1 **Innovative technological paradigm-based approach towards biofuel feedstock**

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6 **Abstract**

7 Biofuels produced from renewable energy biomass are playing a more significant role
8 because of the environmental problems resulting from the use of fossil fuels. However,
9 a major problem with biofuel production is that despite the range of feedstock that can
10 be used, raw material availability varies considerably. By combining a series of
11 theories and methods, the research objective of this study is to determine the current
12 developments and the future trends in biofuel feedstock. By combining technological
13 paradigm theory with literature mining, it was found that biofuel feedstock production
14 development followed a three-stage trajectory, which was in accordance with the
15 traditional technological paradigm - the S-curve. This new curve can be divided into
16 BFDP (biofuel feedstock development paradigm) competition, BFDP diffusion, and
17 BFDP shift. The biofuel production diffusion velocity model showed that there has
18 been constant growth from 2000, with the growth rate reaching a peak in 2008, after
19 which time it began to drop. Biofuel production worldwide is expected to remain
20 unchanged until 2030 when a paradigm shift is expected. This study also illustrates
21 the results of our innovative procedure - a combination of the data analysis system
22 and the technological paradigm theory- for the present biofuel feedstock soft path that

will lead to this paradigm shift, with integrated biofuel production feedstock systems expected to be a significant new trend.

Keywords

Biofuel feedstock; Literature mining; Technological paradigm; Biofuel feedstock development paradigm; Paradigm shift

1. Introduction

Because of diminishing supplies and greenhouse gas (GHG) emissions concerns related to climate change, continuing to use fossil fuels has been seen to be unsustainable. Biofuels derived from biomass are one of the most feasible alternatives to petroleum and many countries have initiated extensive biofuel research and development programs to develop sustainable and renewable energy transportation fuels [1, 2]. Produced from plants or organic waste, biofuels could assist in reducing both the world's dependence on oil and CO₂ emissions. Additionally, biofuels have the potential to deliver at least one-quarter of the world's projected energy needs of 623 exajoules by 2035 [3], which would significantly limit the effects of climate change, create jobs in rural areas and improve energy security. Some countries, notably the United States, Austria, Brazil, and China, have made substantial developments by dramatically accelerating their biofuel technological development. Despite the above advantages, there is still some debate about the social, economic, environmental, and technical issues related to biofuel production and utilization. Of these, the "food vs. fuel" issue has been the most discussed in biofuel feedstock

production research [4, 5]. Although corn-based and sugar-based biofuels are promising substitutes for gasoline in the transportation sector, there are insufficient quantities available to replace the fossil fuels consumed annually worldwide. Lignocellulosic biomass has been found to be a substantial renewable substrate for biofuel production which does not compete with food or animal feed production. However this also has limitations in terms of technology even though it can be supplied on a large-scale using different low-cost raw materials such as municipal and industrial waste, wood, and agricultural residue [6]. Besides the above mentioned biofuel feedstocks, cellulosic plants, corn stover and algae are regarded as the most promising feedstocks for the next biofuel generation.

The research objectives aim to discover the current and future biofuel feedstock developments through a combination of theories and methods on biofuel production feedstock conditions, for which no systematic analytical framework has yet been developed. Further, much of the previous research in the related fields has lacked integrity and universality, so there is a need to explore biofuel production feedstock development so as to allow for an extension to other new renewable energy feedstocks.

To focus on feedstock use for biofuel production, a data analysis system (DAS) was created based on bibliometrics and certain mining methods to allow for a comprehensive literature analysis to determine whether the focus trends, as expressed by the keywords, were in accordance with the paradigm theory first defined by Kuhn [7], was a typical example or pattern of something. Dosi later proposed the

67 technological paradigm to solve economic problems using solutions based on natural
68 science principles, which became a classic concept in innovation and technological
69 change literature [8]. Similar to the gradual evolutionary process of life, the
70 technological paradigm also evolves under the driving forces of market demand and
71 industrial competition [9]. Through paradigm theory and a literature analysis, three
72 phases were identified and a biofuel feedstock development paradigm (BFDP) was
73 proposed to describe the evolution and provide a method for an investigation of past
74 trends a prediction of future possibilities [10, 11, 12].

75 A biofuel production diffusion velocity model based on a logistics model is proposed
76 here to demonstrate the biofuel production conditions and predict the feedstock
77 development. Thomas Kuhn's paradigm shift theory argues that paradigm shifts occur
78 because the existing paradigm no longer fits the traditional framework. According to
79 the DAS and literature support, our contribution was to find that a soft path [13] was
80 required to generate this paradigm shift. The soft energy path was first proposed by
81 Lovins, which was then used for water management. However, this concept has not
82 been used for other energy sources. Therefore, the soft path used in this paper seeks to
83 improve the management of biofuel sources rather than merely find new technologies
84 or sources, so offers a marked improvement on today's approaches and provides an
85 entirely new perspective.

86 The remainder of this paper is structured as follows. Materials and methods are
87 presented in Section 2, which includes the DAS and literature mining based on
88 bibliometrics, the combination of the technological paradigm theory and literature

89 mining to determine current development of biofuel feedstock, and a biofuel
90 production diffusion velocity model to simulate and predict future trends. Results and
91 discussion are presented in Section 3 along with the data mining results analyses, the
92 three BFDP stages, the model results, and a paradigm shift discussion. Through an
93 analysis of the keyword foci in accordance with the theoretical paradigmatic
94 framework, three biofuel feedstock stages are proposed. The model results reveal a
95 need for a new path and a paradigm shift. Combining the data mining results with the
96 soft path, conclusions are given in Section 4 and an integrated system proposed for
97 the coming paradigm shift.

98 2. Materials and methods

99 This section introduces the literature mining and analytical process, then discusses the
100 combination of the technological paradigm theory with relevant paradigm theories to
101 explore current biofuel feedstock trajectories, after which a diffusion velocity model
102 is proposed to predict the future development of biofuels through a biofuel production
103 simulation.

