortunately, impurities induced when crude HMF or biomass are used as the starting material for the creation of pure HMF, and later FDCA, make the process inefficient due to lowered catalyst activity as noted by Schade et al. (2019), Liu et al. (2020) and Rathod and Jadhav (2018). In this regard, Ogunjobi et al. (2019) also refer to catalysts as critical elements in FDCA synthesis due to their high economic value and the tendency to deplete if used continuously, as well as the fact, that their supply could be restricted for geopolitical reasons. Moreover, HMF itself is currently produced only to a limited extent from mono- and polysaccharides such as glucose and fructose, as noted by Shen et al. (2018), which is a barrier to the utilization of bio-based FDCA as a substitute for TPA in industrial applications.

Therefore, the choice of feedstock is a key consideration in the scale and efficiency of renewable resource-based processes (Schade et al., 2018). Also, according to Jong et al.

(2012), a strategy that allows great flexibility in obtaining feedstock for companies is beneficial, ranging from sustainable production to availability at the production site, as well as reliable logistics and general affordability.

According to Ogunjobi et al. (2019), cellulose is the most attractive feedstock for the synthesis of bio-based PET, given its high abundance and the large amounts of cellulose waste produced annually in Europe. The successful production of FDCA from lignocellulosic biomass is demonstrated in studies like Zhang, J. et al. (2015) or Jing et al. (2019) and discussed in e.g. Bello et al. (2019). The conducted literature review identified a few more papers dedicated to FDCA synthesis from other starting materials than HMF. For example, Ban et al. (2019) studied the preparation of FDCA from the chemically more stable 5-methylfurfural (MF), but yield and purity were found to be lacking behind, compared to the conventional oxidation of HMF. Shen et al. (2018) produced FDCA through carbonylation of 5-bromofuroic acid with excellent yield. According to Jong et al. (2012), Avantium planned to use commercially available carbohydrates like sugar and starch, but non-food feedstocks would be compatible with the process as well. Furthermore, Nocito et al. (2019) discussed the use of 2-FCA for FDCA synthesis, which can be sourced from biomass.

A different route of FDCA synthesis is discussed in a handful of papers focusing their attention on the improvement of biotechnological approaches in this area, an emerging field that was also highlighted by workshop participants as being important. These publications work towards finding ways to synthesize FDCA using biocatalysts in multi- or single-stage (e.g. Hossain et al., 2017) processes which can often be carried out under ambient conditions avoiding the high temperatures and pressures needed in most conventional processes (Lin et al., 2020). Furthermore, current biotechnological processes were able to offer equally high FDCA yield (e.g. 94.2% in Chang et al., 2019) while producing fewer toxic waste (Lin et al., 2020). However reaction times of these processes were relatively long, ranging from about 10 hours (Wu et al., 2020) up to multiple days (Hsu et al., 2020; Lin et al., 2020; Rajesh et al., 2019; Wang et al., 2018). Further challenges of the reported biocatalytic processes include the need for continuous feeding and low product recovery in whole-cell variants according to Wu et al. (2020), or enzyme instability and limited reusability as stated in Wang et al. (2018). It remains questionable, whether the benefits regarding environmental sustainability outweigh the drawbacks related to the long reaction times, which could hinder these processes to be implemented on an industrial scale.

5.2 Economic aspects

Workshop participants identified economic considerations, in particular the price of FDCA, as the primary factor in the current challenges to bringing FDCA-based products to market. Also, according to Motagamwala et al. (2018), the only bottleneck in producing pure bio-based PEF is the lack of economical FDCA production. In the literature only two papers were identified that address techno-economic issues, although a few technological papers also provide considerations of this type. These papers indicate possible prices for FDCA. Dessbesell et al. (2019) presented a techno-economic analysis for the production of FDCA from starch, glucose, and high-fructose corn syrup (HFCS) via the HMF route. They demonstrated that the production of FDCA using low-cost catalysts is promising. For all scenarios studied, it was found that they become attractive with a selling price above 2000 $/t FDCA. The economically most beneficial commercialization process identified was the production of FDCA from HFCS, with a minimum selling price (MSP) of ~1800 $/t for FDCA and a discounted payback period (PBP) of 5 years. Variations in feedstock costs, catalyst costs, selling price of recovered catalyst, and total investment were identified as the factors to which the technology is most sensitive. Further research was considered necessary, particularly in the uncertainties of scaling up the process, to reduce risks and achieve successful implementation of commercial FDCA production (Dessbesell et al., 2019).

Triebl et al. (2013) compared two different production routes for FDCA from oxidation of HMF in their techno-economic study and were able to show how the selling price of FDCA changes when various factors are changed in production. They were able to reduce the MSP significantly by using crystallization, filtration, and pure oxygen as the oxidant. Thus, depending on the scenario, the MSP ranged between 2458 $/t and 3885 $/t (Triebl et al., 2013).

Rao et al. (2018) also carried out a preliminary techno-economic investigation in their technological study on the preparation of a catalyst for the oxidation of HMF to FDCA. They found, that for the production of 42638 t/a of FDCA from corn starch the economic feasibility of the process, with a total investment of about $27 million (2016), is highly dependent on the selling price of FDCA. In their analysis, the break-even selling price of FDCA is about 1,800 $/t for profitable production of FDCA from starch, while at a FDCA selling price of 2,000 $/t, the net present value (NPV) would be $90 million, with a payback period of about 5 years. However, they also note that the current selling price of FDCA is not available due to the lack of large-scale production (Rao et al., 2018).

Motagamwala et al. (2018) also included a techno-economic model in their study on the production of FDCA from fructose via the HMF pathway. They were able to produce FDCA at an MSP of 1490 $/t with the help of a special solvent system, the ease of product separation, the use of stable heterogeneous catalysts, and the use of FDCA as a dehydrogenation catalyst. HMF production accounts for the largest share of total costs due to high feedstock costs, followed by FDCA production as the second largest contributor. They state, that increased catalyst activity and lower feedstock costs could further reduce the MSP of FDCA to 1310 $/t (Motagamwala et al., 2018).

Since FDCA is considered a direct substitute for TPA, the price of FDCA should be competitive with, or, at best, be below the price of TPA to facilitate market entry. As TPA is produced from fossil raw materials, its price is strongly dependent on crude oil prices and thus subject to fluctuations. However, Dessbesell et al. (2019) give a range of 900 to 2200 $/t for the TPA price citing Burry (2015) and Guzman (2012), whereas Motagamwala et al. (2018) assume a value of 1445 $/t. In this respect, the market size for TPA is also worth considering, which is said to be over 50 million tons per year, according to Shen et al. (2018).

The workshop participants also mentioned economies of scale as a relevant factor in the current challenges in commercializing FDCA. This can be seen as a barrier, as they do not yet exist, but also as an opportunity, as they could reduce costs by increasing production volume. According to Ghatta et al. (2019), the separation and purification steps in FDCA production are crucial for a possible scale-up of FDCA production. Gao et al. (2018) state, that the development of non-precious metal catalysts for the selective oxidation of HMF is highly desirable because the very high cost of noble metals is an obstacle to large-scale industrial implementation.

5.3 Sustainability aspects

Furthermore, issues with sustainability along the production chain were apparent when studying the current literature. Four scientific papers were identified, that specifically address the environmental sustainability of FDCA and FDCA-based products. Bello et al. (2019) performed a life cycle assessment (LCA) to gain a better understanding of the production of FDCA and HMF from lignocellulosic feedstock from an environmental perspective. They state that the whole process is still energy-demanding and in need of conventional solvents, some of which have been shown to be harmful for environment and health (Bello et al., 2019).

The key substance regarding environmental concerns seems to be HMF, as various studies mention its problematic nature. On the one hand, a study by Chen, G. et al. (2016) on the soil toxicity of FDCA, HMF and TPA found significant negative influence of HMF on the reproduction of certain soil invertebrate in sterilized soil, while FDCA and TPA did not exhibit the same behavior. The authors conclude that, in order to keep the environmental risk during FDCA production low, the process should be performed under contained and controlled conditions, thus minimizing the risk of HMF being released into the environment (Chen, G. et al., 2016). The environmental impact of HMF was also identified as highly relevant in a life cycle assessment performed by Bello et al. (2020), which compared FDCA production processes based on crystallization and distillation.

However, even though García González et al. (2018) noted that more in-depth research on the environmental burden of FDCA is needed, they were able to assess a reduction of 79% of greenhouse gas emissions in their LCA regarding a furan-based polyester binder in comparison with its traditional fossil-based counterpart.

Participants in the backcasting workshop also mentioned concerns related to environmental sustainability as an important factor affecting the market introduction of FDCA and FDCA-based products. However, their statements were mainly related to end-of-life related issues, such as the biodegradability and difficulties in processing FDCA products together with already established materials in the existing recycling facilities. According to Terzopoulou et al. (2016), furan-based polymers are recyclable, yet non-biodegradable. However, according to Avantium (2021a), degradation tests show, that compared with PET, PEF degrades much faster under industrial composting conditions and an ongoing 10-year degradability field trial so far showed, that PEF degrades under ambient conditions. Ogunjobi et al. (2019) note that, while the primary use of FDCA to date is replacing TPA in PET, the influences of PEF in the existing PET recycling stream are still subject to investigations, but a possible way of tackling furanoate in a terephthalate recycling stream could be, that furanoate impurities in terephthalate streams convert to terephthalate itself, thus offering an alternative for chemical recycling (Ogunjobi et al., 2019). On the other hand, according to Avantium (2021b), PEF has proven fit with existing sorting and recycling streams. They also state, that due to its good barrier properties for carbon dioxide and oxygen, it could also enable a longer shelf life of packaged products. Additionally, this makes the production of a lighter bottle compared to PET possible, which could save resources and transport cost (Avantium, 2021b).

Poulopoulou et al. (2020) also propose a solution to the lack of industrialization of furan-based polymers. According to them, the drawbacks of these polymers (slow crystallization, reduced thermal stability, coloration) still hinder their industrialization, although the authors note that exploring blending solutions with polymers of industrial importance might enable an inclusion of furan-based polymers (Poulopoulou et al., 2020). While blending different polymers could be promising from a technological point of view and help the commercialization of FDCA, the impact of such materials on the existing recycling streams could be problematic.

