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Review

Black Soldier Fly Larvae (*Hermetia illucens*) for Biodiesel and/or Animal Feed as a Solution for Waste-Food-Energy Nexus: Bibliometric Analysis

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Abstract: In this research, an emerging study of the utilization of black soldier fly (BSF, *Hermetia illucens*) larvae for the preparation of biodiesel (and organic waste treatment) and the generation of alternative feed for improved food production was mapped bibliometrically from the Scopus database. BSF is a promising biological agent for tackling the waste-food-energy (WFE) nexus, which is a problematic vicious cycle that may threaten Earth's sustainability, hence its emergence. With its short life cycle, ability to consume organic waste equal to its own weight on a daily basis, and ability for conversion to larvae with a high protein and lipid content, BSF larvae is the perfect choice as a one-step solution of the WFE nexus. To further perfect the research of BSF for the WFE nexus, this bibliometric analysis, and the citation evolution profile, were carried out with the objectives of characterizing the progress of publications in the last 10 years (2011–2022) in order to determine future research directions in this field, identify the top publications for wider reach to the public, and identify productive authors and leading countries to visualize opportunities for future collaborations.

Keywords: black soldier fly; biodiesel; bibliometric analysis; waste-food-energy nexus; publications

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1. Introduction

Earth is facing a simultaneous crisis of water (wastewater), food, and energy, called the waste-food-energy (WFE) nexus. The population is projected to reach 9 billion people in 2050 [1]. However, this growth is not balanced with the replenishment of natural resources in terms of quantity and quality, especially with the limited supply of land and reduction in fossil fuels. Therefore, there is an urgent need to alleviate this energy issue before it jeopardizes other aspects in the near future. Attempts to obtain alternative sources of renewable energies such as hydro [2,3], wind [4,5], geothermal [6,7], and solar [8,9] have been carried out. In addition, another renewable energy that has received global attention is biodiesel [10–13].

Biodiesel is a product of the transesterification reaction between triglyceride and alcohol (commonly methanol) to produce fatty esters (biodiesel) and glycerol [11]. Biodiesel is an alternative fuel that can be employed in commercial diesel engines without further modification of the engine [14], and does not need to be mixed with fossil fuel. Therefore, the application of renewable energy can be carried out without sacrificing the consumer's convenience.

Initially, biodiesel was produced from edible oils such as palm oil or soybean oil [10,15]. However, due to the conflict of interest with the human food supply, biodiesel has started to be prepared from non-edible plants such as *Jatropha curcas* [16], Chinese tallow [17], and microalgae [18]. However, those non-edible plants possess limitations such as a long time to harvest (several months) and high water content, which definitely reduces the calorific content of these plants [15]. Thus, an alternative is needed to resolve this issue.

Black soldier fly (BSF, *Hermetia illucens*), as shown in Figure 1, is an insect that can consume nutrition from low-cost materials, such as municipal wastes (household, restaurant, food industries, etc.) and manure (chicken, cow, sheep) [15,19]. The larvae of BSF reproduce in a short time (10–20 days), have high protein and lipid contents, and low moisture, therefore possessing a high calorific value [20]. Generally, the larvae of this insect are directly fed to farmed animals without additional processing. However, with the spirit of generating value-added products, BSF larvae are further processed to obtain biodiesel as one of the products [21–24]. Biodiesel from BSF larvae is considered a simultaneous solution for some problems such as the energy crisis and waste processing (without the need for an excessive area for waste storage, and a reduction in the volume of waste that must go to the landfill).

Figure 1. BSFs inside the rearing chamber.

In addition to the aforementioned energy-related advantages, BSF larvae also represent an additional solution for the improvement of the quantity and quality of animal-based food products when implemented as animal feed. This paper bibiliometrically maps the important role of BSF larvae in the fields of organic waste treatment, food (or feed), and alternative energy, or for the waste-food-energy (WFE) nexus.

2. Materials and Methods

The data for this research were produced from 2011 to 2022 and were collected from the Scopus database (Elsevier) on October 2022 using the Scopus search query in Table 1. The first query was "black soldier fly" and "biodiesel", resulting in 488 entries, and the second query was the use of BSF's scientific name "*Hermetia illucens*" and "biodiesel" in order to obtain complete data from the current publications. The two sets of publication data were combined and duplicates removed to obtain a set of 535 publication data, including their keywords.

A preliminary qualitative analysis of the keywords of this set of publication data obtained from https://www.wordclouds.com/ (accessed on 14 October 2022) is shown in Figure 2. The dominant keywords in this research can be seen as "black soldier fly", "*Hermetia illucens*", "larvae", and their components, along with "waste", "bioconversion", "feed", "food', "lipid", "protein", etc. This quick illustration shows that the utilization of BSF larvae is on the right track for solving the waste-food-energy (WFE) nexus. However, the obtained set of 535 publication data must be further analyzed to obtain more in-depth results displaying the metrics, qualities, research trend, and prominent authors in the field of the preparation of biodiesel from BSF. Furthermore, to acquire a wider understanding of the recent research and determine the research trend, the obtained set was further processed to obtain the visualization of similarities (VOS) using VOSViewer software, a powerful software for bibliometric networks visualization (Version 1.6.17, developed by [25], http://www.voswiever.com (accessed on 24 August 2021)).

Table 1. Scopus search query used to obtain the publication data of papers with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel.

Scopus Search Query	Resulting Entries
(TITLE-ABS-KEY (black AND soldier AND fly)) AND (biodiesel)	488
(TITLE-ABS-KEY (hermetia AND illucens)) AND (biodiesel)	431
Combined search result, with duplicated items removed	535

