Ex-ante Life Cycle Impact Assessment of Insect Based Feed Production in West Africa

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ABSTRACT

While the idea of using insect based feeds (IBFs) offers great potential, especially in developing countries, the environmental impact of implementation remains poorly researched. This study investigates the environmental performance of IBF production in the geographical context of West Africa. Drawing on published life cycle inventory (LCIs) data, the impact of three different IBF production systems were ex-ante evaluated (ReCiPe method) and compared to conventional feed resources. The explorative life cycle study provides a basis for trade-off analysis between different insect rearing systems (*Musca domestica* and *Hermetia illucens*) and provides insights on the environmental performance of IBF in comparison with conventional animal- and plant based protein feeds (fishmeal, cottonseed and soybean meal). The impacts of IBFs were shown to be largely determined by rearing techniques and the environmental loads of rearing substrates, attesting advantages to the rearing of housefly (*M. domestica*) larvae on chicken manure and the use of natural oviposition, i.e., substrate inoculation through naturally occurring flies. A comparison with conventional feeds pointed out the environmental disadvantages of current IBF production designs (especially in comparison to plant based feeds) that were largely attributable to their different position in the trophic network (decomposers) and the systems' sub-standard capacity utilisation (insufficient economy of scale effect). When larvae are reared on substrates of low economic value (i.e., waste streams), IBF impacts were comparable to fishmeal. The results of the comparative

assessment also highlighted a methodological limitation in the ReCiPe method, which does not account for impacts related to the use of biotic resources. As a consequence, the utilization of naturally grown resources, such as wild anchoveta, was treated as an ecosystem service of no environmental charge, providing disproportionate advantages to the fishmeal system.

1. INTRODUCTION

For generations, insects have been used as a valuable source of protein for livestock across continents other than Europe (Van Huis et al., 2013). This traditional practice is nowadays met with renewed interest as recent research suggests insect based feeds (IBF) as a possible solution for improving food self-sufficiency in economically disadvantaged regions.

This notion is supported by various studies investigating the benefits of IBF in the framework of a circular economy. Rearing dipteran species (flies) on different low-value wastes (e.g.,livestock manure, food processing and market wastes etc.) provides high value protein while facilitating significant reductions in waste volumes (Makkar et al., 2014; Riddick, 2014; Sánchez-Muros et al., 2014; Surendra et al., 2016). Dipteran insect species, such as the common housefly, *Musca domestica (L. Diptera: Muscidae),* or the black soldier fly, *Hermetia illucens* (L. *Diptera, Stratiomyidae*), show a similar amino acid profile to fishmeal (Barroso et al., 2014; Bosch et al., 2016). Of particular interest are the relatively high levels of the amino acids lysine and methionine, commonly found limiting in most conventional plant based protein feeds (Riddick, 2014). Larvae of *M. domestica* and *H. illucens* are also rich in fat, whereas the chitin they contain may confer beneficial probiotic effects in animal nutrition (Bosch et al., 2016; van Zanten et al., 2015). The nutritional benefits of IFB are supported by recent feeding trials demonstrating that a full or partial replacement of fishmeal by dried larvae and pre-pupae from *M. domestica* and *H. illucens* feasible for a number of fish species, as well as for chickens (layers and broilers) and pigs (Devic et al., 2013; Fanimo et al., 2006; Henry et al., 2015; Hwangbo et al., 2009; Makkar et al., 2014; Riddick, 2014; Wang et al., 2017).

While the nutritional value of IBF and technical feasibility for production at scale are recognised and backed by a growing body of research, the environmental impact of the substitution of conventional feeds in developing countries remains inadequately researched (Halloran et al., 2016). Publications that have investigated life cycle performances of *M.. domestica* (Roffeis et al., 2015; van Zanten et al., 2014) and *H. illucens* larvae (Prandini et al., 2015; Salomone et al., 2017; Smetana et al., 2016) production all focus on IBF systems developed for application in Europe. Accounting for the significant disparities in climate and socio-economic conditions, these studies enable no conclusions to be drawn on the potential environmental ramifications in developing countries.