5.4 Professional backgrounds and perceptions of the future

Given the scale of the current packaging market (as shown in Geyer et al., 2017), PEF has great potential as an end-use application. However, workshop participants expressed neutrality toward the statement that demand for PEF will increase and that the market prospects are bright (S04). Although in the expressed future visions very concrete ideas became apparent, especially in relation to PEF (e.g., detailed shares with which PET could be replaced), the workshop participants also critically noted the strong focus on PEF and pointed out, that suitable niche applications for FDCA also need to be explored. This could also be important in another respect, as PEF is considered to be the bio-based alternative to fossil-based PET, but as recent advances have shown, the production of ethylene glycol and bioterephthalic acid is feasible, making bio-based PET also possible (Chen, L. et al., 2016). In terms of alternative applications, the literature review was able to show that a wide range of applications for FDCA is possible and is also being explored.

An interesting shift of sentiment could be observed in the last part of the backcasting workshop. While the role of society and politics was found to be miniscule in the question about significant milestones, it was mentioned as the most important lever to reach them. This indicates the need for more regulatory measures like (fossil-based) plastic bans or levies (see e.g. UNEP, 2018), but participants also demanded more funding and education of consumers. It can be assumed, that an elaborated socio-economic approach including regulatory push instead of a neo-classical economy (e.g., profit maximization) trusting on a “perfect” market will be needed to get FDCA into the masses.

The cross-table showed that especially those workshop participants, whose professional background is in the field of resources, refer to environmental aspects and ecological sustainability in their vision of the future. Furthermore, the results of the Pearson chi-squared test show an interesting dependency of the given answers to the question about desired future visions of the industry experts. Those participants who work in technology development tend to refer to developments in the fields of markets and applications for FDCA in their future vision, while those participants who assign themselves to product development tend to refer to technological aspects in their future visions. Thus, both groups tend to refer to developments in the field to which they do not assign themselves.

This result illustrates that stakeholders, depending on their position in the FDCA value chain, have different perceptions regarding the future. It could indicate that there is a need to include industry experts in research activities and vice-versa, and thus tackling information asymmetries, as demanded by one workshop participant.

5.5 Limitations of the study

The limitations of the literature review relate to the described keywords, the selected time frame, and the selected database. The main limitation of the backcasting method used in this thesis lies in the fact that it had to be adapted for a time-limited online workshop. Nevertheless, it was possible to maintain the interactive character with suitable tools, albeit with some compromises in terms of the methodological approach.

6 Conclusion

Although research on FDCA has been going on for many years, no considerable commercialisation has yet taken place. Unlocking FDCAs full potential is restricted by several barriers, which are strongly related to technological and market-related aspects in FDCA production as the conducted literature review and backcasting workshop show. In particular, these barriers include the price of the feedstock, but also resources necessary for production, such as catalysts, solvents and energy demand. The same factors were found to be the biggest influence on the selling price of FDCA, one of the most important levers mentioned for a successful market introduction by the workshop participants. In economic studies figures for a possible FDCA selling price were provided, laying within a competitive range to fossil counterparts like TPA.

While the workshop participants had specific future visions mostly concerning PEF, the products discussed in literature were more versatile, covering a wide array of niche applications. But also, among the workshop participants diverging visions of the future became apparent. Whereas participants with a background in FDCA production referred mostly to required developments in the field of FDCA applications in their desired future vision, participants concerned with FDCA products development mainly referred to open issues related to FDCA synthesis. This indicates a great need for intensified cross-disciplinary communication and collaboration.

While the currently developed plant for large scale production of FDCA brings the market to the brink of widespread availability of FDCA, the market for the promising molecule is still in its infancy. It remains questionable if the price alone can enable the successful market introduction of FDCA (neo-classical economy), since the fossil-based production systems it competes against have been established for decades. The role of society and politics in this regard was also emphasized by the workshop participants, calling for adapted legislation and more funding.

This shows that bringing FDCA products to market is an interdisciplinary process that requires corresponding interdisciplinary approaches. Future research could therefore address uncertainties in the techno-economic area (e.g. feedstock, improvement of production processes, cost reduction) on the one hand, but also those related to environmental aspects regarding FDCA-based products. In addition, further research can promote cross-disciplinary collaboration, for example by including other decision-makers' perspectives (e.g., policy makers, consumers).

7 List of figures

8 List of tables

9 References

9.1 References considered in the literature review

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10 Appendix

Appendix

Table 6: List of scientific papers examined for the systematic literature review, categorized according to scientific focus; Papers related to the synthesis of FDCA are categorized as Step 1; Papers related to the production of products from FDCA are categorized as Step 2

Scientific focus of the paper	Total	Step	Author and year
Technological	66	1	Ardemani et al. (2015); Ban et al. (2019); Chen et al. (2017); Gao et al. (2018); Gao et al. (2019); Gao et al. (2020); Gawade et al. (2018); Ghatta et al. (2019); Gong et al. (2017); Gonzalez-Casamachin et al. (2020); Kubota and Choi (2018); Latsuzbaia et al. (2018); Li et al. (2019); Liguori et al. (2019); Liu et al. (2015); Liu et al. (2020); Liu, H. et al. (2019); Liu, K.-J. et al. (2019); Mei et al. (2015); Motagamwala et al. (2018); Nam et al. (2018); Nocito et al. (2019); Rao et al. (2018); Rathod and Jadhav (2018); Schade et al. (2018); Schade et al. (2019); Shen et al. (2018); Shen et al. (2019); Taitt et al. (2019); Ventura et al. (2018); Wang et al. (2015); Wang et al. (2017); Wojcieszak and Itabaiana (2019); Yan et al. (2017); Yan, Wang et al. (2018); Yan, Xin et al. (2018); Yang et al. (2017); Yang et al. (2020); Zhang et al. (2018); Zhang, L. et al. (2017); Zhang, S. et al. (2017); Zhang, Z. et al. (2015); Zhou et al. (2015); Zhou, H. et al. (2019); Zhou, X. et al. (2019); Zuo et al. (2016)
		2	Banella et al. (2019); Bao et al. (2019); Cao et al. (2017); Dreischarf et al. (2017); Fan et al. (2020); Guidotti et al. (2019); Joshi et al. (2018); Lomelí-Rodríguez et al. (2018); Ma et al. (2016); Ma et al. (2018); Miao et al. (2017); Ogunjobi et al. (2019); Poulopoulou et al. (2020); Smirnova et al. (2020); Sousa et al. (2016); Sun et al. (2018); Wei et al. (2019); You et al. (2020); Zhang et al. (2019); Zhao et al. (2017)
Reviews	16		Chernyshev et al. (2017); Deng et al. (2016); Gandini et al. (2016); Hameed et al. (2020); Jing et al. (2019); Kucherov et al. (2018); Papageorgiou et al. (2016); Rajesh et al. (2020); Sajid et al. (2018); Sousa et al. (2015); Xia et al. (2018); Yuan et al. (2020); Zhang and Deng (2015); Zhang and Huber (2018); Zhang, J. et al. (2015); Zia et al. (2016)
Biotechnological	12	1	Chang et al. (2019); Hossain et al. (2017); Hsu et al. (2020); Lin et al. (2020); Rajesh et al. (2018); Rajesh et al. (2019); Wang et al. (2018); Wu et al. (2020); Yang and Huang (2016, 2018)
		2	Cruz-Izquierdo et al. (2015); Jiang et al. (2015)
Environmental	4	1	Bello et al. (2019); Bello et al. (2020); Chen, G. et al. (2016)
		2	García González et al. (2018)
Techno-economic	2	1	Dessbesell et al. (2019); Triebl et al. (2013)

Table 7: Frequencies with which FDCA is produced from specific resources in the selected literature technological, biotechnological, environmental and techno-economic focus

Resource for FDCA production	Total	Author and year
5-hydroxymethylfurfural	51	Ardemani et al. (2015); Bello et al. (2019); Bello et al. (2020); Chang et al. (2019); Chen et al. (2017); Dessbesell et al. (2019); Gao et al. (2018); Gao et al. (2019); Gao et al. (2020); Gawade et al. (2018); Ghatta et al. (2019); Gong et al. (2017); Gonzalez-Casamachin et al. (2020); Hsu et al. (2020); Kubota and Choi (2018); Latsuzbaia et al. (2018); Li et al. (2019); Liguori et al. (2019); Lin et al. (2020); Liu et al. (2015); Liu et al. (2020); Liu, H. et al. (2019); Liu, K.-J. et al. (2019); Mei et al. (2015); Motagamwala et al. (2018); Nam et al. (2018); Rajesh et al. (2018); Rajesh et al. (2019); Rao et al. (2018); Rathod and Jadhav (2018); Schade et al. (2019); Taitt et al. (2019); Triebl et al. (2013); Ventura et al. (2018); Wang et al. (2015); Wang et al. (2017); Wang et al. (2018); Wu et al. (2020); Yan et al. (2017); Yan, Xin et al. (2018); Yang et al. (2017); Yang et al. (2020); Yang and Huang (2016, 2018); Zhang et al. (2019); Zhang, L. et al. (2017); Zhang, Z. et al. (2015); Zhou et al. (2015); Zhou, H. et al. (2019); Zhou, X. et al. (2019); Zuo et al. (2016)
Fructose	6	Dessbesell et al. (2019); Liu, H. et al. (2019); Motagamwala et al., 2018; Rathod and Jadhav (2018); Wang et al. (2015); Yan, Wang et al. (2018); Yang et al. (2017)
Furfural-based furoic acid (5-bromofuroic acid, 2-furancarboxylic acid)	5	Nocito et al. (2019); Shen et al. (2018); Shen et al. (2019); Zhang et al. (2018); Zhang, S. et al. (2017)
Glucose	1	Dessbesell et al. (2019); Wojcieszak and Itabaiana (2019)
Starch	1	Dessbesell et al. (2019)
5-Methylfurfural	1	Ban et al. (2019)
Sucrose	1	Schade et al. (2019)

Table 8: Frequencies with which specific products are made from FDCA in the selected literature with technological, biotechnological and environmental focus