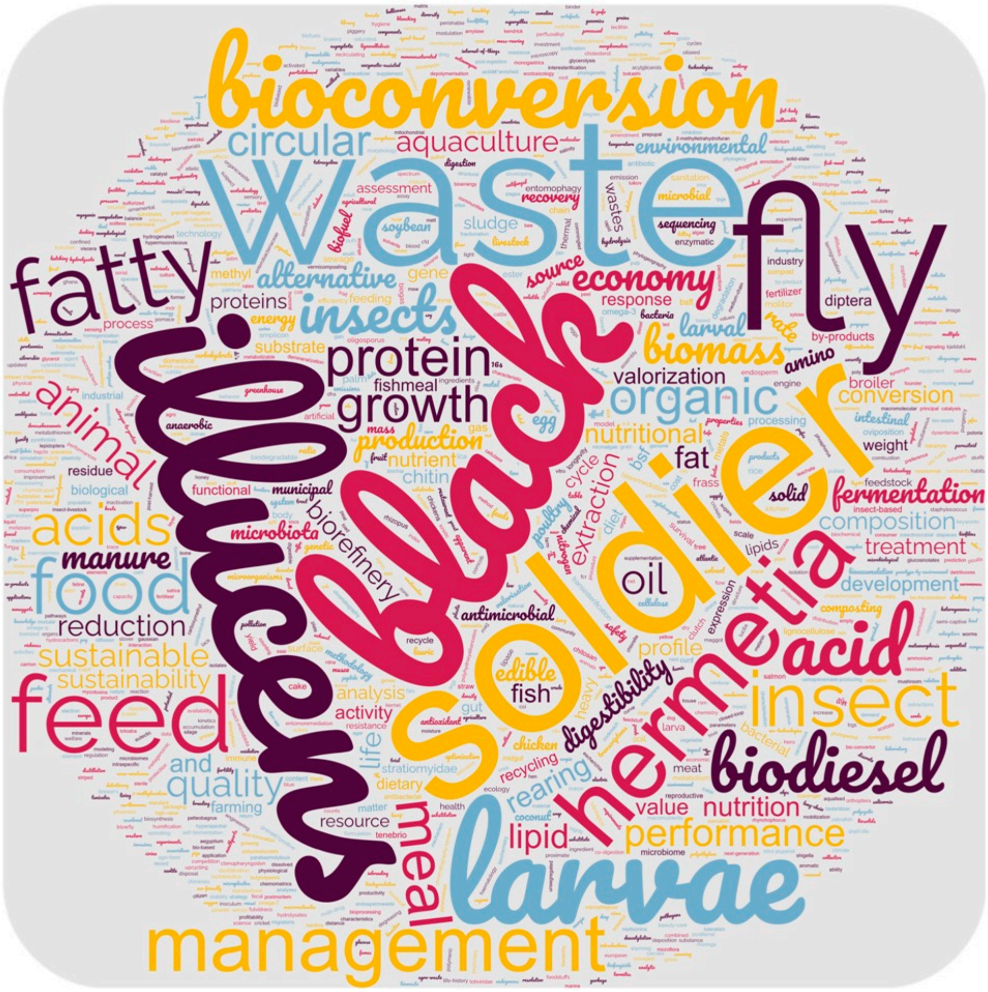

Figure 2. Word cloud extracted from https://www.wordclouds.com/ (accessed on 14 October 2022).

3. Results and Discussion

3.1. Characteristic of Publications (2011–2022)

It was found that the publication of biodiesel from BSF was pioneered in 2011 [15,26], but there was limited development until 2016 (a total of 37 publications). However, between 2017 and 2022, the number increased rapidly (498 publications) or by more than one degree of magnitude under the same span of duration (Table 2). It is believed that this boost was catalyzed by the Sustainable Development Goals established by United Nations General Assembly in 2015 (UN SDGs https://sdgs.un.org (accessed on 1 November 2021)), with goals such as #1 No Poverty, #6 Clean Water and Sanitation, and #7 Affordable and Clean Energy supporting the development of BSF for biodiesel (and other products) to tackle the water-food-energy (WFE) nexus.

Table 2. Number of publications of papers with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel (2011–2022).

Year	Number of Publications
2011	2
2012	5
2013	4
2014	4
2015	13
2016	9
2017	23
2018	50
2019	71
2020	104
2021	119
2022	131

3.2. Top 20 Journals

In addition to the launching of the UN SDGs in 2015, the BSF research to date has been amplified by the establishment of the *Journal of Insects for Food and Feed* (*JIFF*, 2021 impact factor 5.099) by Wageningen Academic Publishers Netherlands. It is clearly shown in Table 3 that this journal leads the top 20 publications supporting the development of the utilization of BSF larvae (although it mainly includes development for food, feed, and their nutritional properties rather than biodiesel fuel), with the highest number of 33 publications. Trailing *JIFF* with 22 publications is the *Journal of Cleaner Production* and *Waste Management*, both from Elsevier (displaying a high 2021 impact factor of 11.072, and 8.816, respectively). It is worth noting that 8 of the top 20 journals in Table 3 are from Elsevier, signifying the role of Elsevier in the development of BSF to solve the WFE nexus, contributing a total of 103 high-impact articles (with an average 2021 impact factor of 8.133) from a wide range of areas such as energy, waste treatment, environmental, feed, etc. Moreover, a considerably new open-access publisher, Multidisciplinary Digital Publishing Institute (MDPI), also collectively published more than *JIFF*, with a cumulative total of 35 articles. In addition, there are also some publishers with publications $\leq$ 10 articles with impact factors ranging from 3.313 to 8.431 (namely Elsevier, Frontiers Media S.A, Public Library of Science (PLoS), Springer Nature, MDPI, and Nature Publishing Group) or without an impact factor (due to the publication of conference papers only, such as the Institute of Physics (IOP) and American Institute of Physics (AIP)).

Table 3. Top 20 journals (with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel) with the highest number of articles.

No.	Journal Name	Publisher	2021 Impact Factor	Total Articles
1.	*Journal of Insects as Food and Feed*	Wageningen Academic Publishers	5.099	33
2.	*Journal of Cleaner Production*	Elsevier	11.072	22
3	*Waste Management*	Elsevier	8.816	22
4.	*Animals*	Multidisciplinary Digital Publishing Institute (MDPI)	3.231	17
5.	*Insects*	MDPI	3.139	15
6.	*IOP Conference Series: Earth and Environmental Science*	Institute of Physics (IOP)	-	15
7.	*Journal of Environmental Management*	Elsevier	8.910	15
8.	*Science of the Total Environment*	Elsevier	10.753	14
9.	*Sustainability*	MDPI	3.889	12
10.	*Frontiers in Microbiology*	Frontiers Media S.A.	6.064	10
11.	*Renewable Energy*	Elsevier	8.634	10
12.	*Aquaculture*	Elsevier	5.135	9
13.	*PLoS ONE*	Public Library of Science (PLoS)	3.752	9
14.	*Waste and Biomass Valorization*	Springer Nature	3.449	9
15.	*AIP Conference Proceedings*	American Institute of Physics (AIP)	-	8
16.	*Processes*	MDPI	3.352	8
17.	*Scientific Reports*	Nature Publishing Group	4.996	8
18.	*Environmental Research*	Elsevier	8.431	6
19.	*Environmental Science and Pollution Research*	Springer Nature	5.190	6
20.	*Animal Feed Science and Technology*	Elsevier	3.313	5