104 2.1 DAS and literature mining

105 Kuhn (1962) first popularized the terms “paradigm” and “paradigm shift”. Dosi (1982)
106 investigated technological trajectories on the basis of paradigm shift and found that
107 continuous innovation could proceed within a technological paradigm, while
108 discontinuous innovation could indicate the initiation of a new paradigm. Many
109 studies have subsequently proposed and applied these methodologies across various
110 fields to seek further understanding of the paradigm and its dynamic development in

selected fields [14]. The methodology usually used has been a bibliometric analysis of literature publication metadata and information. Several previous studies have used bibliometric techniques to analyze the status and trends in technological development [15].

2.1.1. Keywords for forecasting

Kostoff combined text mining and statistics for a study of scientific papers and proposed a systematic literature-related discovery method [16]. Also, citation-based analyses together with keyword analyses have been investigated. Kajikawa utilized citation analysis on SCI papers together with a clustering of citation network actors and analyzed the keywords to understand structural changes in sustainable energy [17], biomass and bio-fuels [18].

Given the increasingly fierce controversy on the choice of biofuel feedstock, energy research needs to consider a broader coverage of scientific and technological research so as to be able to make effective investment decisions on promising and emerging sources [19]. Forecasting is a descriptive approach based on retrospective data from the past to the present [20]. In this sense, to enable precise forecasting and effective road maps, policy makers and R&D managers have to understand the global trends in research and emerging technologies.

Keywords are essential to clearly identify the range within a specified boundary to provide an objective foresight definition. As a type of co-word analysis, keyword-based analysis has played an important role in understanding knowledge development dynamics [21]. Baldwin et al. mapped ethics and dementia research

using keywords [22]. Tian et al. used the Institute of Scientific Information (ISI) database to measure scientific output in the Geographic Information System (GIS) field using keywords [23].

Keywords can be filtered out to motivate researchers to define a new research field, or can be retrieved from published research to be used as network actors. Also, by combining social network analysis and bibliometric analysis for the systematic foresight field method using a keyword-based bibliometric analysis and social network analysis, a quantitative, visual knowledge map can be obtained. Therefore, to visualize the global biofuel feedstock research structure, a data analysis system (DAS) was used to develop a keyword-network analysis of scientific publications.

2.1.2. Data analysis system (DAS)

Literature mining from published scientific literature is useful to discover key areas and trends [24]. To determine the relevant research foci, intensive research using popular academic search engines is conducted, after which appropriate technology and software are used to evaluate the relevant research papers [25]. In this section, the development of the DAS and the research process are described, and the visualization results given. The organization of the data analysis system (DAS) is shown in Fig. 1. The four necessary modules are on the left of Fig. 1, the center shows the specific procedures used, and the software interface diagrams are on the right.

Fig. 1. DAS Literature mining

The data collection module interrogates the initial literature database to obtain the most relevant information. The ISI Web of Science was chosen as the primary database because of its powerful access to multiple research databases. Using Boolean Logic technology and the search string “(TI = biofuel production) AND (TS = biofuel feedstock)” “biofuel production (feedstock)”, related literature was first identified. When the search was completed, filtering to select the research field was conducted on some reselected articles to identify the specific target. Then, 355 related articles were downloaded directly to NoteExpress.

2.1.3. Keywords foci trend analysis

Keywords are an important index term used by authors to provide access to articles that have been published or presented in journals and databases. A key word acts as a representative focus for specific research. The keywords in the 355 related articles were extracted to create a new database to analyze the feedstock tendency. However,

before extraction, keyword pre-treatment was conducted using the NoteExpress interface. When the articles were imported into NoteExpress and the duplicates removed, 2072 keyword items were extracted for 1980 to 2015.

NodeXL allows for a visual social network analysis of related concepts and methods through cluster analyses and visualization modules. It is a free interactive network visualization and analysis tool that leverages the widely available MS Excel® application as the platform to present generic graphical data. NodeXL imports graphical data (nodes and edge lists) into the Excel's spreadsheet from multiple social network data providers, and from these visual analyses, biofuel feedstock production development from 1980 to 2015 was clearly shown. The terms 'publication year' and 'keyword' were used to form 4011 edges with 2072 vertices, a process that effectively identified and visualized the networks between the keyword and publication year nodes [26].

2.2. Technological paradigm theory combination

As defined by DOSI, the technological paradigm is a model and pattern of solutions for selected technological problems with specific rules aimed at acquiring new knowledge that is based on highly selective principles from the natural sciences [27].

Kuusi used a literature coupling method to identify technological bottlenecks and the technological paradigm in the field of nanotechnology for patents related to carbon nanotubes [28]. The above studies examined the technological paradigm from different aspects by selecting a scientific carrier as the research object. Therefore, the technological paradigm can also be used with previous research as the scientific

189 carrier.

190 This study seeks to provide a systematic approach to an integrated trend analysis of
191 biofuel feedstock development using keywords analysis combined with the
192 technological paradigm. Although there are short-term ripples in biofuel feedstock
193 development, the long-term trends cannot escape the natural laws of growth. It is well
194 known that human and animal population growth trajectories follow a logistic curve
195 [29], also known as the S-shaped curve, which is also mirrored in the technological
196 paradigm life cycle. The S-curve is also known as a logistics curve and is used to
197 evaluate the technological growth at each stage in its life cycle and to predict when a
198 specific technology will reach a particular stage. If time is depicted on the x-axis, and
199 the technological evolution is the y-axis, then the relationship follows an 'S'-like
200 curve, which can be divided into three stages (competition, diffusion, shift), each of
201 which has four key phases (emergence, growth, maturity, and saturation), as shown in
202 Fig. 2 [30]. When the exponential growth encounters resource limitations, growth
203 slows and eventually reaches a level where the driving forces and resource constraints
204 are in balance.