Products produced from FDCA	Total	Author and year
Adipic acid	1	Wei et al. (2019)
Coordination polymers (CPs) and metal organic frameworks (MOFs)	4	Dreischarf et al. (2017); Ma et al. (2016); You et al. (2020); Zhao et al. (2017)
Multiblock copolymer	1	Guidotti et al. (2019)
Heat resistant epoxy resin	1	Miao et al. (2017)
Oligoesters	1	Cruz-Izquierdo et al. (2015)
Ester lubricating oil	1	Fan et al. (2020)
FDCA-poly((ether)ester) (PEE)	1	Sousa et al. (2016)
Polyamides	3	Cao et al. (2017); Jiang et al. (2015); Smirnova et al. (2020)
Polyester blends (PEF, PPF, PBF, PCHDMF)	1	Poulopoulou et al. (2020)
PET	1	Ogunjobi et al. (2019)
Poly (aryl ether ketone)	1	Bao et al. (2019)
poly(hexylene 2,5-furandicarboxylate) (PHF)	1	Zhang et al. (2019)
Polyester binders for polyurethane coatings	1	García González et al. (2018)
Polyester coil coatings	1	Lomelí-Rodríguez et al. (2018)
Polyimides	1	Ma et al. (2018)
Poly(ethylene 2,5-furandicarboxylate) (PEF)	2	Banella et al. (2019); Joshi et al. (2018)
Copolyesters PEFTs and PEIT	1	Sun et al. (2018)

Table 9: Responses on the professional background and level of agreement with statements 1-10 on the current FDCA situation, assigned to the respective voters (1-42)

Voter	Please assign yourself to the stage that fits your daily work and expertise best!	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
1	Resources	3	2	4	3	4	3	3	4	4	4
2	Other	5	3	5	4	3		4	3	5	5
3	Other										
4	FDCA Products and Applications	4	2	4	3	4	4	3	3	3	4
5	FDCA Products and Applications	3	5	4	3	5	5	5	5	3	5
6	Material production	5	4	5	4	3	4	2	4	5	4
7	Other										
8	FDCA Synthesis	5	3	5	4	4	2	5	5	3	3
9	Material production	2	4	3	3	5	5	5	4	2	2
10	Other	5	5	4	1	5	1	5	4	4	5
11	Material production	4	5	5	3	5	5	4	5	4	5
12	FDCA Synthesis	4	4	4	3	5	4	4	5	3	4
13	Material production	4	4	5	4	5	3	1	5	4	5
14	Material production	3	4	4	3	4		4		3	
15	Material production	4	5	5	3	5	4	2	3	4	5
16	FDCA Products and Applications	4	4	4	3	5	4	3	4	3	4
17	Resources	3	5	3	3	5	5	4	1	2	1
18	Other	3	5	3	2	5	3	3	4	5	5
19	End-of-life and Recycling	4	4	4	4				5	4	4
20	Material production	4	2	4	3	3	3	2	3	4	4
21	FDCA Synthesis	4	3								
22	FDCA Products and Applications	5	5	4	4	4	4	5	5	4	4
23	Material production	4	4	3	3	4	4	4	4	3	3
24	Material production	5	3	4	2	4		2	5	3	4
25	FDCA Synthesis	4	2	4	3	5	5	5	5	5	2
26	Material production	3	5	3	3	3	4	3	4	4	4
27	Material production	5	3						4	4	4
28	Material production	4	2								
29	Material production	4	5	5	5				5	5	5
30	Material production	5	4	5	2	4	1	3	5	3	5
31	FDCA Products and Applications	5	4	5	3	4	5	2	4	5	3
32	Material production	5	5	5	3	4	3	3	3	3	3
33	End-of-life and Recycling	3	4	2	4	2	5	2		3	3
34	Material production	4	2	4	3	4	3	2			
35	Material production	4	4	5	4	3	5	3	2	4	5
36	Material production	4	3	4	3	4		4	5		4
37	Material production	5	3	4	3	3	4	5	5	5	3
38	FDCA Products and Applications	1	1	4	2	5	3	5	1	2	4
39	Resources	3	3	4	4	3	3	3			
40		3	2	4		4		4	4	4	4

Table 10: Responses given for a more detailed description of the current FDCA situation, assigned to the respective voters (1-42), classifications: [ec] = economics, [en] = environmental, [pt] = production and technology, [sp] = society and politics, [ap] = applications, [bs] = blind spots

Voter	What challenges and opportunities do you see at the present time with regard to FDCA products?
1	The price [ec]
4	regulatory framework [sp]; not market competitive regarding oil prices yet [ec]; EoL scenarios [en]
5	Low oil prices [ec]; Finding the right niche application [bs]; Economies of scale [ec]
6	The price/kg for FDCA [ec]; economic drivers to move from fossil to biobased [ec]
8	Challenges: Side products of the FDCA production [pt], price [ec]; Opportunities: Economic drivers to move from oil to biobased derivatives [ec]
9	too much focus on FDCA [bs]; investigate other furan derivatives, too much focus on PEF [bs]; price too high [ec]; other derivatives [bs]
11	Purity [pt] & price [ec]
12	Regulations [sp]; Consumer reception [sp]
13	High price [ec]
14	Price [ec]; End of life [en]
15	high price for FDCA [ec]
16	Price [ec], Limited knowledge in comparison with other polymer products [bs]
17	Life cycle assessment of FDCA production compared to other carbon sources [en]
18	Biodegradability of the products [en]; Biodegradability of products [en]
22	Too expensive [ec]
23	Biodegradability [en], price [ec]
24	Side products of the FDCA production [pt]
25	Politics [sp]
26	people mind change [sp]; change in the thinking of politicians [sp]
27	Compatibility with PET and infrastructure [pt]
29	too high cost [ec]
30	FDCA is currently still too expensive and limited available! [ec]; opportunities: there is life besides FDCA and PEF on furans! [bs] opportunities: coatings! [bs]
31	The fact that FDCA contains 6 carbons coming directly from sugars containing 6 carbons as well. So, there is an atom economy compared for instance to Terephthalic acid (containing 8 atoms). [pt]; Barriers: need FDCA applications as additives or as thermoset instead of only focusing on PEF [bs]
32	The price too high [ec]
33	Commercial availability of FDCA is very limited [ec]; Thermal stability of Furans [pt]
34	High price of FDCA [ec]; Biodegradability of products [en]
35	Price [ec]
36	Purity [pt], price [ec]
38	Processing issues and compatibility with recycling of existing materials [en]; End of life [en]
41	FDCA is too expensive [ec]

Table 11: Responses given for the preferred time frame and detailed descriptions of future visions, assigned to the respective voters (1-42), classifications as above

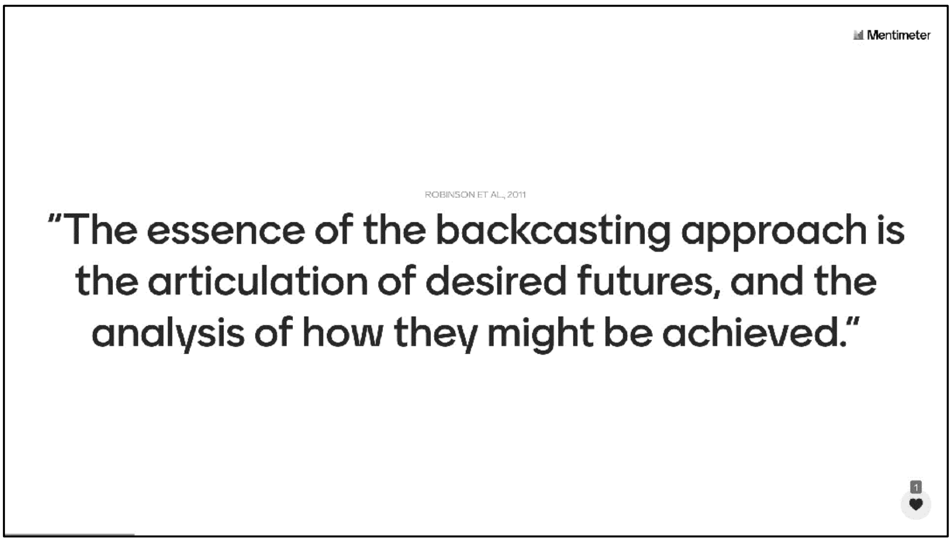
Voter	How far away is our desired vision of the future?	Imagine your ideal vision for a future for FDCA products in year X. What does it look like?
1	2034	Maybe a cleaner planet? [en]
2	2025	
4	2040	in 2032, several facilities all over Europe will produce FDCA for applications, where the FDCA-product is more sustainable to its current (oil-based) counterparts [ec]; production - but also environmentally and socially preferable EoL scenarios (recycling?) - for FDCA-based products [en, pt]; production of FDCA from non-food resources [pt]; carbon taxes [sp]; a political and regulatory framework that encourages a more sustainable production [sp]; time and money for further process development/optimization [pt]; pilot and demonstration plants [pt]; regulations need to be elaborated on European-level that favor the production of FDCA products (e.g., carbon taxes, funding of more sustainable alternatives) [sp]; more money for R&D - technical & natural sciences, but also environmental, social and socio-economics [pt]; campaigns to raise consumer awareness [sp]; development of EoL scenarios (sustainability, tech. feasibility) [en]; more research [pt]
5	2035	FDCA has a specific market share in a competitive market [ec]
6	2025	High-performance engineering biobased plastics [ap]
8	2031	PEF is on the market [ap]; 40% PEF [ap]
9	2030	FDCA derivatives available for a reasonable price (market conformity) [ec]; furan technology developed [pt]
11	2030	10% content in polymers for coatings [ap]
12	2035	Circular FDCA-based economy [ec]
13	2033	Replaced 30% of PET [ap]
14	2034	Partial replacement of PET for gas barrier [ap]; Scale up [ec]; Consumer education on sustainable plastics [sp]; Regulation [sp]; Consumer education, marketing [sp]
15		50% replacement of PET [ap]
16	2030	New materials based on FDCA [ap]; Sustainability [en]
17	2031	Reduced combustion of carbon [en], less consumption of materials per capita [en], circular economy [ec]; Reduce per capita consumption [en], use solar and wind power [en], carbon capture and utilization [en]
18	2043	Completely replaced terephthalic acid [ap]; Economic production [ec]; Product based (material synthesis) on FDCA improvement/development/optimization [pt]
20	2028	
22	2029	Packaging industry dominated by PEF [ap]
23	2041	Replaced partially pet [ap]
24	2030	
25	2036	20% PEF [ap]
27	2030	FDCA will be used in various products in everyday life. Bottles, fibers, belts... [ap]
30	2030	PEF is on the market [ap]; Other furan products are boosted by PEF introduction... [ec]; Recycling will have a huge revolution [en]; green chemistry principles applied to furans products development [pt]
31	2036	50 % PET 50% PEF stream for bottle packaging in 2035 [ap]; 100 % PEF textile fibers in 2040 [ap]; 200 kT/annum of FDCA production in 2030 worldwide. 100 kT per annum dedicated to PEF the rest for other applications [ec]
32	2035	FDCA- based polymers in food packaging [ap]; Recycling of PEF [en]; Partial replacement of PET with PEF [ap]; Lower price and higher cheap feedstock [ec]
33	2035	With high bio-content in commercial products [ec]
34	2030	Bottles based on PEF [ap]; Replacement PTT and PEF - 30 % [ap]
35	2030	
36	2030	
38	2045	A material, among others [ap]. When necessary, where necessary; Green chemistry more than green material [pt]; Clever
41	2025	PEF becomes a commercial bioplastic [ap]
42		bottles based PEF [ap]; new material