3.3. Top 20 Articles

Among the publishers engaging with the issue of the WFE nexus, there are individual articles that have had a high impact, as demonstrated by their 100 citations or more, as tabulated in Table 4. Please note that there are two articles in 20th position due to the identical number of citations (146 citations). This list is championed by a review of the use of insects as animal feed [27], cited 789 times. This is of high interest since high-quality feed means enhanced production of meat as a protein source (poultry, beef, and fish meat). This is a such a pioneering and fundamental paper that the four articles below it only barely reach half its number of citations (300–400 citations), with all of them discussing the future applications of BSF for food and/or feed as part of solving the WFE nexus [28–31]. In sixth position, there is a paper focused on fly larvae for organic waste treatment (although it is not focused exclusively on the preparation of biodiesel) [32].

In the next 7–20 papers, there are 5 papers that specifically highlight biodiesel production [21,33,34], including the classic trailblazer papers in 2011 that paved the way for the development of BSF for biodiesel [15,26], with around 180–200 citations. The rest of the papers are focused on waste management [35–37] and/or alternative feed or food [38–42]. In addition, the average number of citations in Table 4 is 258.9, with average 2021 impact factor of 6.537.

The top 20 articles in Table 4 were obtained from the search terms in Table 1, which were limited to "black soldier fly", "biodiesel", and "*Hermetia illucens*". These search terms were chosen to reflect the exploration of the research of alternative renewable energy from organic waste (waste-energy nexus) and as the priority in this report. On the other hand, the food-related nexuses (mainly the waste-food nexus, followed by the food-energy nexus) were less prioritized in this study. The analyses of the food-related nexuses were derived from the data collected using the methods defined in Table 1 (for the waste-energy nexus). This limitation was used because of the open debate about the acceptance of BSF larvae for human consumption [31,43], especially regarding its implication to the halal status of meat products [44]. Furthermore, the nexus(es) addressed by the top 20 articles investigated in this study are classified in Table 4, column 6.

Table 4. Top 20 articles (with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel) with the highest number of citations.

No.	Title	Journal Name	Citations	2021 Impact Factor	Type(s) of WFE Nexus	Year	Burst Begins	Burst Ends	Peak	Ref.
1.	State-of-the-art on use of insects as animal feed	*Animal Feed Science and Technology*	789	3.313	Food (or feed)	2014	2015	2022	2021	[27]
2.	Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products	*PLoS ONE*	403	3.752	Food (or feed)	2015	2016	2022	2021	[29]
3.	Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates	*Journal of the Science of Food and Agriculture*	395	4.125	Food (or feed)	2017	2017	2022	2021	[30]
4.	Review on the use of insects in the diet of farmed fish: Past and future	*Animal Feed Science and Technology*	385	3.313	Food (or feed)	2015	2015	2022	2021	[28]
5.	Review of black soldier fly (*Hermetia illucens*) as animal feed and human food	*Foods*	312	5.561	Food (or feed)	2017	2019	2022	2021	[31]
6.	The use of fly larvae for organic waste treatment	*Waste Management*	280	8.816	Waste	2015	2016	2022	2022	[32]
7.	Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed-a review	*Journal of Insects as Food and Feed*	241	5.099	Food (or feed)	2017	2018	2022	2021	[45]
8.	Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using *Hermetia illucens*	*Journal of Cleaner Production*	230	11.072	Waste	2017	2017	2022	2021	[46]
9.	Nutritional value of two insect larval meals (*Tenebrio molitor* and *Hermetia illucens*) for broiler chickens: Apparent nutrient digestibility, apparent ileal amino acid digestibility and apparent metabolizable energy	*Animal Feed Science and Technology*	216	3.313	Food (or feed)	2015	2015	2022	2021	[38]
10.	Bioconversion of organic wastes into biodiesel and animal feed via insect farming	*Renewable Energy*	215	8.634	Waste, energy	2016	2017	2022	2021	[21]
11.	Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production	*Waste Management*	214	8.816	Waste, energy, food	2011	2013	2022	2020	[26]
12.	Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss* Walbaum) diets	*Journal of Animal Science and Biotechnology*	213	5.032	Food (or feed)	2017	2018	2022	2021	[39]

Table 4. *Cont.*

No.	Title	Journal Name	Citations	2021 Impact Factor	Type(s) of WFE Nexus	Year	Burst Begins	Burst Ends	Peak	Ref.
13.	Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae	*Journal of the Science of Food and Agriculture*	209	4.125	Waste	2018	2019	2022	2022	[35]
14.	Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*)	*Journal of Cleaner Production*	206	11.072	Waste	2019	2019	2022	2022	[36]
15.	Sustainability of insect use for feed and food: Life Cycle Assessment perspective	*Journal of Cleaner Production*	184	11.072	Food (or feed)	2016	2017	2022	2020	[40]
16.	From organic waste to biodiesel: Black soldier fly, *Hermetia illucens*, makes it feasible	*Fuel*	180	6.609	Waste, energy	2011	2012	2022	2021	[15]
17.	Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: A review	*Waste Management*	165	8.816	Waste	2018	2019	2022	2021	[37]
18.	Double the biodiesel yield: Rearing black soldier fly larvae, *Hermetia illucens*, on solid residual fraction of restaurant waste after grease extraction for biodiesel production	*Renewable Energy*	160	8.634	Waste, Energy	2012	2015	2022	2020	[33]
19.	Nutritional value of a partially defatted and a highly defatted black soldier fly larvae (*Hermetia illucens* L.) meal for broiler chickens: Apparent nutrient digestibility, apparent metabolizable energy and apparent ileal amino acid digestibility	*Journal of Animal Science and Biotechnology*	147	5.032	Food (or feed)	2017	2018	2022	2021	[41]
= 20a.	Partial or total replacement of soybean oil by black soldier fly larvae (*Hermetia illucens* L.) fat in broiler diets: Effect on growth performances, feed-choice, blood traits, carcass characteristics and meat quality	*Italian Journal of Animal Science*	146	2.217	Food (or feed)	2017	2017	2022	2021	[42]
= 20b.	Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes	*Energy*	146	8.857	Waste, energy	2012	2015	2022	2020	[34]

In addition to the citation growth of the aforementioned articles in Table 4, the citation burst profiles of these articles were also analyzed (Table 4, column 8–9) and are visualized in Figure 3. The citation burst analysis is useful for assessing the evolution of a topic over time in order to detect emerging research [44,47]. For the papers with the keywords of BSF and/or *Hermetia illucens* and biodiesel, there is a unique observation in that some focused on the nexus of food (or feed), as shown in Figure 3a,b. Both figures show the citation evolution in the nexus of food (or feed), but Figure 3a shows those with >300 total citations while Figure 3b displays those with 140–300 citations.