Fig.2. Life cycle of the technological paradigm–S-curve

Schilling and Esmundo [31] analyzed renewable energies using a technological S-curve perspective and identified some important implications for both governments and industry. Chen et al. [32] predicted the technological S-curves for hydrogen energy and fuel cell technologies by integrating bibliometric analysis into a logistics growth curve model. In this study, to understand the development status of each major biofuel feedstock, a classification of collected biofuel feedstock research is required. Keywords in the text provide rich information on the characteristics of a feedstock, so this information can be used to categorize the keywords and the feedstock types. Grouping the feedstock types enables a detailed examination of the growth trajectory of each biofuel feedstock. Therefore, the development trajectory for biofuel feedstock can be elucidated from the keywords linked to the relevant technological paradigm theory.

2.3. Biofuel production diffusion velocity model

The objective of the diffusion velocity model is to represent the level of spread of an

innovation so as to depict the successive increases in the number of adopters to predict the continual development of a diffusion process already in progress. A diffusion model also refers to aspects of the technological diffusion model, which is often used to predict the future spread of technology [33]. As the biofuels market is essentially a product market, the development evolution can be estimated using a diffusion equation simulation. From a macro perspective, it also evolves following an initialization, maturity and barrier trajectory similar to the S-curve. Therefore, based on the Logistics principle, the biofuels velocity diffusion model can be developed to study its current state and then to predict future trends.

2.3.1. Diffusion velocity model sources

By extrapolating current trends to the future, we can predict future trends and obtain a prospective perspective. Qualitative methods for forecasting include Delphi and scenarios, and for quantitative methods extrapolations of a time series of the growth curves using logistics or Gompertz functions [34] can be used. Here, the diffusion velocity model can assist in making future predictions. Researchers typically measure diffusion speed by first estimating a specific diffusion model, then using one or more parameter estimates as an indicator of the diffusion speed. As an important type of diffusion model, the velocity model, also known as the general model, macro analysis model or S-series model, considers the overall diffusion rate based on statistical analyses and reflects the process of the required time for the technological diffusion velocity, with its basic approach being curve fitting [35].

Studies in economics and the history of technology have typically used the logistics

model. Griliches [36] and Mansfield [37] found that the growth of certain technological innovations can be represented by an S-shaped or logistics curve: diffusion rates first rise and then fall over time, as shown in Fig. 2. Many studies have shown that the simplest and most commonly used form has been based on the logistics model. The behavioral justification for the use of logistics in characterizing the endogenous learning effects in the diffusion process is analogous to the spread of epidemics in the biological sciences [38].

Empirical evidence for the economic, demographic and product effects on the diffusion velocity model can provide decision support for managers and analysts when using generalizable patterns across products to make forecasts [39]. Further, the application of the diffusion S-shaped curve can be a useful tool in understanding new market potential through the growth in new technologies or product categories [40]. To describe the diffusion production changes, biofuel production diffusion velocity characteristics and existing studies were used to develop the logistics model below. The rate and direction of the production change, or the production choice process, was decided on as a result of the competition between the fully developed and the emerging feedstock systems. Here, a diffusion model based on field theory is proposed for biofuel production study.

2.3.2. Modeling and data collection

The application of a selected model to study biofuel production diffusion velocity was based on a theoretical basis which states that diffusion processes follow S-shaped curves as described above. However, the diffusion model parameters needed to be

adapted to reflect biofuel market potential, the policy drivers and the technological improvements. Therefore, managers or policy makers could use the diffusion model to assess the impact of their policies as well as to determine direction to inform the design of new renewables.

Biofuel production diffusion characteristics and existing studies were used to develop the logistics model below which describes the diffusion changes in biofuel market. The rate and direction of the feedstock choice process, or technical change, was probably decided on as result of the competition between fully developed and emerging integrated systems. Based on a logistics model, a field theory originally derived from a physics concept is introduced.

$$\frac{dV(t)}{dt} = \gamma V \left(1 - \frac{V}{V_{pred}}\right) \quad (1)$$

In Eq. 1, $\frac{dV(t)}{dt}$ refers to the variation in the share of specific technologies in the market at time t , V is the existing market share, V_{pred} represents the preliminary market occupancy, and γ is the natural diffusion rate. When $\alpha = \gamma / V_{pred}$, the biofuel production diffusion model is derived as Eq. 2.

$$V = \frac{V_{pred}}{1 + C e^{-\alpha t}} \quad (2)$$

In Eq. 2, C is a constant coefficient, and α is the self-diffusion rate, which indicates the possibility of new feedstocks or technologies. After taking the derivative of Eq. 2, the biofuel production diffusion velocity model is set in Eq. 3, where $v(t)$ within which represents the growth speed in annual biofuel production capacity. This model was used to simulate production and illuminate the diffusion velocity changes in the

emerging feedstocks or technologies.

$$v(t) = \frac{dV}{dt} = \frac{CV_{pred}\alpha e^{-\alpha t}}{(1 + Ce^{-\alpha t})^2} \quad (3)$$

Although, the diffusion of production or technologies does not follow a single uniform pattern and is a complex phenomenon, models have been used to explain diffusion rates and to estimate the parameters or coefficients for the diffusion model equations. Biofuel production capacity refers to a thousand tonnes of oil equivalent (Ktoe). The accumulative total annual biofuel production capacity (V) is introduced into the mathematical model above as an independent variable, and was taken from the Statistical Review of World Energy 2015 by BP Amoco [41]. The diffusion velocity v represents the annual added production (v). The basic data are presented in Table 1.

Table 1. The basic data of v and V

Year	t	Annual added production $v(Ktoe)$	Total added production $V(Ktoe)$
2000	0	-	9,179
2001	1	848	10,024
2002	2	1,811	11,835
2003	3	2,851	14,686
2004	4	1,759	16,445
2005	5	3,259	19,704
2006	6	5,972	25,676
2007	7	9,165	34,841
2008	8	11,661	46,502
2009	9	5,384	51,886
2010	10	7,866	59,752
2011	11	1,136	60,888
2012	12	770	61,658
2013	13	4,270	65,928
2014	14	4,864	70,792

3. Results and discussion

3.1. Mining results analyses

After Graph Metrics, Group Calculation and Graph rearrangements connected to NodeXL, the results were displayed graphically in a network, as shown in Fig. 3. The two graphs in Fig. 3 are shown using the different Harel-koren Fast Multiscale and Circle layouts. The red and circle 'year' vertices, and the green, blue, orange and black 'keyword' vertices are displayed using different shapes selected according to the calculation index Degree ($\text{Degree} \geq 7$). The two graphs below are the same graph at different times, so illustrate the research focus keywords over three time frames: area I (green triangle), area II (green circle), and area III (green square).