Table 12: Responses given for perceived milestones on the way to a future vision and ways to reach them, assigned to the respective voters (1-42) classifications: [ec] = economics, [en] = environmental, [pt] = production and technology, [sp] = society and politics, [ap] = applications, [bs] = blind spots

Voter	Which milestones connect the current situation to the desired future vision?	How can these milestones be reached?
4		...my last few answers starting from "regulations that favor the..." were actually meant for this category - sorry
5	Regulations on conventional plastic [sp]; Commercial production scale [ec]; Plastic bans [sp]; Public perception pushing politics [sp]	Public perception pushing politics [sp]; Climate change pressures [en]
6	MTons scale production of FDCA (ready in 2023) [ec]	Legislation [sp], education [sp]; Industry willing to change [sp]
8	Price [ec]	EU boosts investigation in FDCA derivatives [sp]
9	fully developed sugar to furan technology [pt]	more research on sugar to furan conversion [pt]; also biotechnology [pt]
11	1. meeting technical requirements [pt]; 2. competitive price (< 10€/kg) [ec]	more dedicated research projects [pt]
12	Price [ec]; Scale-up & process development [ec, pt]	
13	Drastically lower price [ec]; high volume production [ec]; Legislatives [sp]	Political regulations which will enforce big investments in furan production [sp]
15	pricing and availability [ec]	legislation [sp]
16	Availability & price of FDCA [ec]	New methods of FDCA production (not only chemical but enzymatic) [pt]
		Behavior change [sp], legislation [sp]
18	Economic production of FDCA [ec]; Development/optimization of material based on FDCA [pt]	R&D [pt]
22	High availability of FDCA in reasonable price [ec]	
23	Competitive price [ec]	More producers, biotechnology [pt]
24	availability [ec]	
25		Politics [sp]
27	Commercialization of low cost and high purity FDCA [ec, pt].; Large scale production of PEF and other FDCA polymers by 2025. [ec]	Improvement in catalysis and reactors [pt]. New green chemistry pathways for FDCA [pt]. Modifications in PET plants to allow large scale PEF production [pt]. PET-PEF blends and recycling. [pt]
30	Number of FDCA producers increasingly higher [ec]; more FDCA producers [ec]; legislation boost bio-products [sp]; furans reach other markets besides the traditional ones [ec]; use of lingo-cellulosic feedstocks [pt]; involvement of industry in academic work [pt]; redirection of pure academic research to more applied vision [pt]; involvement of end-users and manufactures in projects [pt]	
31	Huge investment from EU stakeholder to create big plant of FDCA production utilization lignocellulosic biomass [ec, pt, sp]; Diverse the portfolio of application of FDCA to compete with several polymers (and not only PET) [ec]; Furan is safe and 'healthy' (not dangerous after decomposition in the environment) [en]	industry need to change asset and not only remain with the existing PET asset (in the example of PEF) [pt]
32		EU should finance more research and sustain also from political regulations [sp]
33	Cheap feedstock availability [ec]; Outstanding performance of furan based products [pt]; Efficient and cost-effective production of furan products [ec, pt]	Funding availability for furan based research [sp]; Willingness to pay more for furan based products [sp]
34	Reducing of FDCA price [ec]	Changing of our mind about biobased materials [sp]; Education [sp]
36	purity [pt], price [ec], production volume [ec]	
38	Integration in supply chain respecting nowadays needs [ec]	Molecules producers have to understand that material only exist after processing. Compounding and microstructure DO make the material [pt]; Consumers have to accept paying more [sp]
41	replacement of terephthalate-based plastics [ec]	more investigations related to the application of FDCA-based plastics at industrial scale [pt]
42	price [ec]	

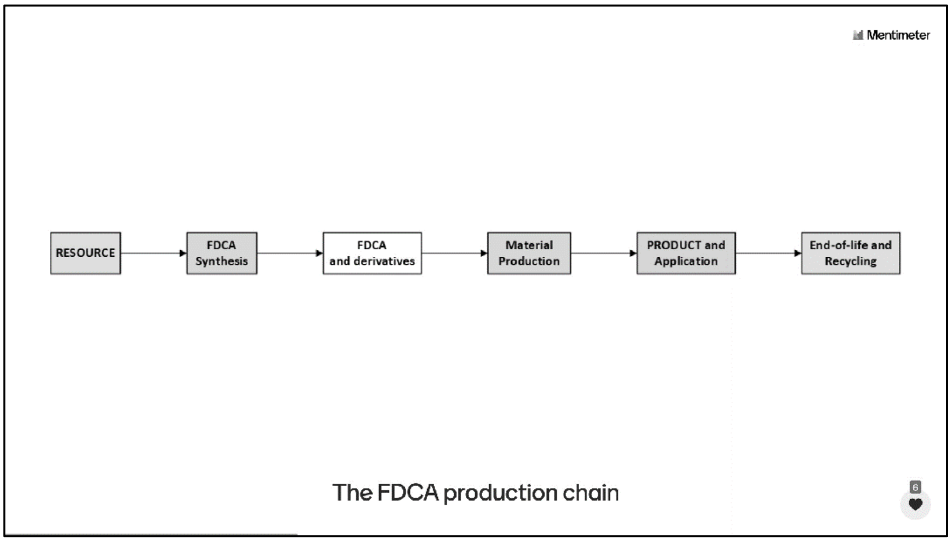
1

2

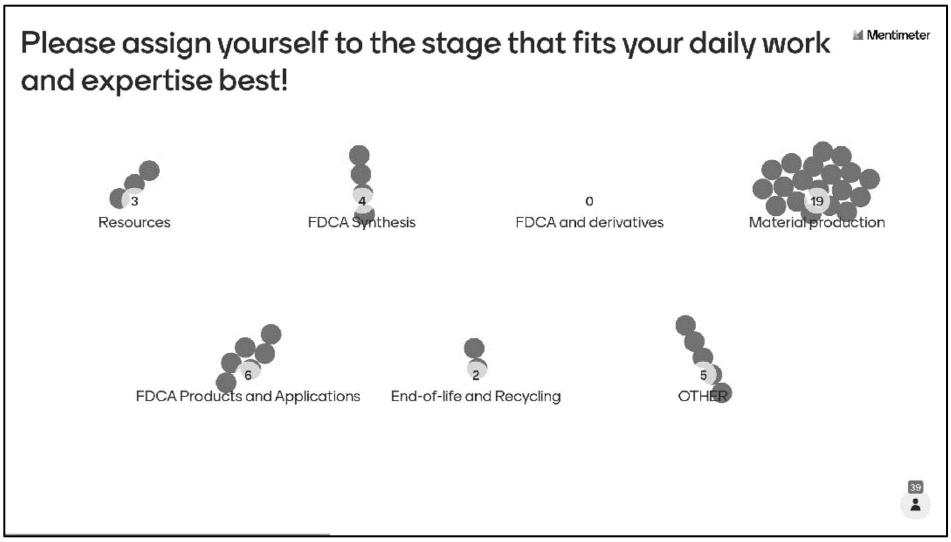


3

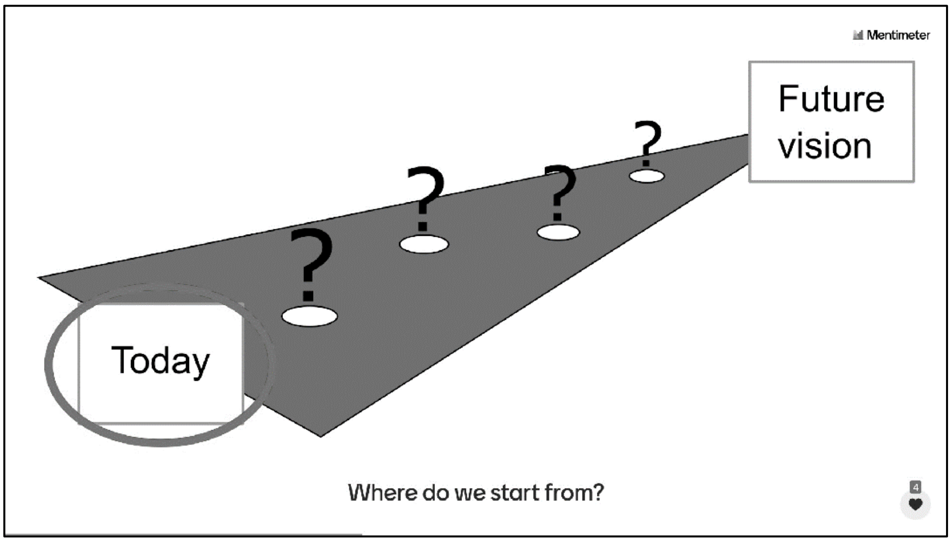
Figure 16: Slides used in the workshop with practitioners along the FDCA value chain


Mentimeter
RESOURCE
FDCA Synthesis
FDCA and derivatives
Material Production
PRODUCT and Application
End-of-life and Recycling
The FDCA production chain
6