It can be observed that although the reports have the keywords of BSF and biodiesel, they were also of interest for food (or feed) applications and were popular and mostly cited from 2015–2016 (except for #1, from 2014). The citations of the papers in Figure 3a,b increased up to 2022 but with some signs of slowing down, where the citations peaked in 2021. This diminishing trend might have resulted from the shift from the nexus of food to the nexus of waste, as shown in Figure 3c. The citation burst for the nexus of waste showed variation (between 2015 and 2019 for five papers), and the burst has not finished (up to

2022), with only two papers showing a reduced number of citations (#8 and #17 peaked in 2021).

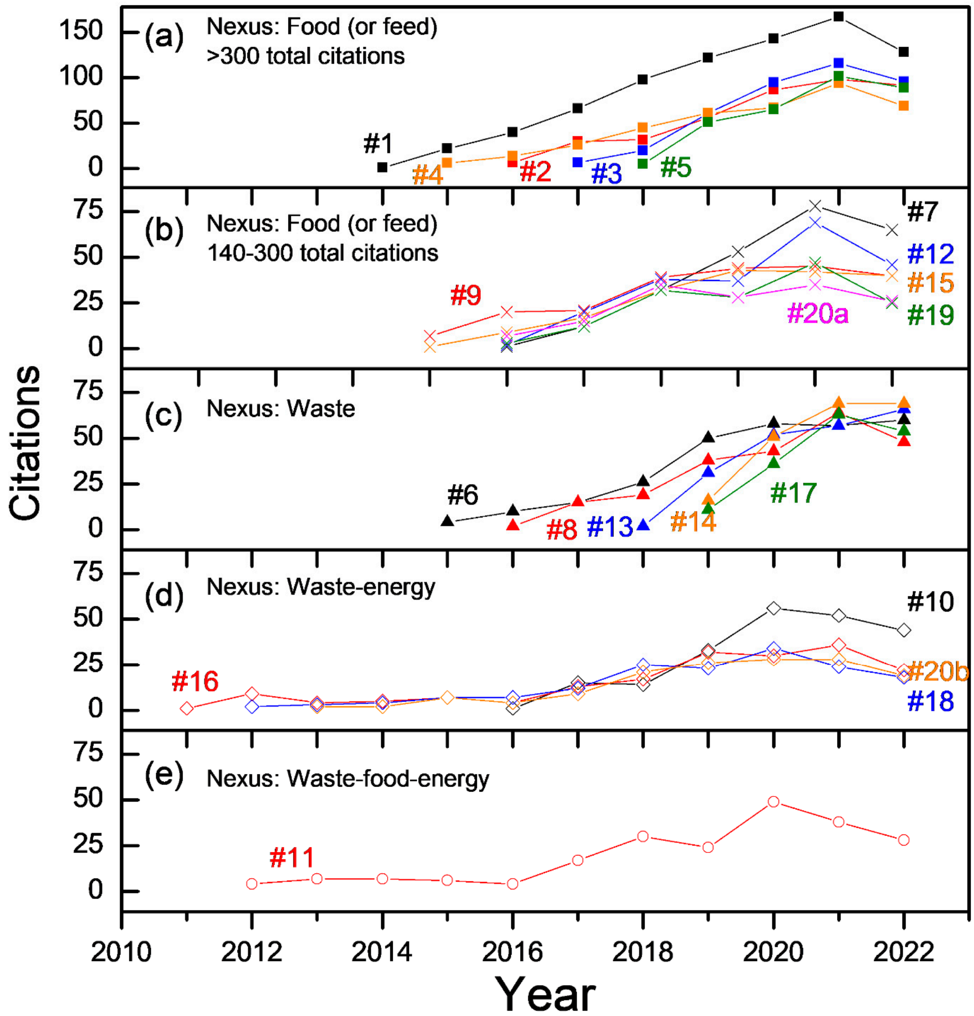

Figure 3. Citation burst of the top 20 articles from Table 4 (with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel) from 2011–2022. (**a**) Nexus: food (or feed), total citations >300, (**b**) nexus: food (or feed), 140–300 citations, (**c**) nexus: waste, (**d**) nexus: waste-energy, and (**e**) nexus: waste-food-energy.

For the papers about BSF in the energy-related nexuses (waste-energy in Figure 3d or waste-food-energy in Figure 3e), the trend is different from that shown in Figure 3a–c. Papers that focused on the energy-related nexus started early (between 2011 and 2013), suggesting the research priority of alternatives to renewable energy during this period. Although the total number of citations is moderate for the papers shown in Figure 3d,e, their longevity must be appreciated. Their citation burst has continued to 2022 while the peak of their citation burst occurred in 2020, which is comparable to those shown in Figure 3a–c (mostly peaked in 2021). Therefore, based on Figure 3, it is suggested that the research directions in terms of BSF for food, feed, waste treatment, biodiesel as renewable energy, etc. are still considered exciting and on the right track for the near future. Based on this finding, the biodiesel production processes from BSF larvae are covered in Table 5 in order to provide the state-of-the-art of this particular research direction.

Table 5. Selected biodiesel production processes from BSF larvae.