Fig. 3. Keyword focus trend analyses (The first displayed graph)

In Fig. 4, the year by year keyword trends are shown. In Area I (probably from 2002 to 2007), the keywords 'corn', 'maize' and 'sugarcane', amongst others, were the main research foci. In Area II (probably from 2007 to 2013), the keywords 'lignocellulosic biomass', 'switchgrass', 'cellulose', 'miscanthus' and 'corn stover' were the main research foci. For the more recent years from 2013 to 2015 (Area III), the only keywords found were 'microalgae' and 'algae'.

Fig. 4. Keyword focus trend analyses (“I,” “II,” “III” areas)

In Fig. 5, besides three areas mentioned above, some other information is displayed.

Below the ‘year’ vertices, there are several keywords (blue triangle vertexes, “B” Area) such as ‘biomass’, ‘energy’, ‘biofuels’, ‘biofuel’, ‘biofuel production’, ‘bioenergy’, ‘fuels’, ‘fuel’ and feedstock’, which are the main topics in this research, as they are the keyword foci across all years. Other keywords (blue solid triangle vertexes, “P” Area) below the ‘year’ vertices, such as ‘bioethanol’, ‘ethanol’, ‘biodiesel’, ‘biodiesel production’ and ‘bio-oil’, are the main products or items related to these main topics. The keywords have had a consistent focus from 1980 to 2015 (but mainly in last ten years).

Fig. 5. Keyword focus trend analyses (“B”, “P”, “T”, “M” areas)

The keywords above the dotted line area (orange triangle vertices, “T” Area) show the main technologies used for the biofuel production such as ‘fermentation’, ‘pyrolysis’, ‘pretreatment’, ‘conversion’, and ‘performance’, and the others (orange square vertices, “M” Area) show the relevant management items such as ‘management’, ‘policy’ and ‘system’.

All keywords are summarized in Table 2.

Table 2. The keywords lists grouped by areas

Area	Vertexes	Keywords
I	green triangle	corn, maize, sugarcane
II	green circle	lignocellulosic biomass, switchgrass, cellulose, miscanthus, corn stover
III	green square	microalgae, algae
B	blue triangle	biofuel production, biofuel, bioenergy, biomass, biofuels, fuels, fuel, energy, feedstock
P	blue solid triangle	bioethanol, ethanol, biodiesel, biodiesel production, bio-oil

T	orange triangle	performance, fermentation, conversion, pretreatment, pyrolysis
M	orange square	Management, policy, systems

336

337 3.2. Three BFDP stages

338 According above literature analysis and paradigm theory combination, a novel
339 concept for the biofuel feedstock development paradigm (BFDP) is proposed to
340 illustrate the feedstock development evolution, which to the best of our knowledge is
341 a new research area. The technological paradigm is a long term, continuous process
342 which goes through a complete life cycle from birth, growth, maturity to retirement.
343 Each paradigmatic phase is characterized by technical solution selection and a
344 self-structuring process which features an industrial learning of the new technical
345 solutions [42]. This paradigmatic phase was added to describe the biofuel production
346 feedstock evolution.

347 From the literature mining, we concluded that the feedstock for biofuel production
348 met the laws of the paradigm and could be summarized in three stages characterized
349 by the different biofuel generations: competition, diffusion, and shift. The first
350 generation is derived edible biomass, the second generation is derived non-food
351 biomass and the third generation is carbon dioxide sequestration such as microalgae
352 [43]. With this analysis, we combined paradigm theory with biofuel production
353 feedstock and proposed a novel biofuel feedstock development paradigm (BFDP).
354 The three BFDP stages were identified as BFDP competition, BFDP diffusion, and
355 BFDP shift, all of which are discussed in the following.

The model shown in Fig. 6 was derived from the well-known S-curve [44]. The first competition stage represents the early development of the technological paradigm and involves numerous trajectories and barriers. In the second diffusion phase, a dominant path prevails in the potential market. Technological shift occurs with technological saturation and natural limits. We estimated that biofuel production feedstock along with reasonable management and technological improvement is likely to break through the technical barriers and enter an emerging new competition phase for the next advanced technological paradigm.

Fig. 6. BFDPP evolution based on the technological paradigm

3.2.1. BFDPP competition

From Area I, the first stage, “first-generation biofuel” was the main feedstock used for biofuel production, which included corn, maize, and sugarcane. As shown in Fig. 7, in this area, the connecting lines between the ‘year’ and the ‘keyword’ were concentrated.

Therefore, from the keyword focus trend analysis and the theory of paradigmatic evolution, “first-generation biofuel” was the main feedstock in the BFDP competition phase.

Fig. 7. Keywords focus trend analysis (Stage I, Stage II and Stage III)

Over the past few years, the demand for first-generation biofuel produced mainly from agricultural crops traditionally grown for food and animal feed purposes, has continued to increase significantly. These biofuels are derived from the starch, sugar, animal fats, and vegetable oil that these crops provide. Corn, wheat, maize, sugarcane and other starchrich crops are commonly regarded as first-generation biofuel feedstock [45]. First-generation biofuel was initially adopted as oxygenate and then as a primary transportation fuel in the United States, Brazil, Canada, and several European nations [46].