This study explores the environmental performance of small-scale IBF production systems operating in the geographical conditions of tropical West Africa. Drawing on generic Life Cycle inventory (LCI) data presented in Roffeis et al. (2017), the environmental impact of three ex-ante modelled IBF production systems are assessed: (i) production of *M. domestica* larvae on chicken manure, inoculated through natural oviposition, i.e., attracting naturally occurring flies from the facilities' surroundings to lay eggs on the rearing substrate (hereafter named IER_A); (ii) production of *M. domestica* larvae using a mixture of sheep manure and fresh ruminant blood, inoculated through natural oviposition (hereafter named IER_B); and (iii) production of *H. illucens* larvae using chicken manure and fresh brewery waste (solid, protein-rich residues of fermented brewery grains), inoculated artificially, i.e., inoculated with larvae from a captive adult colony (hereafter named FfA) (Roffeis et al., 2017).

The modelled IBF production systems serve as the basis for a comprehensive life cycle impact assessment (LCIA), in which inventory flows are characterised by environmental impacts using ReCiPe (V 1.11) characterisation factors (Goedkoop et al., 2008). A benchmark comparison is made with the environmental impacts of customary plant based protein feeds (cottonseed meal and soybean meal), as well as imported Peruvian fishmeal, an animal based feedstuff whose widespread use is considered irreconcilable with sustainable development imperatives (Olsen and Hasan, 2012).

This LCA study provides first insights on the environmental impacts of the prospective implementation of IBF in West Africa and illustrates the use of life cycle thinking as a decision-making tool in the early stages of product development.

2. MATERIAL AND METHODS

The explorative life cycle study was conducted in conformity with the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards (not third-party reviewed against ISO 14040). All methods, materials, and assumptions that are relevant to the results presented will be detailed in the following sections.

2.1. Goal and Scope

This study aims at ex-ante evaluation of the environmental performance of small-scale IBF production systems in the geographical context of tropical West Africa. The explorative life cycle study is expected to (1) identify environmentally critical aspects of prospective IBF production in West Africa; (2) reveal trade-offs between different insect rearing systems (*M. domestica* and *H. illucens*) and rearing substrates; and (3) aid future research and development activities by offering suggestions to improve the environmental performance of current production designs.

In order to fulfil these objectives, a comprehensive attributional LCA analysis is conducted, in which ex-ante modelled IBF production systems are characterised by environmental impact data using the

ReCiPe method (V 1.11). To test for advantages in sustainability, the estimated impacts of IBFs are compared with those of conventional feeds. As the nutritional properties and position in the trophic network are similar (i.e., animal based feed), the environmental impacts of the IBF systems are compared with Peruvian fishmeal produced from wild-caught anchoveta. Additionally, to explore the differences between animal- and plant based feeds, the impacts of IBFs are benchmarked against cottonseed meal and soybean meal.

2.1.1. Geographical context

The IBF systems examined typify up-scaled system versions of existing rearing trials in West Africa, i.e., Ashaiman, Ghana (FfA system) and Bamako, Mali (IER systems). The conditions at the two sites serve as examples for the diverse geographical characteristics of West Africa. The climatic conditions range from semi-arid and arid conditions in the northerly expansion, such as Mauritania and parts of Mali, to humid and sub-humid conditions in the southern coastal areas, in countries like Liberia, Ivory Coast, Ghana, Togo, Benin and Nigeria (Schmidhuber and Tubiello, 2007). While West Africa's economy relies strongly on primary production, the food and livestock producing sectors are fairly underdeveloped and largely dominated by small-scale farming operations. These are either managed in integrated systems that are organised around rain-fed cropping systems, or run as specialised operations, that draw on the supply of local value chains and/or imports (e.g., fertilizers, agrochemicals, feeds) (Jalloh et al., 2013; Zhou and Staatz, 2016).