No.	Pretreatment	Reactant	BSF Feed	Mixing Ratio	Reaction	Condition	Biodiesel Yield	Unit of Yield	Ref.
1.	None	Dried BSF larvae	Wheat bran	Dried BSFL/methanol/hexane = 1/4/2 *w/v/v*	Acid -catalyzed reaction	H_2SO_4 60% at 120 °C for 90 min	28.4	wt.% per dried BSF larvae	[48]
2.	Solvent extraction with petroleum ether for 6 h	BSF larvae oil	Soya residue	Oil/methanol = 1/8, 1/10, 1/12, 1/14, 1/16 molar ratio	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, 45 °C, 60 min, followed with NaOH (0.5–1.5%), 45–65 °C, 20–40 min	35–90	wt.% per BSF larvae oil	[49]
3.	Solvent extraction with petroleum ether for 24 h	BSF larvae extract	Fermented coconut endosperm waste	Extract/methanol = 1/8 *w/w*,	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, 75 °C, 200 rpm, 1 h, followed with KOH 0.8% in methanol, 65 °C, 200 rpm, 30 min.	35–40	wt.% per powdered BSF larvae	[50]
4.	Solvent extraction with petroleum ether for 24 h	BSF larvae extract	Fermented coconut endosperm waste (0.0–2.5% mixed-bacteria, 0–28 days fermentation	Extract/methanol = 1/8 *w/w*,	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	HCl 1% in methanol, 75 °C, 1 h, followed with KOH 1% in methanol, 65 °C, 30 min.	35–38.5	wt.% per powdered BSF larvae	[51]
5.	Solvent extraction with petroleum ether for 6 h, followed with addition of 1% (*v/v*) concentrated H_3PO_4 (85%)	BSF larvae oil	Restaurant kitchen waste	Oil/methanol = 1/10 molar ratio	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, 50 °C, 41 min, followed with NaOH 1.1% in methanol, 62 °C, 61 min	97	wt.% per BSF larvae oil	[52]
6.	Solvent extraction with petroleum ether for 6 h	BSF larvae oil	Restaurant kitchen waste	Oil/methanol = 1/6–1/14 molar ratio	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, followed with NaOH (0.5–1.5%), 35–65 °C, 40–60 min	24–95	wt.% per BSF larvae oil	[53]
7	Solvent extraction with petroleum ether for 6 h, followed with addition of 1% (*v/v*) concentrated H_3PO_4 (85%)	BSF larvae oil	Pig manure	Grease/methanol = 1/8 *w/w* (for acid -catalyzed reaction), 1/6 (for alkaline-catalyzed reaction)	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, 75 °C, 60 min, followed with NaOH 0.8% in methanol, 65 °C, 30 min	94.91	Wt.% per BSF larvae grease	[54]
8.	Solvent extraction with petroleum ether for 48 h (twice)	BSF larvae extract	Restaurant food waste	Extract/methanol = 1/8 for acid -catalyzed reaction, 1/6 for alkaline -catalyzed reaction	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% at 75 °C for 1 h, followed with NaOH 0.8% at 65 °C for 30 min	36.3	wt.% per dried BSF larvae	[33]
9.	Solvent extraction with petroleum ether for 16 h	BSF larvae grease	Fresh manure	Grease/methanol = 1/8,	Acid -catalyzed reaction followed with alkaline -catalyzed reaction	H_2SO_4 1% in methanol, 73 °C, 2 h, followed with NaOH 0.8% in methanol, 65 °C, 30 min	96.34	wt.% per BSF larvae grease	[26]
10.	Solvent extraction with petroleum ether for 48 h	BSF larvae extract	Pig manure	Extract/methanol = 1/8 for acid -catalyzed reaction, 1/6 for alkaline -catalyzed reaction	Acid -catalyzed reaction followed with alkaline-catalyzed reaction	H_2SO_4 1% at 75 °C for 1 h, followed with NaOH 0.8% at 65 °C for 30 min	27.9	wt.% per dried BSF larvae	[15]
11.	Solvent extraction with petroleum ether for 12 h	Milled dried BSF larvae	Solid digestate of chicken manure and rapeseed straw	200 larval/150 g digestate	Alkaline transmethylation	Fatty residue dissolved in hexane, KOH 5% in methanol, mixed for 5 min.	14.36	g per kg waste	[55]
12.	Solvent extraction with hexane for 24 h	BSF larvae extract	Food waste	Extract/methanol = 1/8 *w/w*	Alkaline-catalyzed reaction	KOH 5% at 65 °C for 8 h	33.9	wt.% per dried BSF larvae	[56]
13.	Solvent extraction with n-hexane for 48 h	BSF larvae fat	Wheat bran	Fat/methyl acetate = 1/14.64 molar ratio	Enzymatic reaction	Novozym 435 (4% concentration, loaded at 17.58% shaken at 40 °C, 12 h.	96.97	wt.% per BSF	[57]

Table 5. *Cont.*

No.	Pretreatment	Reactant	BSF Feed	Mixing Ratio	Reaction	Condition	Biodiesel Yield	Unit of Yield	Ref.
14.	Solvent extraction with n-hexane for 48 h	BSF larvae fat	Wheat bran	Fat/methanol = 1/6.33 molar ratio	Enzymatic reaction	Novozym 435 (4% concentration, loaded at 20%, shaken at 26 °C, 9.48 h.	96.18	wt.% per BSF fat	[58]
15.	None	Dried BSF larvae	Food waste	Dried BSFL/methanol = 1/10 *w/w*	Non-catalytic reaction	SiO_2 at 390 °C for 1 min	34.7	wt.% per dried BSF larvae	[56]
16.	Solvent extraction with hexane for 24 h	BSF larvae extract	Food waste	Extract/methanol = 1/20 *w/v*	Non-catalytic reaction	SiO_2 at 390 °C for 1 min	34	wt.% per dried BSF larvae	[56]
17.	Solvent extraction with n-hexane for 48 h	Powdered BSF larvae	Wheat bran	Methanol/BSF powder = 4:1 to 10:1 mL/g	Switchable -solvent -catalyzed (using polarity switchable solvent, DBU (1,8-diazabicyclo [5.4.0]undec-7-ene))	DBU/biomass = 8:1 to 20:1 mL/g, 90–120 °C, 30–120 min.	96.2%	actual biodiesel produced per theoretical biodiesel produced	[59]

The selected processes for the production of biodiesel from BSF larvae shown in Table 5 are dominated by the two-step esterification reaction [48–56], i.e., acid-catalyzed reaction (dilute H_2SO_4 or HCl, typically 1% in methanol), followed by alkaline-catalyzed (NaOH or KOH, 0.8–5.0% in methanol) reaction, as pioneered by [15,26,33]. In addition, the grease, fat, or oil from BSF larvae are mostly pretreated using solvent extraction (with petroleum ether or n-hexane) for 6–48 h to extract the lipid content for a further transesterification process to produce biodiesel. The BSF larvae were fed various feed such as wheat bran, restaurant waste, coconut endosperm waste, soya residue, and manure (pig, chicken, human) to achieve larval growth. It is therefore interesting to explore the research on renewable energy from organic waste or underutilized carbon sources to lower the carbon footprint via the utilization of BSF larvae.