First-generation biofuel sources have GHG emission avoidance potential, can provide

useful and valuable coproducts, and, if carefully managed, are able to support the drive for sustainable development in many developing countries. However, the potential to meet government liquid transport fuel targets for oil-product substitution, economic growth, and climate change mitigation goals is limited by the competition for the land and water used for food and fiber production [47, 48], the high production and processing costs needed to compete with petroleum products, which often require government subsidies [49], and the widely varying assessments of the net greenhouse gas (GHG) reductions once land-use change is taken into account [50, 51]. Therefore, the sustainable and economic production of first-generation biofuel has come under close scrutiny.

As mentioned above, in the evolutionary BFDP competition process, many early feedstock types emerged, which were utilized in the first-generation biofuel derived from traditional food sources. The production of first-generation biofuel from these crops has increased rapidly over the past few years. As the technologies have matured, other issues have arisen, such as unsustainable production relating to deforestation, water use, and land management, the inflation of food commodity prices because of competition for food feedstock crops, and the need for generous government support schemes to remain competitive. Therefore, the perceived environmental benefits of first-generation biofuel have recently been called into question. As a result, first-generation biofuel in the BFDP competition stage has significant limitations, and hope has been placed on second-generation biofuel production [50]. Therefore, based on demand-pull and technology-push theories, market forces and technological

innovation is expected to contribute to a new renewable energy framework in the near future.

3.2.2. BFDP diffusion

From Area II, the second stage, “second-generation biofuel” was identified as the main biofuel production feedstock, which includes lignocellulosic biomass, switchgrass, cellulose, miscanthus and corn stover. As shown in Fig. 7, the connecting lines between the ‘year’ and the ‘keyword’ are mainly concentrated in this area.

Because of the rising food prices and land-use problems of the “first-generation biofuels” in the competition stage, the main feedstock for biofuel production in the BFDP competition phase needed to encourage the evolution of more suitable feedstock. The paradigmatic evolution in the diffusion stage is the most important feature of these common technological innovations [52]. As market demand increased because of industrial competition, the BFDP diffusion stage gradually emerged. By combining advanced systems with intensive additional research to eliminate bottlenecks, second-generation biofuel could surpass traditional firstgeneration biofuel to become dominant in the BFDP diffusion stage [53]. Therefore, from the keyword focus trend analysis and paradigmatic evolution theory, “second-generation biofuel” is maturing and developing as a stable feedstock structure.

Second-generation biofuel, also known as advanced biofuel, are fuels that can be manufactured from various types of biomass, like crop residues, forest by-products, perennial grasses, and other forms of plant biomass that are collectively termed “lignocellulosic” [54]. Second-generation biofuel produced from non-food crops has

been developed to overcome the limitations inherent in first-generation biofuel. Second-generation biofuel is more cost competitive with existing fossil fuels [55], and life cycle assessments of second-generation biofuels have also indicated that they can increase 'net energy gains'.

However, second-generation biofuel has its drawbacks. Production still requires land, so even plants that need minimal input compete with food crops for some resources. Further, first-generation biofuel has had a head start of more than half a century, but second-generation biofuel production has been estimated to take at least five to ten years to become large-scale [56]. Higher costs and technological limitations are the main contributions. For example, the complexities of saccharification are a major limitation in the conversion of lignocellulosic biomass to ethanol [57].

In summary, because of the advantages of these non-food crops, "second-generation biofuel" is playing a significant role in the BFDP diffusion stage. However, because of problems such as technological limitations, more paths need to be developed for the beginning of the next technological paradigm.

3.2.3. BFDP shift

From Area III, the third stage, "third-generation biofuel" is the main biofuel production feedstock, represented by microalgae and algae [58]. As shown in Fig. 7, the connecting lines between the 'year' and the 'keyword' are mainly concentrated in this area.

The technological paradigm moved into the shift phase because of the emergence of disruptive technologies [59] and technological limitations [60]. Full competition in

specific areas led to disruptive technologies, and technological limitations began to emerge because of product demand in the market. Therefore, market demand and industrial technological competition were the main reasons for the technology shift. The BFDP shift stage occurred because of the need to guarantee land for food crops, and other environmental and societal problems [61]. A new sustainable feedstock was then developed to solve or mitigate the first and second generation biofuel production problems. As identified in the keyword analysis, the most promising biofuel feedstock in this third generation biofuel phase has been microalgae and algae.

Corn and sugarcane are currently regarded as industrial feedstocks, but the “food versus fuel” concerns preclude any long-term use. Therefore, inedible lignocellulosic plant materials became a more preferred feedstock, but microbial technologies for the fermentation of the simple sugars in the lignocellulose have yet to overcome the cost of the complex processes needed to release these sugars from recalcitrant polysaccharides [62]. Therefore, distinct strategies are required to develop scalable and sustainable nonlignocellulosic biomass resources such as macroalgae for use as the next-generation feedstock. Requiring no arable land, fertilizers, or fresh water resources, macroalgae is already being grown for human consumption, but not as a staple crop [62].

Successful microalgae-production systems are the key to the development of the third biofuel generation, as they could provide an alternative to one of the most difficult problems of large-scale biomass production deployment [63, 64]. Further, algae are the fastest growing plants on earth. Depending on processing methods, algae can be

used to produce biodiesel, ethanol, and many other products [65].

Despite the apparent advantages of algal biofuels, significant economic, technical and environmental challenges still need to be solved to scale-up algal biofuel production.

Most current algal biofuel technologies have been focused on cultivating relatively pure, high-oil algal species and extracting the oil for conversion to biodiesel via transesterification. Maintaining a pure high-oil algae culture, however, is difficult [66].

Further, microalgae biomass is not yet a viable choice for commercial biofuel production due to the extensive energy inputs needed compared to current terrestrial energy crops [64]. One key practical limitation for the algal biofuel industry is the achievement of a net positive cost and an energy balance for the extraction of biofuel from wet algal biomass, and concerns about the freshwater and fertilizer needed for full-scale algal biofuel production have been raised [67]. Further, the extensive antibiotic use to ensure disease free algae cultures remains an unresolved issue [63].

However, at the current stage, microalgae biomass is still not a viable choice for commercial biofuel production because of the extensive energy inputs required compared to current terrestrial energy crops [64]. To grow algae, there are large energy requirements because of the nutrients required, and environmental sustainability challenges because of the need for large quantities of water and nutrients.