2.1.1. System boundaries

Following the boundary settings of Roffeis et al. (2017), the LCA analysis encompasses the extraction of raw materials, manufacturing of inputs including rearing substrates, the insect rearing and residue substrate separation, and the processing of the final co-products, i.e., from "cradle to gate". The system boundary definition and allocation procedures used in the assessment of the IBF models are consistent with the decisions taken for the reference systems (i.e., conventional feeds).

In a similar way to the production of fishmeal and oilseed cakes, IBFs are produced from multi-functional processes, i.e., processes that have more than one functional outflow (ISO, 2006b). In IBF systems, multi-functionality is afforded through the co-production of feed (IBF) and residue substrate. The latter is rich in available plant nutrients (e.g.,nitrogen, phosphorous and potassium) and, likewise chicken and sheep manure, qualifies as an organic fertilizer (Kenis et al., 2014; Roffeis et al., 2017). Since the outflows of IBF and residue substrate presuppose each other and functional traits of both products are not yet sufficiently investigated (i.e., ileal digestibility, fertilising effect), a circumvention of the multi-functionality problem through sub-division of functional in- and outflows or system expansion was not practical. Thus, as suggested in the ISO 14044 guidelines, impacts are allocated on the basis of causal relationships, using market prices as a measure to capture the complex relations and varying attributes of jointly produced products. (e.g., economic allocation) (Ardente and Cellura, 2012; Guinée et al., 2004; ISO, 2006b). Owing to similar product utilities (i.e., organic fertilizer) and to ensure consistency, economic allocation was also applied to the livestock systems that provide the manure rearing substrate. Assumptions on market prices and share in revenues underlying the calculation of allocation factors are detailed in Appendix A, Table A1 – A5. To analyse how choices on allocation procedures affect the assessment results, a sensitivity analysis was conducted in which impacts were recalculated under the condition of varying fertilizer prices (section 3.2.), which affects both the process impacts allocated to the insect product and the burdens associated with the rearing substrate used as input for the production system. Further, the sensitivity of the results in response to an impact allocation by physical attributes, i.e., mass and energy content, was analysed (Appendix B).

2.1.2. Functional unit

As there is insufficient data on the livestock-specific ileal digestibility of IBFs (protein turnover/protein intake), the environmental performances of the IBF systems are measured against a reference flow of 1 kg IBF provided to a generic market in West Africa. Here the designation '1 kg IBF' stands proxy for 1 kg whole dried larvae with a residual water content of less than 10%. Relating the LCA results to a mass flow allows for a consistent comparison between IBFs and conventional feeds and provides opportunity to recalculate the results based on more appropriate measures once sufficient evidence is available (e.g.,ileal digestibility).

For reasons of transparency, the environmental performances of the IBF production systems are quantified for two functional units (FUs); a (1) process-based FU (hereafter called FU_A) that calculates the system's performance without allocating impacts between IBFs and co-produced quantities of residue substrates; and (2) an output-based FU (hereafter called FU_B), where process impacts are partitioned between IBFs and jointly produced residue substrates using economic allocation (see section 2.1.1).

2.2. Life cycle inventory (LCI)

This life cycle study expands on the research of Roffeis et al. (2017), who employed experimental data of existing rearing trials in Ghana and Mali to model generic LCIs of three small-scaled IBF production systems operating in the geographical context of tropical West Africa . The generic modelling approach of Roffeis et al. (2017) facilitated consistency to the comparative impact assessment and allowed for a transparent analysis of contributing process flows. The generic LCI data of West African IBF production systems used in this LCA study are presented in Table 1 and Appendix C (Table C1 – C3).

Table 1. Life Cycle Inventory (LCI) of different insect based feed (IBF) production models according to Roffeis et al. (2017). Comparison of the generic IER_A, IER_B and FfA system by relevant material and energy flows associated with the provision of 1 kg IBF and co-produced quantities of residue substrate to a generic market in West Africa. Inventory items categorised as 'manufacturing equipment' and 'consumables & supplies' are detailed in Appendix C, Table C1 – C3. All data presented are subject to rounding.