Interestingly, there are several novel approaches to the production of biodiesel from BSF larvae in addition to the common acid- and alkaline-catalyzed two-step reactions. A green approach using enzymes represents a breakthrough, where the use of acid and alkaline in methanol is eliminated [57], or a tandem with methyl acetate is used as an alternative to methanol [58]. The elimination of catalyst (acid, alkaline, enzymes) is also quite a radical approach, as shown by [56] by their non-enzymatic process involving SiO_2. However, there is still a drawback where a high temperature of 390 °C is required. In addition, the use of a unique solvent with a switchable polarity (DBU, 1,8-diazabicyclo [5.4.0]undec-7-ene) is also a novelty [59], with relatively mild conditions. However, the price and availability of this kind of solvent must be properly assessed.

3.4. Attributes of the Top 20 Articles

3.4.1. Analysis of Keywords

After the specific investigation of the top publications and top articles with their respective metrics, it is also important obtain a broader vision of the set of 535 publication data by visualizing them in a web of entangled keywords as shown in Figure 4. It was found that there are 342 significant items (that occurred more than 5 times) classified into 6 clusters, with 20,380 links and a total link strength of 54,160. Each cluster is differentiated, as shown in Table 6, with a different color and group to summarize the co-occurrence and connectedness of each keyword represented by the 20,380 links. The top 10 keywords included in Figure 4 are shown in Table 7.

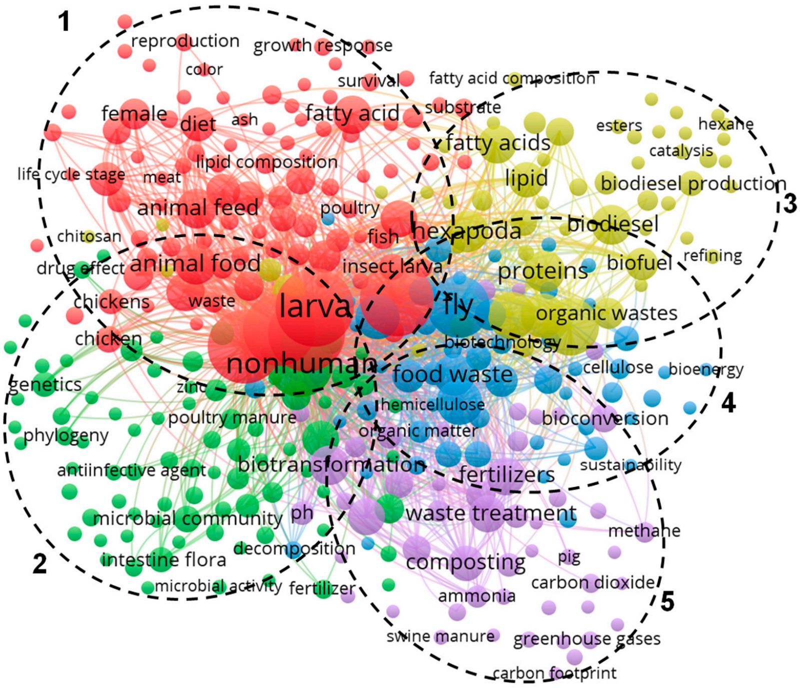

Figure 4. Visualization of the keywords from the 535 articles (with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel). Items = 342, clusters = 5, links = 20,380, total link strength = 54,160. The classification of the clusters can be observed in Table 6.

Table 6. Classification of the clusters in Figure 4.

Cluster	Color	Description
1	Red	Animal feed preparation and experiments
2	Green	Entomology, microbiology, biochemistry
3	Yellow	BSF and biodiesel, biofuels
4	Blue	Agricultural waste management
5	Violet	Municipal waste management

Table 7. Top 10 keywords in each cluster in Figure 4.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Hermetia illucens	nonhuman	fly	black soldier fly larvae	biotransformation
larva	maggot	simuliidae	biomass	manure
animals	biodegradation	waste management	black soldier fly	fertilizers
diptera	bioremediation	food waste	hexapoda	waste treatment
animal	heavy metal	organic waste	fatty acids	composting
animal food	microbial community	waste disposal	insect	nitrogen
fatty acid	human	animalia	biodiesel	nutrients
protein	intestine flora	fermentation	proteins	pH
animal experiment	livestock	refuse disposal	lipid	manures
animal feed	rearing	growth rate	biofuel	moisture

3.4.2. Analysis of a Single Keyword ("Biodiesel")

Biodiesel, of particular interest in this manuscript, can be further traced in the VOSViewer software, with the other terms associated with biodiesel shown in Figure 5. This illustrates that one can click a specific circle with ease in VOSViewer software in order to instantaneously observe the interconnection with other keywords. In Table 8, the details of the top 20 keywords that are linked with biodiesel, along with the weight and cluster, are shown. Figure 5 and Table 8 demonstrate that BSF as an insect and its larvae are directly correlated with biodiesel or biofuel ingredients (fatty acid(s), lipid, obtained via the transesterification process) for a greener world with advanced waste management of food waste and for feedstocks to synergistically solve the waste-food-energy nexus.