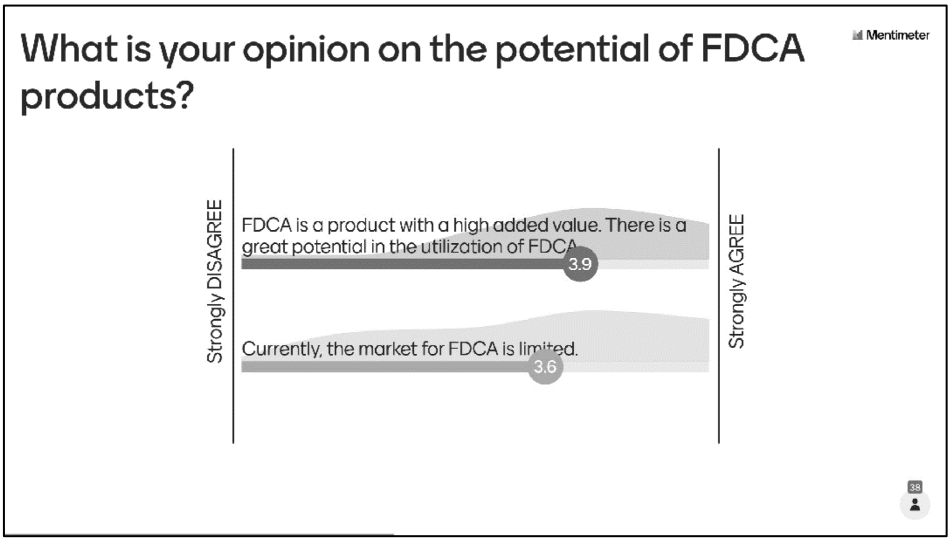
4


Please assign yourself to the stage that fits your daily work and expertise best!
Mentimeter
3
Resources
4
FDCA Synthesis
0
FDCA and derivatives
19
Material production
6
FDCA Products and Applications
2
End-of-life and Recycling
5
OTHER
39

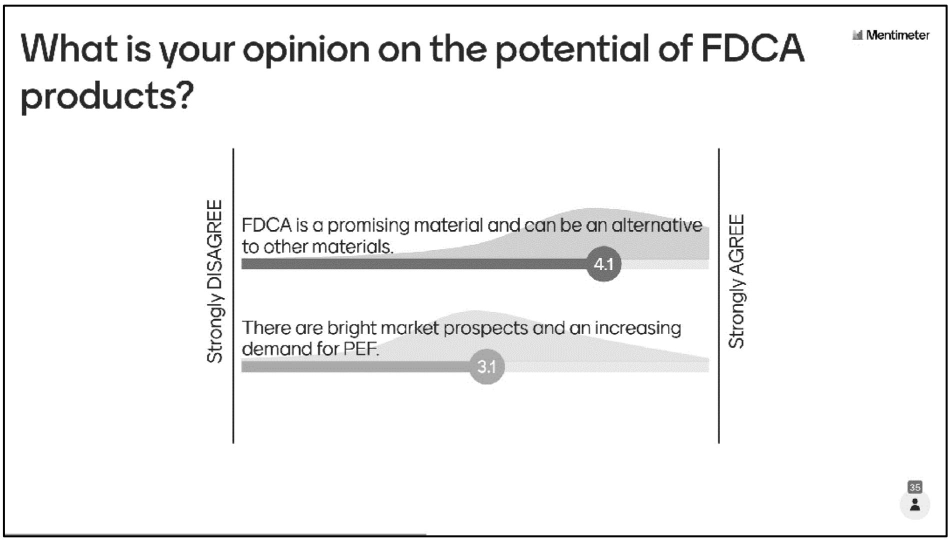
5


Mentimeter
Future vision
?
?
?
?
Today
Where do we start from?
4

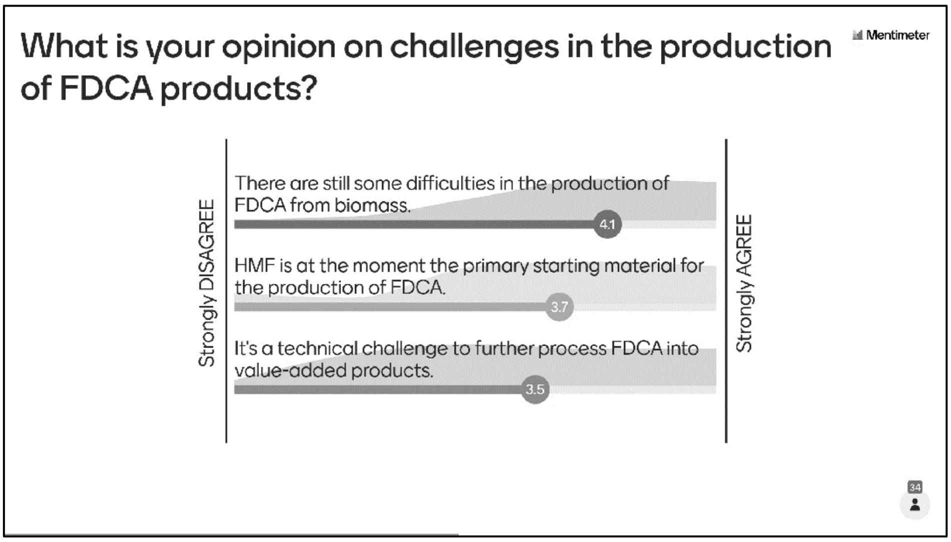
6


What is your opinion on the potential of FDCA products?
Mentimeter
Strongly DISAGREE
Strongly AGREE
FDCA is a product with a high added value. There is a great potential in the utilization of FDCA.
3.9
Currently, the market for FDCA is limited.
3.6
38

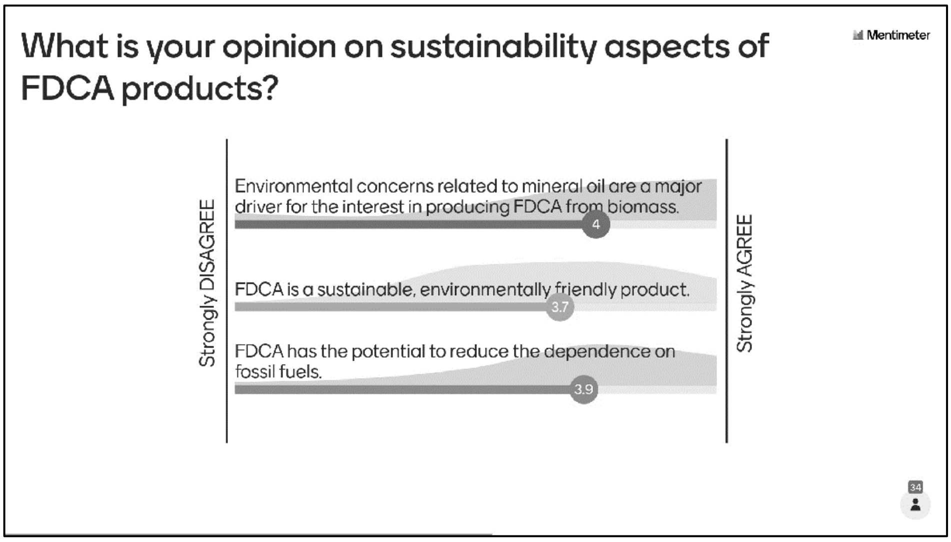
7


What is your opinion on the potential of FDCA products?
Mentimeter
Strongly DISAGREE
Strongly AGREE
FDCA is a promising material and can be an alternative to other materials.
4.1
There are bright market prospects and an increasing demand for PEF.
3.1
35

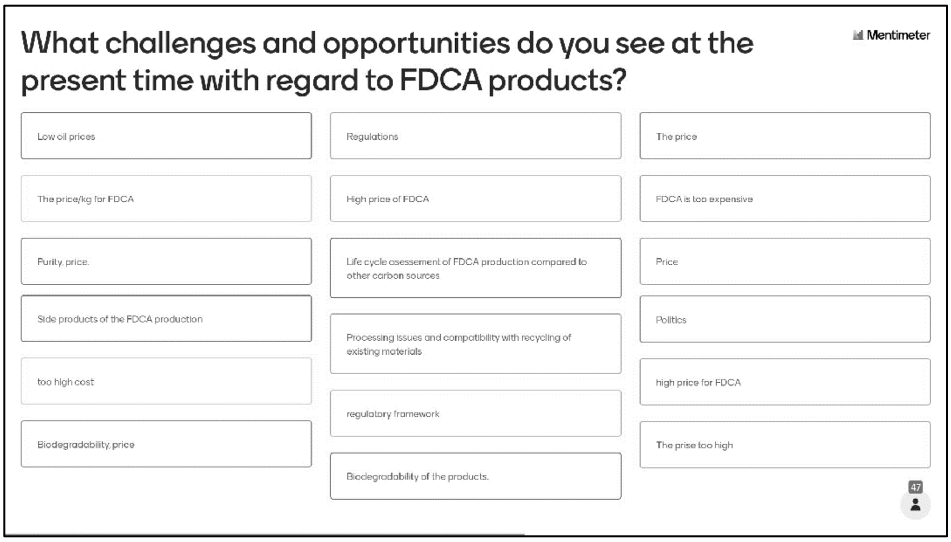
8


What is your opinion on challenges in the production of FDCA products?
Mentimeter
Strongly DISAGREE
Strongly AGREE
There are still some difficulties in the production of FDCA from biomass.
4.1
HMF is at the moment the primary starting material for the production of FDCA.
3.7
It's a technical challenge to further process FDCA into value-added products.
3.5
34