Life Cycle inventory (LCI)	**Unit**	**IBF production models**		
Inventory items		IER_A	IER_B	FfA
PRIMARY FACTORS				
Σ Land	**m^2a**	**0.04**	**0.03**	**0.05**
Fixed	m^2a	0.01	0.01	<0.01
Variable	m^2a	0.03	0.02	0.05
Σ Built infrastructure	**m^2a**	**0.07**	**0.04**	**0.11**
Insect rearing | rendering	m^2a	0.06	0.03	0.10
Storage	m^2a	0.01	0.01	0.01
Σ Labour	**h**	**1.9**	**1.6**	**3.1**
Labour (untrained)	h	1.5	1.1	1.9
Labour (trained)	h	0.3	0.5	1.1
INTERMEDIATE FACTORS				
Σ Substrate	**kg**	**100.0**	**62.7**	**26.8**
Manure (chicken | sheep), dried	kg	40.0	22.8	6.3
Ruminant blood, fresh	kg	-	14.2	-
Brewery waste, fresh	kg	-	-	8.9
Sorghum bran (purging)	kg	0.1	0.1	-
Saw dust (purging)	kg	-	-	0.6
Water (substrate conditioning) [a]	l	59.9	25.6	11
Σ Water	**l**	**68.4**	**32.7**	**63.6**
Water (process)	l	59.9	25.6	13.9
Water (cleaning)	l	8.4	7.1	19.6
Water (separation)	l	-	-	30.2
Σ Energy	**MJ**	**0.7**	**0.7**	**3.3**
Nat. gas (burned in oven/ cooker)	MJ	0.7	0.7	3.3
Σ Transport	**km**	**0.1**	**0.8**	**0.4**
Motorbike	km	0.1	0.1	0.3
Commercial vehicle (3.5 tonne)	km	-	0.7	-
Truck (7.5 tonne)	km	-	-	0.1
OUTPUTS				
Σ Process emissions				
Waste water (COD ~ 2 kg/m^3) [b]	l	8.4	7.1	49.8
Emission CH_4 (to air)	g	15.5	10.0	11.3
Emission N_2O (to air)	g	0.3	0.2	0.2
Emission NH_3 (to air)	g	2.8	1.8	2.1
Volatile solids (≤ 10 ųm, to air)	g	2.5	1.6	1.8
Σ Process products	**kg**	**29.0**	**17.0**	**8.1**
Residue substrate (fertilizer)	kg	28.0	16.0	7.1
IBF, dried	kg	1.0	1.0	1.0
SCALE OF PRODUCTION	kg IBF/ d	12.0	12.0	9.6

[a] Water used for substrate conditioning (rearing substrate), accounted for under inventory item; 'water'. [b] Approximated chemical oxygen demand (COD) of generated waste waters, i.e., 2 kg COD/m^3 (42 kg/21 m^3 waste water).

The three IBF systems share a similar production cycle, which starts with the sourcing of rearing substrates and ends with the killing and drying of insect larvae, that are assumed to be fed to livestock as dried, whole larvae (Roffeis et al., 2017). To ensure comparability and correct for seasonal variations, all production functions were extrapolated from annual averages (Roffeis et al., 2017). Additionally, to account for regular production outtakes (e.g., failed inoculation, parasite infestation, and microbiological spoilage of substrates), safety margins were included (failure of one in 50 batches). To keep transportation needs to a minimum, all IBF systems are assumed to be in close proximity to manure providing facilities (i.e. poultry farm and sheep feeding stables) (Roffeis et al., 2017).

The LCI analysis by Roffeis et al. (2017) revealed marked differences in input and output relations between the IBF systems. Differences in conversion efficiencies (conversion of rearing substrate into IBF), which follow from a complex interaction of determinants such as insect species, nutritional properties of the rearing substrate, rearing techniques and climatic conditions, were identified as the most distinguishing factors. A more detailed presentation and analysis of the modelled LCIs is presented in Roffeis et al. (2017). The main features of the IBF production models are briefly described on the following section.