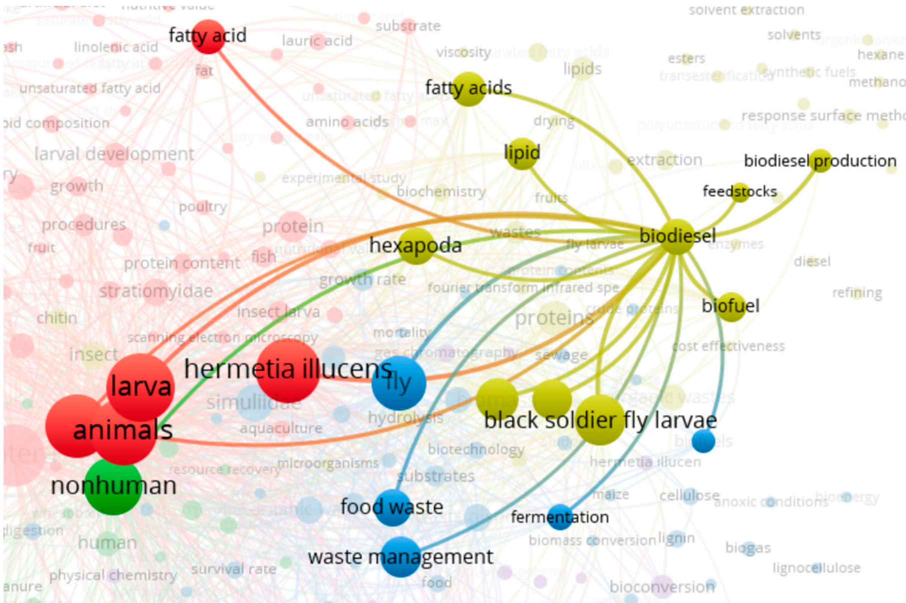

Figure 5. Biodiesel as a specific keyword of interest, along with terms associated with it (from various clusters). Item = biodiesel, links = 218, total link strength = 729.

Table 8. Top 20 terms associated with biodiesel obtained from Figure 5.

No.	Terms Associated with Biodiesel	Weight	Cluster
1.	*Hermetia illucens*	25	4
2.	fly	21	3
3.	black soldier fly larvae	21	4
4.	biofuel	20	3
5.	larva	20	3
6.	biodiesel production	17	4
7.	black soldier fly	16	3
8.	biomass	14	4
9.	nonhuman	14	2
10.	fatty acids	13	3
11.	hexapoda	12	5
12.	food waste	11	4
13.	lipid	9	4
14.	waste management	9	1
15.	fermentation	8	1
16.	feedstocks	8	2
17.	fatty acid	8	3
18.	biofuels	8	5
19.	transesterification	8	5
20.	organic wastes	7	4

3.5. Authors and Countries

In addition to the analysis of the publication data, the data of the authors were also analyzed in order to identify their impact and productivity regarding the research of biodiesel from BSF as one of the solutions of the WFE nexus. The analysis of the authors is shown in Figure 6. Out of 1818 authors, 108 authors have at least 5 publications, and only 94 of them are connected with each other. The authors are classified in 6 distinct clusters, connected with 424 links. The result of Figure 6 was extracted to obtain the top 10 authors, as shown in Table 8.

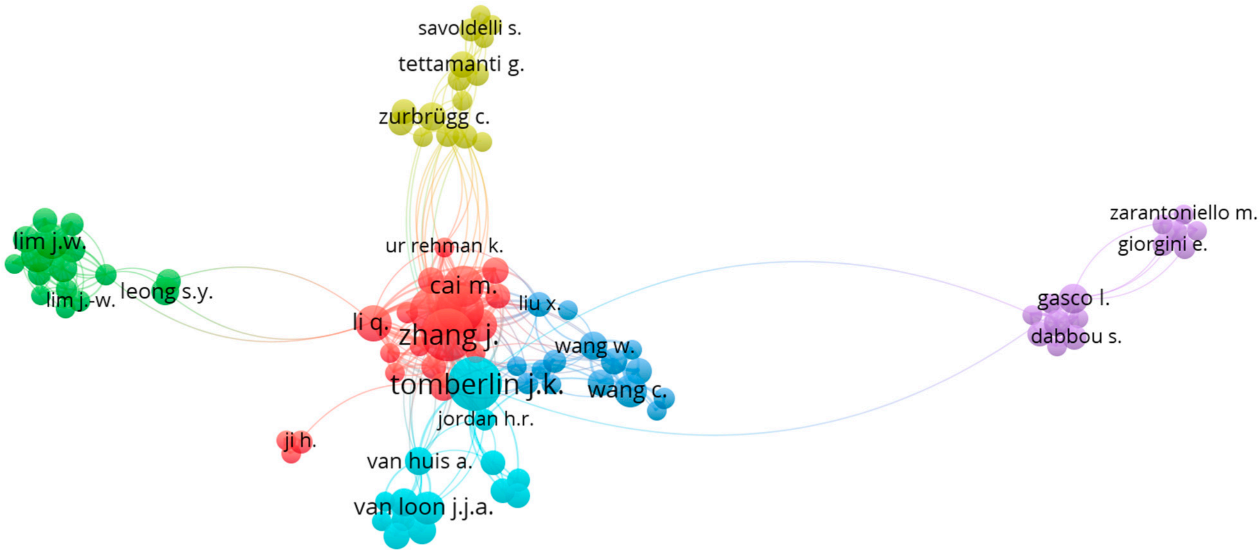

Figure 6. Map of authors with more than five articles (with the keywords of black soldier fly (and/or Hermetia illucens) and biodiesel) and their connectivity with each other. Items = 94, clusters = 6, links = 424, total link strength = 1601.

In Table 9, at least 15 co-authored publications are considered in the top 10 list. In addition, J.K. Tomberlin of Texas A&M University, United States of America, leads the pack with 39 articles, and a total of 7878 Scopus citations. However, in terms of citations, J.J.A. van Loon has around twice the number of J.K. Tomberlin's citations of 14,095, and the highest h-index. However, collectively, Huazhong Agricultural University, China dominates the list, with 5 personnel with more than 3900 citations on average. It is also worth noting that the first two papers on biodiesel from BSF in 2011 are authored by them. In addition to the majority of authors being from China and the Netherlands, there is also a scientist from Malaysia, J.W. Lim, that is on the list with 16 co-authored publications and more than 4500 citations.

Countries that are influential regarding research on the utilization of BSF for biodiesel and other problems in the WFE nexus are displayed in Figure 7, with the top 10 countries shown in Table 10. It can clearly be observed that China and the United States, as global academic powerhouses, lead the list and demonstrate strong cooperation as indicated by the thick link. In the same cluster with China and the United States is also Italy with 22 links of cooperation with Asia, Europe, and Africa.

There is, however, a unique observation in that non-tropical European countries in Table 10 (located 40°–60° North, such as Italy, the Netherlands, Germany, Belgium, and the United Kingdom) are very enthusiastic regarding research on BSF, although BSF research is mainly distributed in 45° North to 40° South (according to the map of Swiss Federal Institute of Aquatic Science and Technology [19]) or geographically distributed in North America, some southern parts of South America, South Africa, and Pacific Asia (Japan, China, Taiwan, Indonesia, Australia) [60].