To summarize, the increasing demands placed on natural resources for fuel and food production require the further exploration of efficient, sustainable feedstocks such as microalgae or other plant sources yet to be exploited [68]. As feedstock for

commercial-scale biofuel production, the mass production of microalgae could play a significant role in the BFDP shift stage. As discussed above, when moving into this phase, there are still difficulties to be overcome, so material sources and alternative methods need to be researched and developed. Therefore, it is important to work towards long term, effective sustainability.

3.3. Model results and thoughts

3.3.1. Parameter simulation

Through the simulation and calculation of SPSS, the original values for C and V_{pred} were assigned. The parameter for α in the nonlinear regression function was estimated using the Statistical Package for Social Science 19.0. After the simulation, α was found to be 0.66, C was 176.79, and V_{pred} was 57006.788. The diffusion velocity model was then constructed using Eq. 4.

$$v(t) = \frac{176.79 \times 57006.788 \times 0.66 \times e^{-0.66 \times t}}{(1 + 176.79 \times e^{-0.66 \times t})^2} \quad (4)$$

The annual added generation was first calculated as the ' $pred - v$ ' curve in Fig. 8 (the figure below). In Fig. 8, it can be clearly seen that around 2008, the biofuel production diffusion velocity had reached a peak. When $t = 24$ (in 2024), the diffusion velocity is estimated at less than 1 and by 2030, it is expected to be close to zero. The actual values for the added installation (v) had a similar trend to the $pred - v$ except for the values in 2013 ($t = 13$) and 2014 ($t = 14$), which were 1170.33 Ktoe and 624.12 Ktoe. Statistics from countries that generate biofuel production can offer an explanation for these results. Data from the Statistical Review of World Energy 2015 shows that the United States and Brazil were the main growth countries in 2013 and

2014, followed by Indonesia and Argentina in 2014. In 2013, biofuel production increased in the United States by 1192 Ktoe, and in Brazil by 2235 Ktoe (80% the total increment) and in 2014 increased in the United States by 1594 Ktoe, Brazil by 874 Ktoe, in Indonesia by 704 Ktoe and in Argentina by 608 Ktoe (78% the total increment). Therefore, the simulated result affected by the external factors in Fig. 8 showed that the development of biofuel production development had a strong inertia force along the S-curve. In other words, the diffusion velocity model is reasonable. From equation $V(t) = V(t-1) + v(t)$, and $pred-V(t) = pred-V(t-1) + pred-v(t)$, the global biofuel production predicted values are shown in Fig. 8 (the figure above).

Fig. 8. Curve for $(V, pred-V)$ and $(v, pred-v)$

3.3.2. Model results and forecast

The specific prediction results are shown in Fig. 8. Around 2008, biofuel production

capacity had peaked and is not expected to be stable until $t = 24$ (in 2024). By 2030, the worldwide biofuel production is expected to be relatively unchanged, as can be seen in Table 3. Therefore, from 2008 to 2024, due to technical innovations, there was and is expected to be a rapid development in biofuel production. However, biofuel production innovations will gradually slow when the diffusion velocity addresses specific levels of need.

Table 3. Actual production V and predicted production V

Year	t	Actual production $V(Ktoe)$	Predicted production $V(Ktoe)$	Year	t	Actual production $V(Ktoe)$	Predicted production $V(Ktoe)$
2001	1	10,024.00	9,581.90	2016	16	-	65,564.61
2002	2	11,835.00	10,345.88	2017	17	-	65,653.34
2003	3	14,686.00	11,768.34	2018	18	-	65,699.31
2004	4	16,445.00	14,328.66	2019	19	-	65,723.10
2005	5	19,704.00	18,666.31	2020	20	-	65,735.40
2006	6	25,676.00	25,305.66	2021	21	-	65,741.76
2007	7	34,841.00	34,023.16	2022	22	-	65,745.05
2008	8	46,502.00	43,403.39	2023	23	-	65,746.75
2009	9	51,886.00	51,557.11	2024	24	-	65,747.62
2010	10	59,752.00	57,437.30	2025	25	-	65,748.08
2011	11	60,888.00	61,137.15	2026	26	-	65,748.31
2012	12	61,658.00	63,271.34	2027	27	-	65,748.43
2013	13	65,928.00	64,441.67	2028	28	-	65,748.50
2014	14	70,792.00	65,065.78	2029	29	-	65,748.53
2015	15	-	65,393.69	2030	30	-	65,748.55

The reality is that in 2013 and 2014, there was an increase in production. The United States and Brazil are the two largest producers and exporters of ethanol in the world, with ethanol being produced from corn feedstock in the United States and sugarcane in Brazil [69, 70]. Biomass energy consumption in the United States grew by more than 60% from 2002 to 2013, which was almost entirely due to increased biomass consumption for the production of biofuels, and primarily ethanol [71].

With ample supplies of reasonably priced feedstocks, a blenders' tax credit, and fuel industry acceptance of the product, biodiesel producers in 2013 experienced the best profits since late 2011, which consequently led to a sharp increase in production in 2013. However, unsettled government policy issues cloud the industry's future for the years ahead, which is causing uncertainty in the industry [72].

Also in 2000, over 90% of the U.S. corn crop went to feed people and livestock, many in undeveloped countries, with less than 5% used to produce ethanol. In 2013, however, 40% went to produce ethanol, 45% was used to feed livestock, and only 15% was used for food and beverage [73].

Because of the present biofuel conditions (land, food problems and technological barriers) and the limited reserves of energy, biofuel feedstock accounts for only a tiny share of the biofuel supply in the global market. From 2008 to 2024, due to technical innovations, there was and is expected to be a rapid development in biofuel production with contributions from various biofuel types. Ethanol from grain and from sugar cane are both expected to continue to grow, but the first will later become irrelevant, while cane ethanol production will level off to below 100 Mtoe by 2025. Cellulosic ethanol became significant in 2015, and is expected to level off at 120 Mtoe by 2040. Biodiesel from seeds is expected to grow to less than 30 Mtoe by 2030 and then decrease [74]. Therefore, in the end, biofuel production innovations are expected to gradually slow when the diffusion velocity addresses a specific level of need, which indicates the need for a paradigm shift.