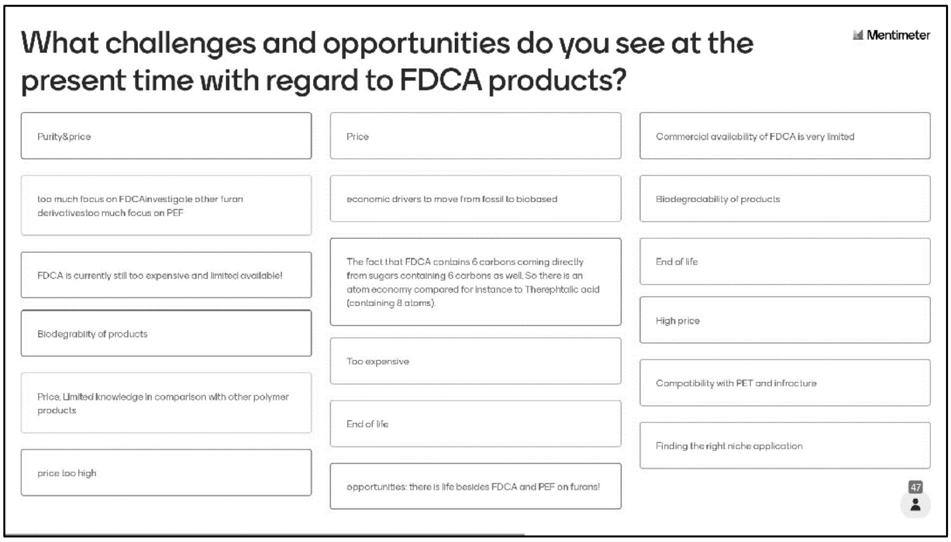
9


What is your opinion on sustainability aspects of FDCA products?
Mentimeter
Strongly DISAGREE
Strongly AGREE
Environmental concerns related to mineral oil are a major driver for the interest in producing FDCA from biomass.
4
FDCA is a sustainable, environmentally friendly product.
3.7
FDCA has the potential to reduce the dependence on fossil fuels.
3.9
34

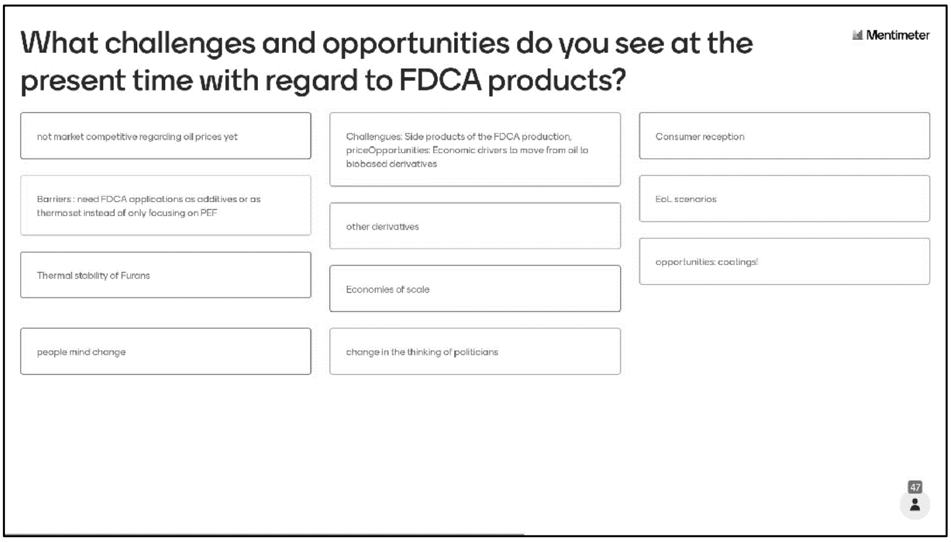
10


What challenges and opportunities do you see at the present time with regard to FDCA products?
Mentimeter
Low oil prices
The price/kg for FDCA
Purity, price.
Side products of the FDCA production
too high cost
Biodegradability, price
Regulations
High price of FDCA
Life cycle assessment of FDCA production compared to other carbon sources
Processing issues and compatibility with recycling of existing materials
regulatory framework
Biodegradability of the products.
The price
FDCA is too expensive
Price
Politics
high price for FDCA
The prise too high
47

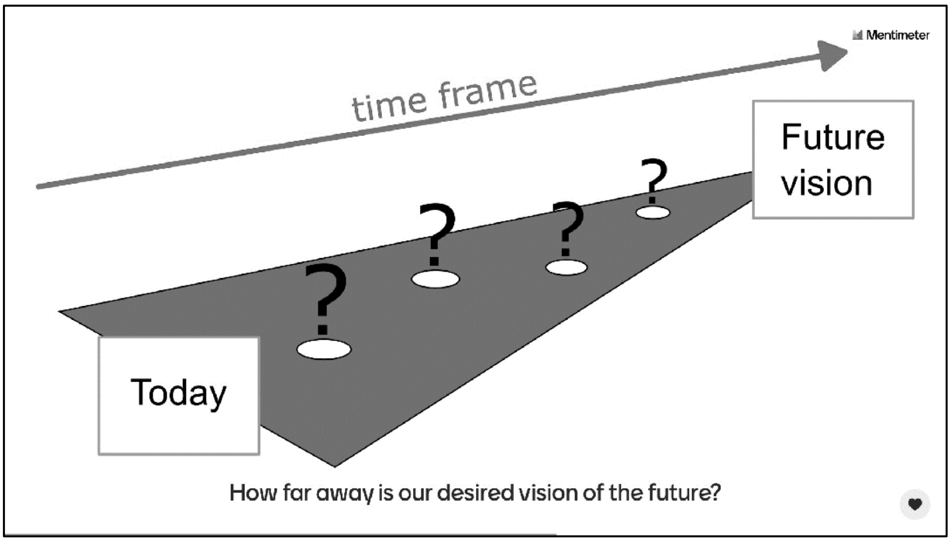
11


What challenges and opportunities do you see at the present time with regard to FDCA products?
Mentimeter
Purity&price
too much focus on FDCAinvestigate other furan derivativestoo much focus on PEF
FDCA is currently still too expensive and limited available!
Biodegrablity of products
Price, Limited knowledge in comparison with other polymer products
price too high
Price
economic drivers to move from fossil to biobased
The fact that FDCA contains 6 carbons coming directly from sugars containing 6 carbons as well. So there is an atom economy compared for instance to Therephtalic acid (containing 8 atoms).
Too expensive
End of life
opportunities: there is life besides FDCA and PEF on furans!
Commercial availability of FDCA is very limited
Biodegradability of products
End of life
High price
Compatibility with PET and infracture
Finding the right niche application
47

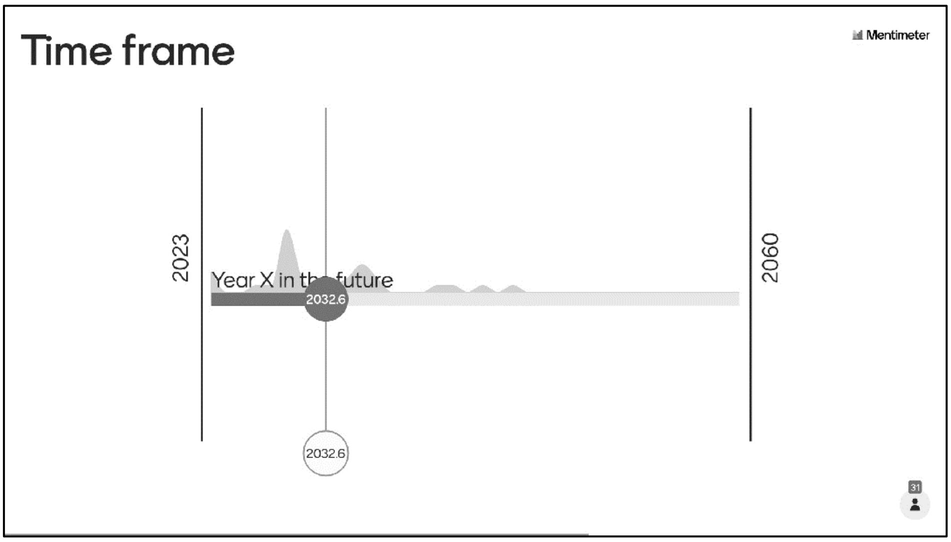
12


What challenges and opportunities do you see at the present time with regard to FDCA products?
Mentimeter
not market competitive regarding oil prices yet
Challengues: Side products of the FDCA production, priceOpportunities: Economic drivers to move from oil to biobased derivatives
Consumer reception
Barriers : need FDCA applications as additives or as thermoset instead of only focusing on PEF
other derivatives
EoL scenarios
Thermal stability of Furans
Economies of scale
opportunities: coatings!
people mind change
change in the thinking of politicians
47

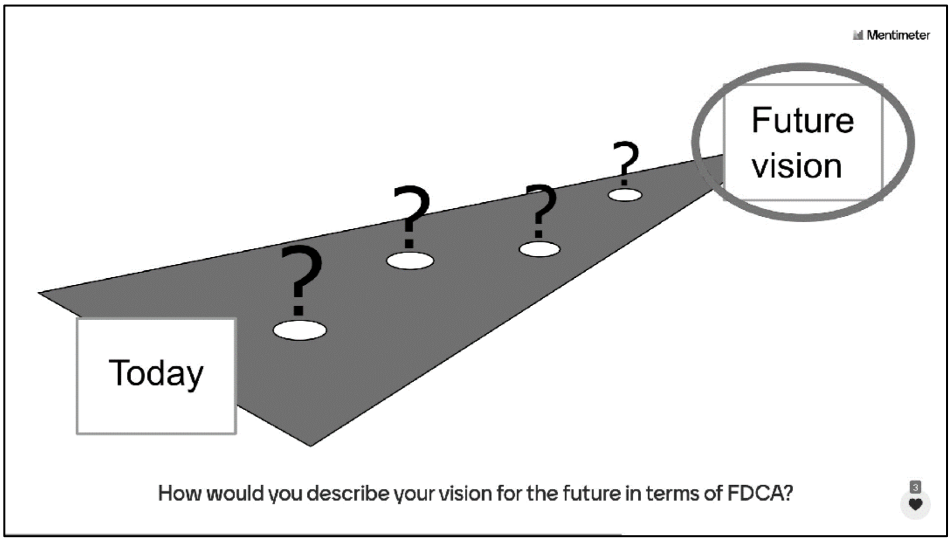
13


Mentimeter
time frame
Future vision
Today
How far away is our desired vision of the future?