2.2.1. IER production models

The LCI data published by Roffeis et al., (2017) include two production scenarios for *M. domestica* reared under condition of natural oviposition. The generic IER_A and IER_B systems represent small commercial-scale production systems that are suitable for implementation in small-holder farming operations in rural areas of West Africa with a tropical savanna climate. The essential difference between the IER systems is the rearing substrate used. The IER_A employs a mixture of water and dried chicken manure. The rearing substrate in the IER_B is a combination of sheep manure, fresh ruminant blood and water. The production process in both IER systems is organised around three basic operational procedures, i.e., substrate conditioning, larval production, and separation and drying. The IER production systems are scaled to facilitate a daily output of 12.0 kg IBF, i.e., 4.4 t annually (Roffeis et al., 2017).

2.2.2. FfA production model

The FfA model portrays a small-scale production facility that provides protein feeds to small-holder aquaculture operations in tropical West Africa. As differentiated from the IER systems, the FfA system produces IBF from *H. illucens* and the rearing substrate consists of a mixture of brewery waste, chicken manure and water that is inoculated through larvae from a captive adult colony (i.e., artificial substrate inoculation). The use of artificial substrate inoculation results in a more elaborate process organisation that cycles through six interrelated unit processes, i.e., substrate conditioning, egg production, larvae production, pupa production, separation (i.e., harvest) and drying. The egg production unit consists of a number of adult colonies of different age and acts as a system-internal hub, where production of pupae and the larvae is synchronized with the calibrated daily egg output. The FfA system is assumed to maintain an adult colony at a constant number of 20,000 adult flies, which allows for a daily output of 9.6 kg dried insect larvae (3.5 t annually) (Roffeis et al., 2017).

2.3. Life cycle impact assessment (LCIA)

2.3.1. Background data

To ex-ante assess the environmental performance of the IBF production models additional data were collected on (i) production characteristics of input factors, (ii) material composition and biophysical attributes of manufacturing equipment, auxiliary- and operating materials, and (iii) the functioning and characteristics of the prevalent agricultural value chains. Inventory data on material composition, energy demand, and electronic devices were obtained from scientific and industrial literature (supplementary material S1). Environmental impact data on the system's material and energy flows have been extracted from the LCA database ecoinvent (V 3.1) (Guinée et al., 2004) using SimaPro® (Pré, The Netherlands).

2.3.1. Impact assessment

The potential environmental impacts of IBFs and conventional feeds are calculated using the ReCiPe method (V 1.11) (Goedkoop et al., 2008). The characterisation results are presented for 18 ReCiPe impact categories at midpoint level and, to aid the comparison of IBFs and conventional feeds, for ReCiPe single score at endpoint level (i.e., aggregated weighted score). The conversion of midpoint characterisation factors into endpoint damage categories followed the egalitarian perspective, a characterisation method that represents precautionary and long-term thinking and values (Aziz et al., 2016; Peregrina et al., 2006). The impact data used for the characterisation of the inventory items are provided in the supplementary material S1.

The impacts of plant based feeds (i.e., cottonseed meal and soybean meal) have been calculated on the basis of generic datasets featured in the LCA database ecoinvent (V 3.1) (Guinée et al., 2004). Environmental impact data of Peruvian fishmeal have been extracted from a study by Fréon et al.

(2017), who conducted LCAs on three Peruvian fishmeal plants using the ReCiPe method (egalitarian perspective).

2.3.2. Data Quality and Uncertainty

The modelling of the IBF systems presented in Roffeis et al. (2017) involved several assumptions and approximations in both foreground and background process flows, which, in addition to the risk of amplification of measuring errors, may undermine the predictive value of the LCA results. Since the investigated LCI models are largely orchestrated from first hand or single point data with no degree of variability, it was impossible to use statistical uncertainty propagation approaches, such as Monte Carlo analysis or fuzzy set theory, to analyse the model parameter uncertainty. However, a comprehensive impact contribution analysis was conducted to illustrate the relative contribution of inventory items to the overall results and thus highlights model parameters that are most influential to the assessment results.