3.4. Need for a paradigm shift

The major problem with current biofuel production from biomass feedstock sources such as wheat, sugar beet, corn, straw, and wood is the availability of raw materials and the development trajectory. In this paper, a DAS was proposed, and then three stages in the biofuel production feedstock development were identified. By combining these results with paradigm theory, a BFDP was proposed, which included BFDP competition (first-generation biofuel in the first stage), BFDP diffusion (second-generation biofuel in the second stage), and BFDP shift (third-generation biofuel in the third stage).

At present there is a global debate over biofuels. For the scientific community, biofuel is a technological system that encompasses complex interactions at the local, national and global levels which can positively address rural poverty and economic development and negatively lead to dramatic land use changes, increasing food prices, decreasing food security and increased water use [75]. Further, the biofuel production diffusion velocity model showed that in 2014, diffusion velocity was estimated to be less than 1, and biofuel production worldwide is expected to remain at around the same levels until 2030. Therefore, to maintain sustainable ecosystems and economic societies, a biofuel production feedstock shift is required, which points to a paradigm shift.

3.4.1. Thoughts on the soft (energy) path

The so-called soft path proposed by Amory Lovins was originally used to manage energy resources and the energy crisis in 1973 in the United States; a concept that has proved to be a great success in practice. Lovins coined the term soft energy path to

587 describe an alternative future where energy efficiency and appropriate renewable
588 energy sources steadily replace a centralized energy system based on fossil and
589 nuclear fuels [76]. The soft energy path is called soft because it emphasizes policy
590 support and any changes have only gentle, manageable impacts. The basic advantage
591 of the soft energy path is that it is expected to result in a set of social impacts that are
592 more desirable than those of the hard energy path.

593 In recent years, the study of the soft path has been concentrated on the management of
594 water resources, as in the papers published in Nature and Science related to water
595 resources management using the soft path [24, 77]. This concept was further refined
596 by Brooks, again for water resources management leading to the development of a
597 theory for water management and water demand management [78].

598 Lovins believed that the main energy decisions were always gradually implemented;
599 therefore, a major shift can take decades. A major factor in the soft path strategy is the
600 flexibility to avoid major infrastructure changes, so that infrastructure is fixed for
601 decades for a specific supply mode [76]. Lovins developed a number of transition
602 strategies to achieve the soft energy path [79], which referred to the rise of a major
603 domestic biofuels industry to replace 25% of US oil demand, which could promote
604 economic development in rural areas through the growing of biofuels plant material.
605 Therefore, the soft path is also introduced here as part of the biofuels new path
606 development.

607 Lovins stated that an energy path can be characterized as a complex, interactive set of
608 mutually reinforcing, internally consistent features that together constitute an energy

system; in effect, a sociotechnical system [80]. The main features and their interrelations were identified as follows:

1. A social context consisting of cultural values (e.g. preferences, policies) and associated institutions and organizations (e.g. economic, political, and legal).
2. A set of technological features (e.g. materials, fuels, processes, flows, skills).
3. A set of impacts related to society welfare.

From an overview of the soft energy notion, we focused on its defining features and on the social impact of the soft energy system. Lovins' original argument for soft energy remains the most influential and is by far the most detailed, systematic, and consistent of the many ideas offered by other soft energy advocates. The biofuel debate and the predicted incrementalism are the main identified problems, indicating that biofuel feedstock development requires a paradigm shift and a new path. Combined with Lovins' soft path, an integrated system may be the best direction.

3.4.2. Paradigm shift and its drivers

Driven by Kuhn's seminal work on scientific revolutions, the word paradigm has been used to refer to a thought pattern in any scientific discipline [7]. A paradigm is a comprehensive model of understanding that provides viewpoints and rules to allow for an examination of the problems, and the development of possible solutions. Paradigm shift, also called paradigm change, is the fifth and final step in the Kuhn Cycle [81] (shown in Fig. 9(a)). Once a single new paradigm is settled on by a few influential supporters, the paradigm change step begins. Here there is a transition from the old to the new paradigm, which then develops to maturity. Eventually, the old

631 paradigm is replaced and becomes the new normal science, and when it ends, the new
632 paradigm becomes the new normal science and the Kuhn Cycle is complete.
633 Therefore, rather than being an evolutionary process, the paradigm shift represents a
634 revolutionary transformation or metamorphosis from one mode of thinking to another.
635 The Structure of Scientific Revolution became one of the most cited works in
636 scientific literature in the second half of the 20th century. However, the Kuhn Cycle
637 can also be applied to critical use knowledge with an evolutionary construction.
638 Therefore, it can be applied to model sustainable biofuel use.

639 The abstraction of the Kuhn Cycle frames the global environmental sustainability
640 problem as something that is part of a predictable system behavior pattern. The
641 biofuel production diffusion velocity model shows that the zero incremental is
642 predictable, and the Kuhn Cycle allows us to see that the next step is probably going
643 to be Model Revolution. This, however, should be avoided because historically large
644 changes in social governance models take a long time and are too often accompanied
645 by excessive amounts of violence, suffering, and unpredictability. Fortunately there is
646 a better way to bypass the Revolution step, and arrive at the next step, Paradigm
647 Change. This can be done by grafting the System Improvement Process onto the Kuhn
648 Cycle as shown in Fig. 9(b) [82], and then promoting biofuel to ensure the correct
649 direction is taken.

Fig. 9. The Kuhn Cycle and the System Improvement Process

The System Improvement Process is a simple, generic, highly analytical process designed to be applied to all complex social system problems. There are four main steps, as shown in the diagram; the first is to formally define the problem to be solved, which focuses all subsequent problems on the solution; the second is to understand system behavior, on which approximately 80% of the time should be spent so that the third step solution can be identified; the fourth step implements the solution.