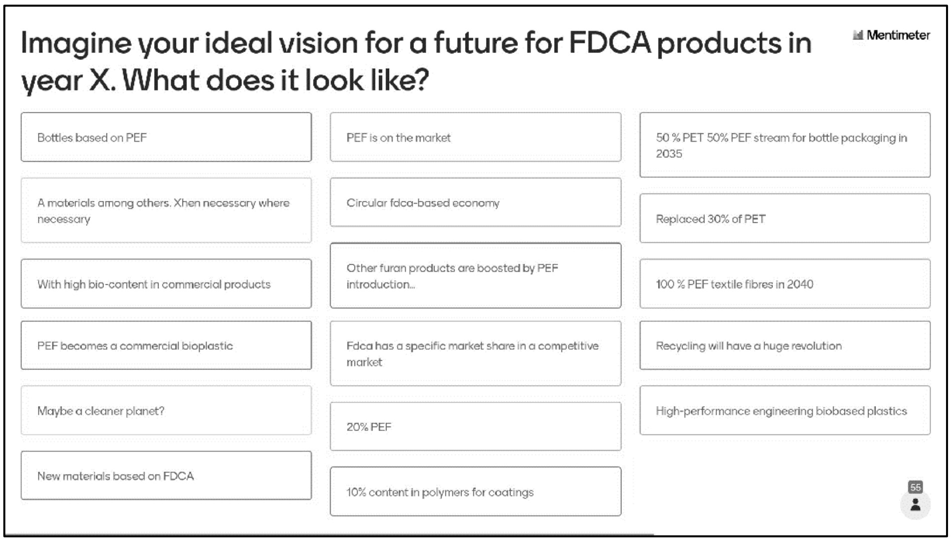
14


Time frame
Mentimeter
2023
Year X in the future
2032.6
2060
2032.6
31

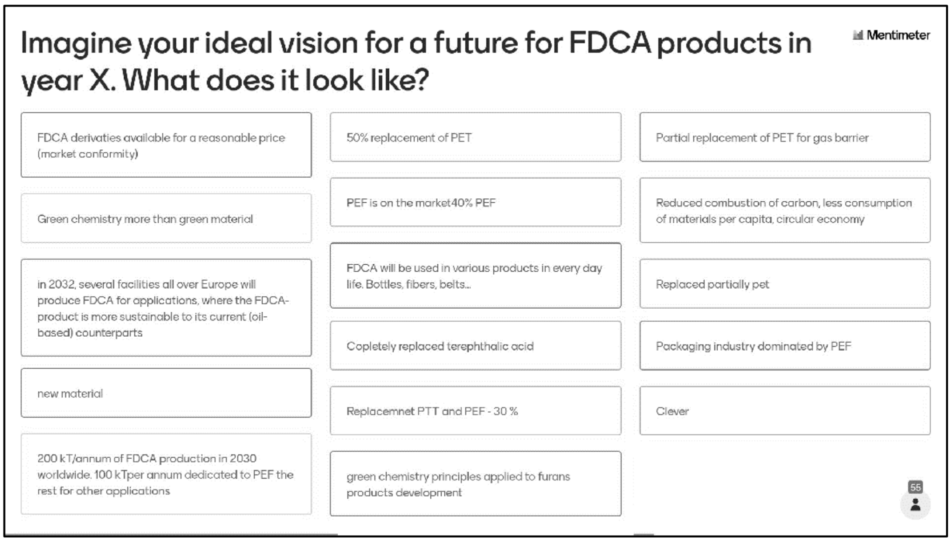
15


Mentimeter
Future vision
?
?
?
?
Today
How would you describe your vision for the future in terms of FDCA?
3

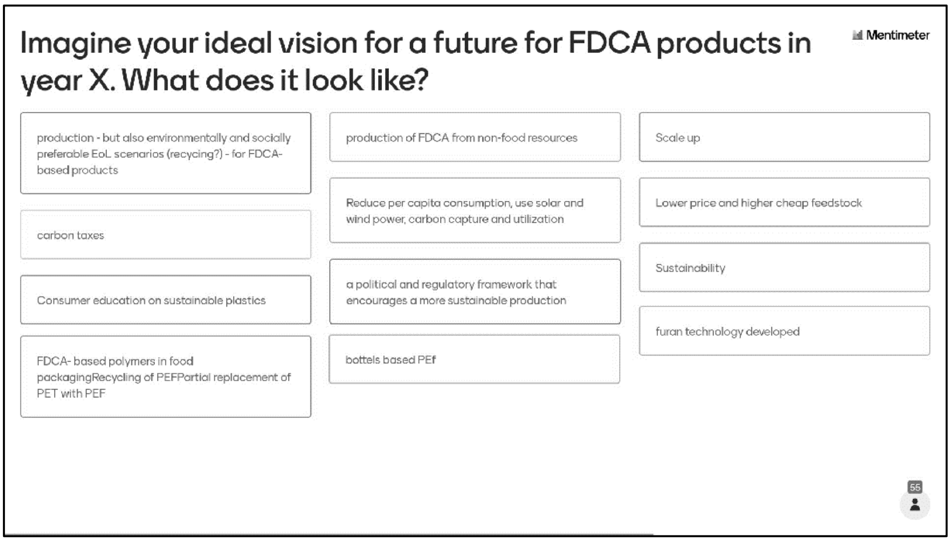
16


Imagine your ideal vision for a future for FDCA products in year X. What does it look like?
Mentimeter
Bottles based on PEF
A materials among others. Xhen necessary where necessary
With high bio-content in commercial products
PEF becomes a commercial bioplastic
Maybe a cleaner planet?
New materials based on FDCA
PEF is on the market
Circular fdca-based economy
Other furan products are boosted by PEF introduction..
Fdca has a specific market share in a competitive market
20% PEF
10% content in polymers for coatings
50 % PET 50% PEF stream for bottle packaging in 2035
Replaced 30% of PET
100 % PEF textile fibres in 2040
Recycling will have a huge revolution
High-performance engineering biobased plastics
55

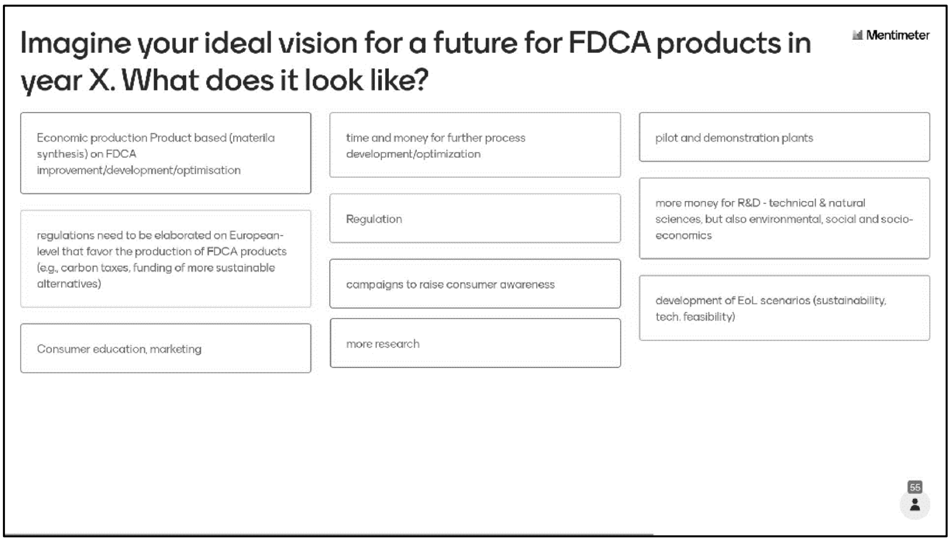
17


Imagine your ideal vision for a future for FDCA products in year X. What does it look like?
Mentimeter
FDCA derivaties available for a reasonable price (market conformity)
Green chemistry more than green material
in 2032, several facilities all over Europe will produce FDCA for applications, where the FDCA-product is more sustainable to its current (oil-based) counterparts
new material
200 kT/annum of FDCA production in 2030 worldwide. 100 kTper annum dedicated to PEF the rest for other applications
50% replacement of PET
PEF is on the market40% PEF
FDCA will be used in various products in every day life. Bottles, fibers, belts...
Copletely replaced terephthalic acid
Replacemnet PTT and PEF - 30 %
green chemistry principles applied to furans products development
Partial replacement of PET for gas barrier
Reduced combustion of carbon, less consumption of materials per capita, circular economy
Replaced partially pet
Packaging industry dominated by PEF
Clever
55

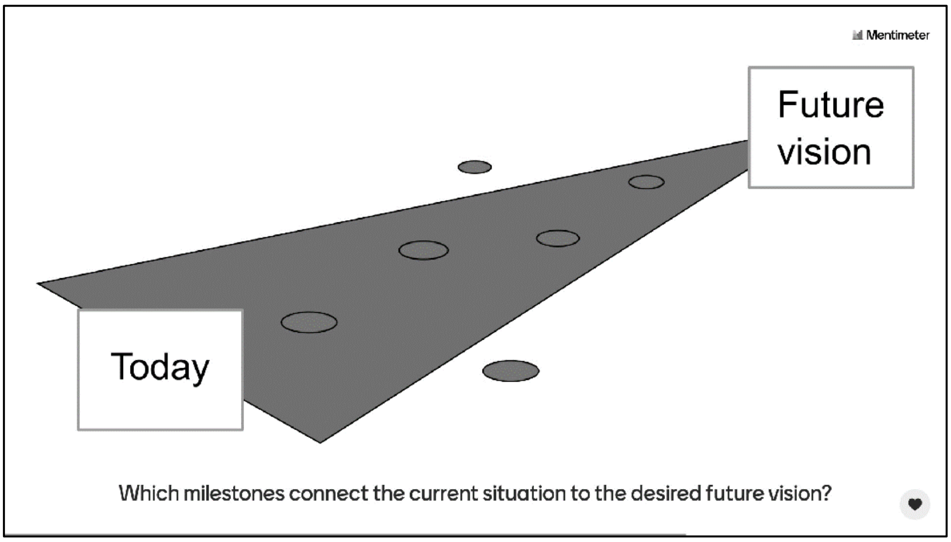
18


Imagine your ideal vision for a future for FDCA products in year X. What does it look like?
Mentimeter
production - but also environmentally and socially preferable EoL scenarios (recycing?) - for FDCA-based products
carbon taxes
Consumer education on sustainable plastics
FDCA- based polymers in food packagingRecycling of PEFPartial replacement of PET with PEF
production of FDCA from non-food resources
Reduce per capita consumption, use solar and wind power, carbon capture and utilization
a political and regulatory framework that encourages a more sustainable production
bottels based PEf
Scale up
Lower price and higher cheap feedstock
Sustainability
furan technology developed
55