As the employed characterization methods and background databases are the same for all production systems, no uncertainty analysis was made for method-related biases. Fuzziness that is owed to the applied characterization methods (ReCiPe V 1.11) and used databases (ecoinvent®, V 3.1) are well documented and can be recalculated from the presented data if required (Roffeis et al., 2017).

3. RESULTS

3.1. Life cycle impact assessment (LCIA)

The LCIA results of the IBF production systems are summarized in Table 2. For reasons of conciseness and clarity, this section focuses only on the ReCiPe single score results (egalitarian perspective) expressed in impacts points (Pt). The assessment results for the 18 ReCiPe impact categories (midpoint level) and three damage categories (endpoint levels) are presented and explained in detail in Appendix D. To avoid suggesting a false level of accuracy, assessment results are presented in scientific notation rounded to one decimal place.

Table 2. Environmental characterisation of the life cycle inventories of different insect based feed (IBF) production systems. Comparison of the IER_A, IER_B, and FfA system by life cycle impacts associated with the provision of 1 kg IBF and co-produced quantities of residue substrates to a generic market in West Africa reported by ReCiPe single score (ReCiPe V 1.11; World | egalitarian perspective) expressed in impact points (Pt). Impacts related to the inputs of 'manufacturing equipment' and 'consumables & supplies' are detailed in Appendix C, Table C4 – C6. All data presented are subject to rounding.

Life Cycle impact (LCIA)	**Unit**	**IBF production models**			**Data sources**	
Inventory items		IER_A	IER_B	FfA	Foreground	background
PRIMARY FACTORS						

Σ Land	**Pt**	**2.6×10^{-3}**	**2.1×10^{-3}**	**3.8×10^{-3}**		
Fixed	"	5.6×10^{-4}	5.6×10^{-4}	$1.0\times10^{+0}$	LCI [e]	ID [f]
Variable	"	2.0×10^{-3}	1.6×10^{-3}	3.5×10^{-3}	"	"
Σ Built infrastructure	**"**	**4.2×10^{-2}**	**2.8×10^{-2}**	**7.5×10^{-2}**		
Insect rearing | rendering	"	3.5×10^{-2}	2.2×10^{-2}	6.8×10^{-2}	"	"
Storage	"	6.7×10^{-3}	6.7×10^{-3}	6.1×10^{-3}	"	"
Σ Manufacturing equipment [a]	**"**	**3.4×10^{-3}**	**4.2×10^{-3}**	**3.8×10^{-2}**	**"**	**Table C4 – C6**
Σ Labour	**"**	#	#	#		
INTERMEDIATE FACTORS						
Σ Substrate	**"**	**4.2×10^{-1}**	**1.2×10^{0}**	**4.6×10^{-1}**		
Manure (chicken | sheep), dried	"	4.2×10^{-1}	1.2×10^{0}	6.6×10^{-2}	"	ID [c]
Ruminant blood, fresh	"	-	7.9×10^{-3}	-	"	"
Brewery waste, fresh	"	-	-	3.8×10^{-1}	"	"
Sorghum bran (purging)	"	1.2×10^{-3}	1.2×10^{-3}	-	"	"
Saw dust (purging)	"	-	-	1.6×10^{-2}	"	"
Σ Water	**"**	**3.3×10^{-3}**	**1.6×10^{-3}**	**3.1×10^{-3}**		
Water (process)	"	2.9×10^{-3}	1.3×10^{-3}	2.2×10^{-3}	"	"
Water (cleaning)	"	4.1×10^{-4}	3.5×10^{-4}	9.6×10^{-4}	"	"
Σ Energy	**"**	**5.0×10^{-3}**	**5.0×10^{-3}**	**2.5×10^{-2}**		
Nat. gas (burned in oven/ cooker)	"	5.0×10^{-3}	5.0×10^{-3}	2.5×10^{-2}	"	"
Σ Transport	**"**	**6.1×10^{-4}**	**4.1×10^{-2}**	**2.7×10^{-2}**		
Motorbike	"	6.1×10^{-4}	6.1×10^{-4}	3.9×10^{-3}	"	"
Commercial vehicle (3.5 tonne)	"	-	4.0×10^{-2}	-	"	"
Truck (7.5 tonne)	"	-	-	2.3×10^{-2}	"	"
Σ Consumables & supplies [b]	**"**	**3.4×10^{-3}**	**2.5×10^{-3}**	**1.7×10^{-2}**	**"**	**Table C4 – C6**
OUTPUTS						
Σ Process emissions	"	**1.9×10^{-2}**	**1.3×10^{-2}**	**1.7×10^{-2}**		
Waste water (COD ~ 2kg/m^3) [c]	"	6.4×10^{-4}	5.4×10^{-4}	3.8×10^{-3}	"	ID [c]
Emission CH_4 (to air)	"	5.6×10^{-3}	3.6×10^{-3}	4.1×10^{-3}	"	"
Emission N_2O (to air)	"	2.1×10^{-3}	1.3×10^{-3}	1.5×10^{-3}	"	"
Emission NH_3 (to air)	"	3.0×10^{-3}	1.9×10^{-3}	2.2×10^{-3}	"	"
Volatile solids (≤ 10 ųm, to air)	"	8.0×10^{-3}	5.2×10^{-3}	5.9×10^{-3}	"	"
Σ Total process impact (FU_A)[d]	**"**	**5.0×10^{-1}**	**1.3×10^{0}**	**6.6×10^{-1}**		
Residue substrate (fertilizer)	"	1.3×10^{-1}	1.6×10^{-1}	3.0×10^{-2}	"	IA [g]
Insect larvae, dried (FU_B)	"	3.7×10^{-1}	1.1×10^{0}	6.4×10^{-1}	"	IA [g]