Lovins' research indicated that significant energy decisions are always gradually implemented, so it can take decades to achieve a major shift. However, soft path strategy is also flexible so as to avoid any major infrastructure changes in the specific supply mode. Lovin's discussion included the biofuel market and a proposed sociotechnical system to achieve the soft energy path, which in this paper is seen as part of the System Improvement Process. Therefore, the soft path is introduced to achieve the paradigm shift and to study the development of biofuels in the new path.

"soft path" complements the hard path through investment in decentralized facilities, and the development of efficient technologies, associated policies, and human capital.

668 Compared with the hard path (centralized, inefficient, highly-technological energy
669 supply methods), the soft path seeks to improve the management of sources rather
670 than merely finding new technologies or sources [13, 83]. The soft path attempts to
671 look for innovations that are able to offer a marked improvement on present day
672 approaches or provide an entirely new perspective [11].

673 Instead of moving away from supply-side solutions to meet demand (e.g. expanding
674 physical infrastructure), it is necessary to focus on long-term, comprehensive
675 management approaches that will ensure adequate resource quantities in the future.
676 Therefore, a soft path strategy is proposed to sustainably manage resources now and
677 into the future, which will eventually lead to a paradigm shift. Recent policy
678 developments suggest that the traditional paradigm characterized by a sustained yield
679 is in the process of being invalidated. While a new paradigm has been fully accepted,
680 the emerging paradigm does appear to be based on two principles: ecosystem
681 management and collaborative decision making. The best way to achieve a
682 sustainable future is to develop decision-making processes, institutions, and
683 technologies that emphasize both efficiency and conservation. The soft path supports
684 the next “age” of resource management and is expected to play a key role in system
685 improvement processes which would lead to a paradigm shift.

686 In the DAS tendency analysis, ‘policy’, ‘management’ and ‘system’ in Area M imply
687 measurements on the soft path and the driving power to the next paradigm shift. The
688 improved technological paradigm evolution with the soft path as the driver to the next
689 paradigm is shown in Fig. 10. Competition and technological paradigm shifts in

transportation and industrial production can be characterized by the introduction of a new emerging integrated system that penetrates existing business supply chains and competes for market share in accordance with the paradigm shift. Dynamic management, therefore, is required from researchers, governments and policy makers. The biofuel policy aims to promote the use in transport of fuels made from biomass, as well as other renewable fuels. Biofuels provide the prospect of new economic opportunities for people in rural areas in oil importer and developing countries. The central policy of biofuel concerns job creation, greater efficiency in the general business environment, and protection of the environment.

Fig. 10. Paradigm shift combined with soft path according to technological paradigm

3.4.3. The proposed integrated system

Biofuel development has been generally seen as a promising way to enhance social, economic and environmental sustainability as it has a strong impact on critical issues such as climate change and energy security [84]. The central biofuel policy concerns job creation, greater efficiency in the general business environment and protection of

the environment [85]. However, biofuel production feedstock has become a controversial issue in the biofuel industry. Theories on technological shifts and innovations appear to indicate that biofuel production feedstock is likely to move less towards disruptive innovations but instead focus on incremental innovations and economies of scale. Three kinds of mainstream feedstock have emerged according to the paradigm trajectory. Further, the above methods and discussions from the three BFDP stages, the biofuel production diffusion velocity model results, and the biofuel production background show there is going to be an urgent need for a paradigm shift in the near future as energy system applications are sought for a low-carbon society [77]. The soft path focuses on the management of biofuel sources.

Collaboration is required between governments, communities and private companies to achieve the sustainable development of biofuel sources rather than only focusing on supply. A rational application of technologies and economics, and decision-making at the right levels could improve the productive use of biofuel. Furthermore, in a biofuel industry context, government policies that may influence the competition between the food and energy market need to be developed. Therefore, instead of supply-based approaches, management and policies combined with the technology and resources can push for a paradigm shift that encompasses economic, ecological and social sustainability [78]. An “Integrated biofuel production feedstock system” is the next best “source” of new biofuel feedstock as it takes account of the environmental, technological, economic, institutional and cultural characteristics of biofuel production, as shown in Fig. 11.

Fig. 11. “Integrated biofuel production feedstock system” structure

To achieve sustainable energy production, the potential of biofuel requires a long-term view. New technologies, new sources and, most importantly, the management of these and relevant policy frameworks from the soft path need to be enhanced to generate a paradigm shift. Considerably more investment in research, development, demonstrations, and deployment is needed to ensure that the future production of the various biomass feedstock can be undertaken sustainably and can continue to play a significant role in low-carbon, sustainable energy systems.

4. Conclusions

In this paper, we presented an innovative approach which combined technological paradigm theory with literature mining to discover key areas and trends in biofuel production feedstock. Using appropriate technology and software, a data analysis system (DAS) was developed with four modules to determine the relevant research

foci. Despite significant research having been conducted, there has not yet been a paradigmatic framework for biofuel production feedstock development. Using the DAS, keyword focus trends were identified to assess the three distinct biofuel feedstock stages, which were in accordance with technological paradigm theory.

After combining paradigm theory with the feedstock development research findings, a biofuel feedstock development paradigm (BFDP) was proposed, which included; BFDP competition, BFDP diffusion, and BFDP shift. This paradigm framework gives a view of the current development of biofuel feedstock. Further, a biofuel production diffusion velocity model was proposed to simulate and predict biofuel production in the future. The analyses and results showed that biofuel production development has a similar trajectory to the BFDP, with the diffusion velocity estimated to be close to zero by 2030. Therefore, a paradigm shift is expected from the various biofuel feedstock contributions and the biofuel debates.

Pioneering the use of the soft path and combining it with the analyses results from the biofuel feedstock keywords foci, an "Integrated biofuel production feedstock system" was proposed as an approach for the paradigm shift, which has the potential to play a significant role in a low-carbon, sustainable future.

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