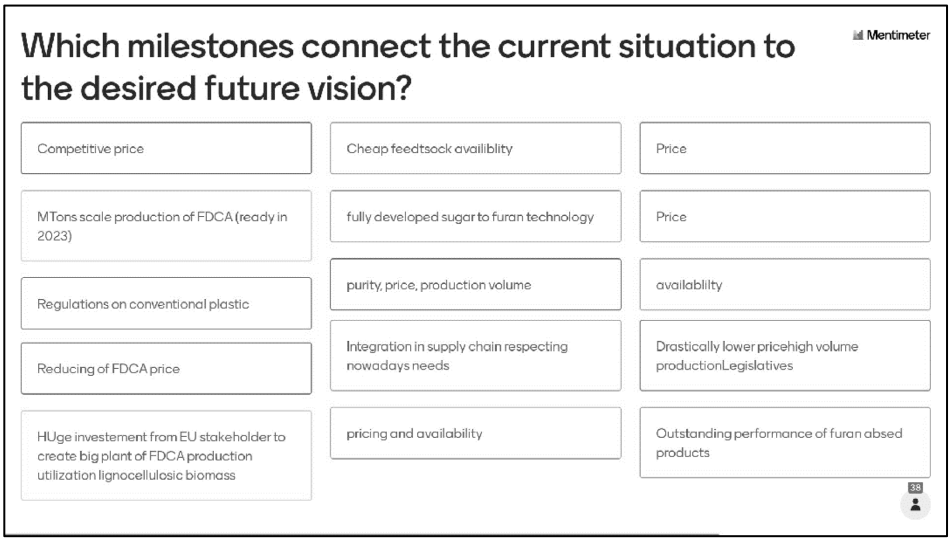
19


Imagine your ideal vision for a future for FDCA products in year X. What does it look like?
Mentimeter
Economic production Product based (materila synthesis) on FDCA improvement/development/optimisation
regulations need to be elaborated on European-level that favor the production of FDCA products (e.g., carbon taxes, funding of more sustainable alternatives)
Consumer education, marketing
time and money for further process development/optimization
Regulation
campaigns to raise consumer awareness
more research
pilot and demonstration plants
more money for R&D - technical & natural sciences, but also environmental, social and socio-economics
development of EoL scenarios (sustainability, tech. feasibility)
55

20


Mentimeter
Future vision
Today
Which milestones connect the current situation to the desired future vision?

21


Which milestones connect the current situation to the desired future vision?
Mentimeter
Competitive price
MTons scale production of FDCA (ready in 2023)
Regulations on conventional plastic
Reducing of FDCA price
HUge investement from EU stakeholder to create big plant of FDCA production utilization lignocellulosic biomass
Cheap feedtsock availiblity
fully developed sugar to furan technology
purity, price, production volume
Integration in supply chain respecting nowadays needs
pricing and availability
Price
Price
availablity
Drastically lower pricehigh volume productionLegislatives
Outstanding performance of furan absed products
38

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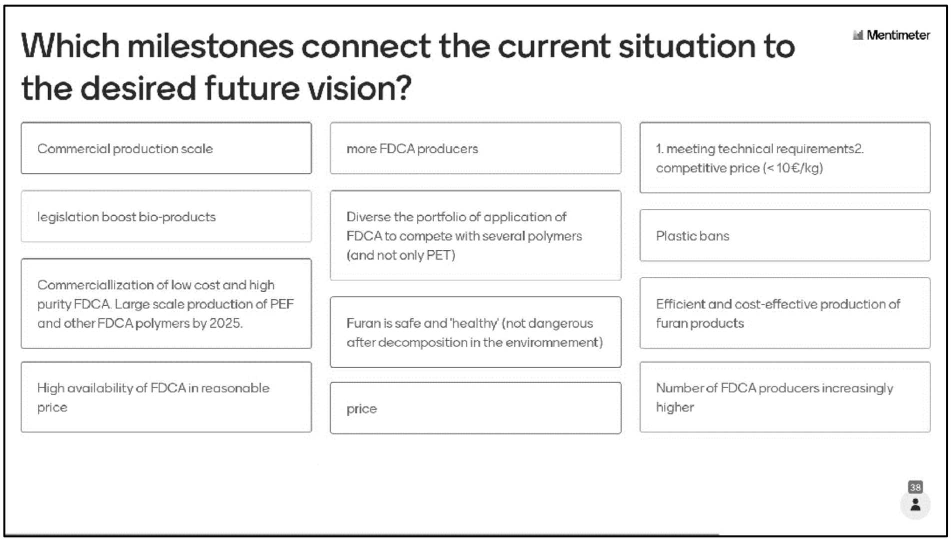
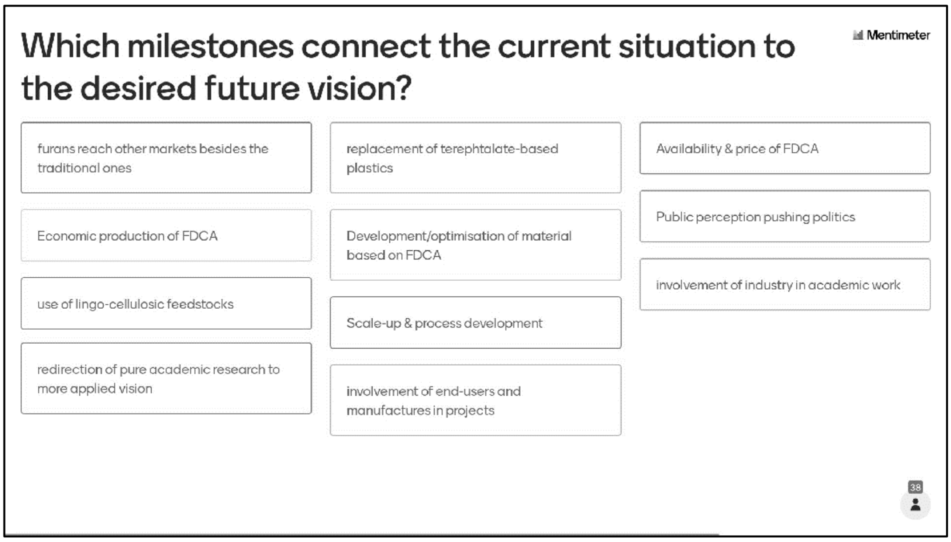
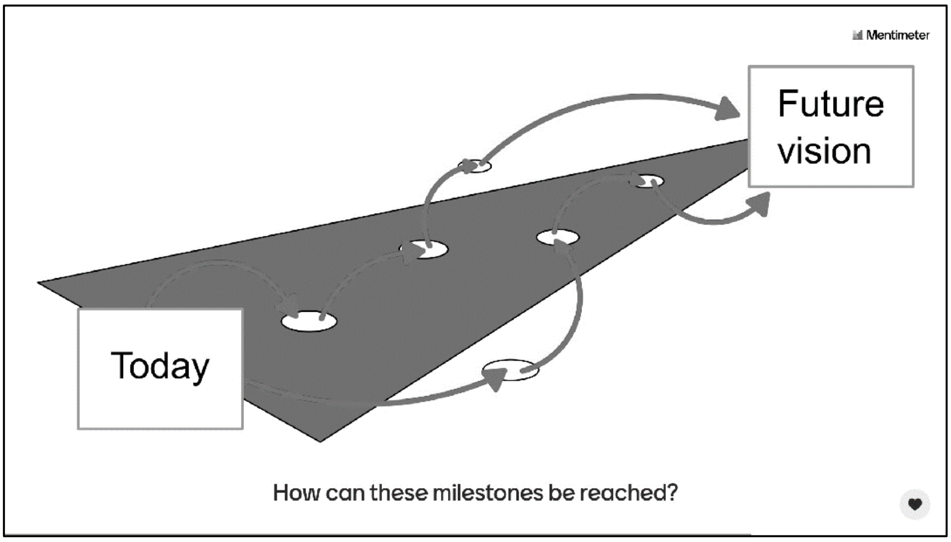

Which milestones connect the current situation to the desired future vision?
Mentimeter
Commercial production scale
legislation boost bio-products
Commerciallization of low cost and high purity FDCA. Large scale production of PEF and other FDCA polymers by 2025.
High availability of FDCA in reasonable price
more FDCA producers
Diverse the portfolio of application of FDCA to compete with several polymers (and not only PET)
Furan is safe and 'healthy' (not dangerous after decomposition in the environment)
price
1. meeting technical requirements2. competitive price (< 10€/kg)
Plastic bans
Efficient and cost-effective production of furan products
Number of FDCA producers increasingly higher
38

23


Which milestones connect the current situation to the desired future vision?
Mentimeter
furans reach other markets besides the traditional ones
Economic production of FDCA
use of lingo-cellulosic feedstocks
redirection of pure academic research to more applied vision
replacement of terephtalate-based plastics
Development/optimisation of material based on FDCA
Scale-up & process development
involvement of end-users and manufactures in projects
Availability & price of FDCA
Public perception pushing politics
involvement of industry in academic work
38

24


Mentimeter
Future vision
Today
How can these milestones be reached?

25


How can these milestones be reached?
Mentimeter
more research on sugar to furan conversion; also biotechnology
Behaviour change, legislation
legislation
Political regulations which will enforce big investments in furan production
more investigations related to the application of FDCA-based plastics at industrial scale
Consumers have to accept paying more
More producers, biotechnology
EU boosts investigation in FDCA derivatives
R&D
more dedicated research projects
Funding availability for furan based research
Climate change pressures
Politics
New methods of FDCA production (not only chemical but enzymatic)
Molecules producer have to understand that material only exist after processing. Compounding and microstructure DO make the material
Legislation, educationIndustry willing to change
Public perception pushing politics
Changing of our mind about biobaasd materials. Education
23

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How can these milestones be reached?
Mentimeter
EU should finance more research and sustain also from political regulations
Industry need to change asset and not only remain with the existing PET asset (in the example of PEF)
Improvement in catalysis and reactors. New green chemistry pathways for FDCA. Modifications in PET plants to allow large scale PEF production. PET-PEF blends and recycling.
..my last few answers starting from "regulations that favor the.." were actually meant for this category - sorry
Willingness to pay more for furan based products
23

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