Table 9. Top 10 authors with the most co-authored articles with the keywords of black soldier fly (and/or *Hermetia illucens*) and biodiesel.

No.	Author Name	Affiliation	Citations	h-Index	Number of Co-Authored Publications
1.	Tomberlin, Jeffrey Keith	Texas A&M University, College Station, the United States of America	7878	48	39
2.	Zhang, Jibin	Huazhong Agricultural University, Wuhan, China	3198	32	37
3.	Yu, Ziniu	Huazhong Agricultural University, Wuhan, China	9479	52	35
4.	Zheng, Longyu	Huazhong Agricultural University, Wuhan, China	2795	30	31
5.	Cai, Minmin.	Huazhong Agricultural University, Wuhan, China	1961	26	23
6.	Li, Qing	Huazhong Agricultural University, Wuhan, China	2075	23	17
7.	Lim, J.-W.	Universiti Teknologi Petronas, Malaysia	4562	39	16
8.	van Loon, J.J.A.	Wageningen University & Research, Wageningen, the Netherlands	14,095	66	15
9.	Li, Wu.	Hubei Polytechnic University, Huangshi, China	1017	13	15
10.	Wang, Cunwen	Wuhan Institute of Technology, Wuhan, China	3912	31	15

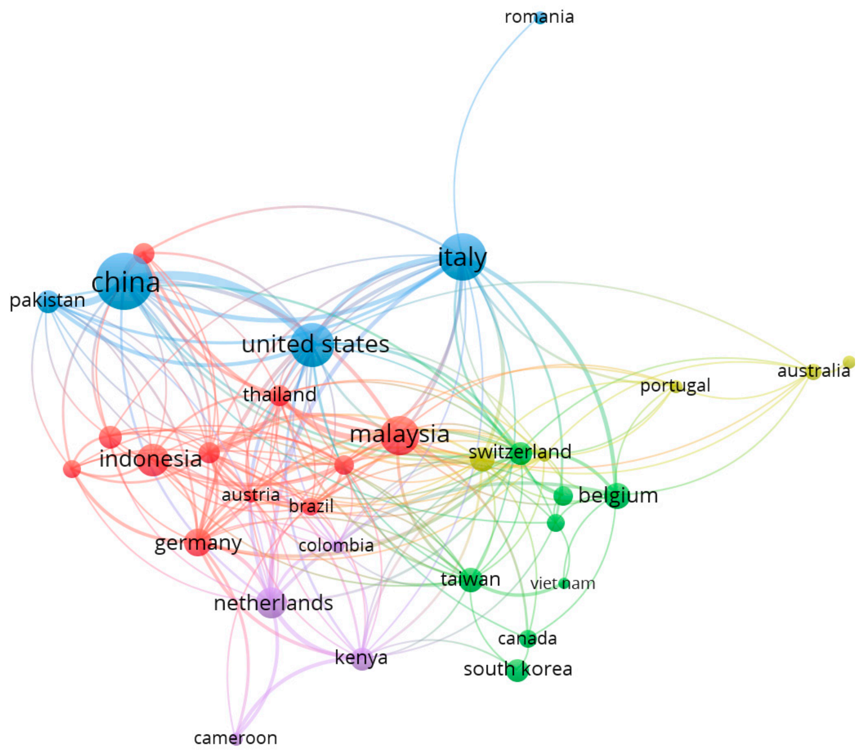

Figure 7. Co-authorship between countries in research on BSF for biodiesel and other applications. Clusters = 5, links = 212, total link strength = 432.

Table 10. Publication productivity of the top 10 countries.

No.	Country	Documents
1.	China	114
2.	Italy	80
3.	The United States	65
4.	Malaysia	55
5.	Indonesia	36
6.	The Netherlands	35
7.	Germany	28
8.	Belgium	25
9.	The United Kingdom	21
10.	Taiwan	21

Based on the co-authorship analysis in Figure 7, the strong desire to study and research alternative energy and food sources of the aforementioned European countries is fulfilled by cooperation with Asian countries (Malaysia, Indonesia, Taiwan, Thailand, and especially China). In addition to this, related to the geographical location, the link strength as a function of the continents is shown in Table 11. It is clearly shown that Europe leads with the highest link strength of 170.5, followed by Asia in second place with a link strength of 131.5, and others (Africa, Americas, Australia) with a combined link strength of 130 (similar to that of Asia). Based on Table 11, it can be suggested that Asia needs to catch up with Europe regarding research on BSF for biodiesel, food waste processing, alternative feed, and other applications related to the waste-food-energy nexus, especially because Asia's geographical position is favorable for BSF.

Table 11. Strength of the connection and research collaboration in different continents related to BSF for biodiesel and other applications.

Continent	Link Strength
Africa	66
America (North, South, Central, Canada)	58.5
Asia (East, South, Southeast)	131.5
Australia (Australia, New Zealand)	5.5
Europe	170.5
Total	432

4. Conclusions

Research from the last 10 years (2011–2022) on black soldier fly (BSF, *Hermetia illucens*) larvae as biodiesel and other promising applications (organic waste treatment, food and feed source) was bibliographically analyzed. The publication data captured by a trusted research database, Scopus, was retrieved, filtered, and sorted to reveal the characteristics of publications in the last decade, which has experienced a substantial increase since 2017. In addition, the top 20 journals and top 20 articles were also identified based on numerous citations, demonstrating their high impact on the research in this field. Based on the citation burst analysis, it is suggested that the research topics of BSF larvae for food, feed, organic waste treatment, and biodiesel as a renewable energy are still sustainable research directions for the foreseeable future.

The current publication data has a vast array of keywords, which were analyzed and distinguished using VOSViewer software to form five clusters of research. The research on biodiesel is, in fact, related to five distinct clusters, revealing the multifaceted approach to BSF larvae as a biological agent to tackle the global issue of the water-food-energy nexus. Therefore, research on BSF is on the right track towards the avenues of (1) waste treatment that is highly useful for (2) creating alternative feed to generate a sustainable food source, and the (3) production of green bioenergy. Furthermore, prominent authors and influential countries regarding research on BSF for biodiesel (also waste treatment and alternative feed or food) were also identified. Global BSF research on biodiesel and other applications in the waste-food-energy nexus was also mapped in this study, which is currently led by European countries. However, Asian countries are encouraged to reach the research performance of European countries in the future, particularly for tropical Asian countries for which BSF is comfortable with.

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