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[a] Durable inventory items that facilitate the production process (results detailed in Appendix C, Table C4 – C6). [b] Wearable inventory items that get used up in the production process and are replaced regularly (results detailed in Appendix C, Table C4 – C6). [c] Estimated chemical oxygen demand (COD) of generated waste waters, i.e., 2 kg COD/ m^3 (42 kg/ 21 m^3 waste water). [d] Impact objects (i.e., total impacts attributed to co-produced outputs). [e] Life cycle inventory data as published by Roffeis et al. (2017). [f] Impact data (ReCiPe single scores) extracted from the LCA database ecoinvent (V 3.1) using SimaPro® (Goedkoop et al., 2008; Weidema et al., 2013). [g] Impact allocation calculated in percentage relative to share in revenues (see Appendix A, Table A3).

The environmental characterisation by ReCiPe single scores (hereafter referred to as 'single score') reveals considerable differences between the IBF systems. The production process (FU_A) of the IER_B system has the highest single score. Here, impacts related to the co-production of 1 kg IBF and 16 kg residue substrate add up to a total 1.3×10^{0} Pt (Table 1-2). The production process of the FfA system, providing 1 kg IBF and 7.1 kg residue substrate to a generic market in West Africa, ranks second with a single score of 6.6×10^{-1} Pt/ kg IBF. The joint production of 1 kg IBF and 28 kg residue substrate in the IER_A system has the lowest impact, expressed by a single score of 5.0×10^{-1} Pt (Table 1-2).

The impact contribution of input categories is notably variable between the three IBF systems. The IER_A system compares favourably for impacts associated with the input of manufacturing equipment, transportation and rearing substrate (Table 2). Pronounced advantages of the FfA system over either one of the two IER systems are apparent in the impacts relating to the use of rearing substrates, transportation and process-related emissions. The IER_B system, although having the highest single score, outperforms the IER_A and FfA system in impacts associated with the input of built infrastructure, water, consumables & supplies and process emissions (Table 2).

The breakdown of the LCIA results by contributions of relevant inventory items offers insights on the formation of the single score results (Figure 1). While systems show considerable differences in-between specific input categories (Table 2), the relative contribution of inventory items to the overall results appear similar in all three systems (Figure 1).

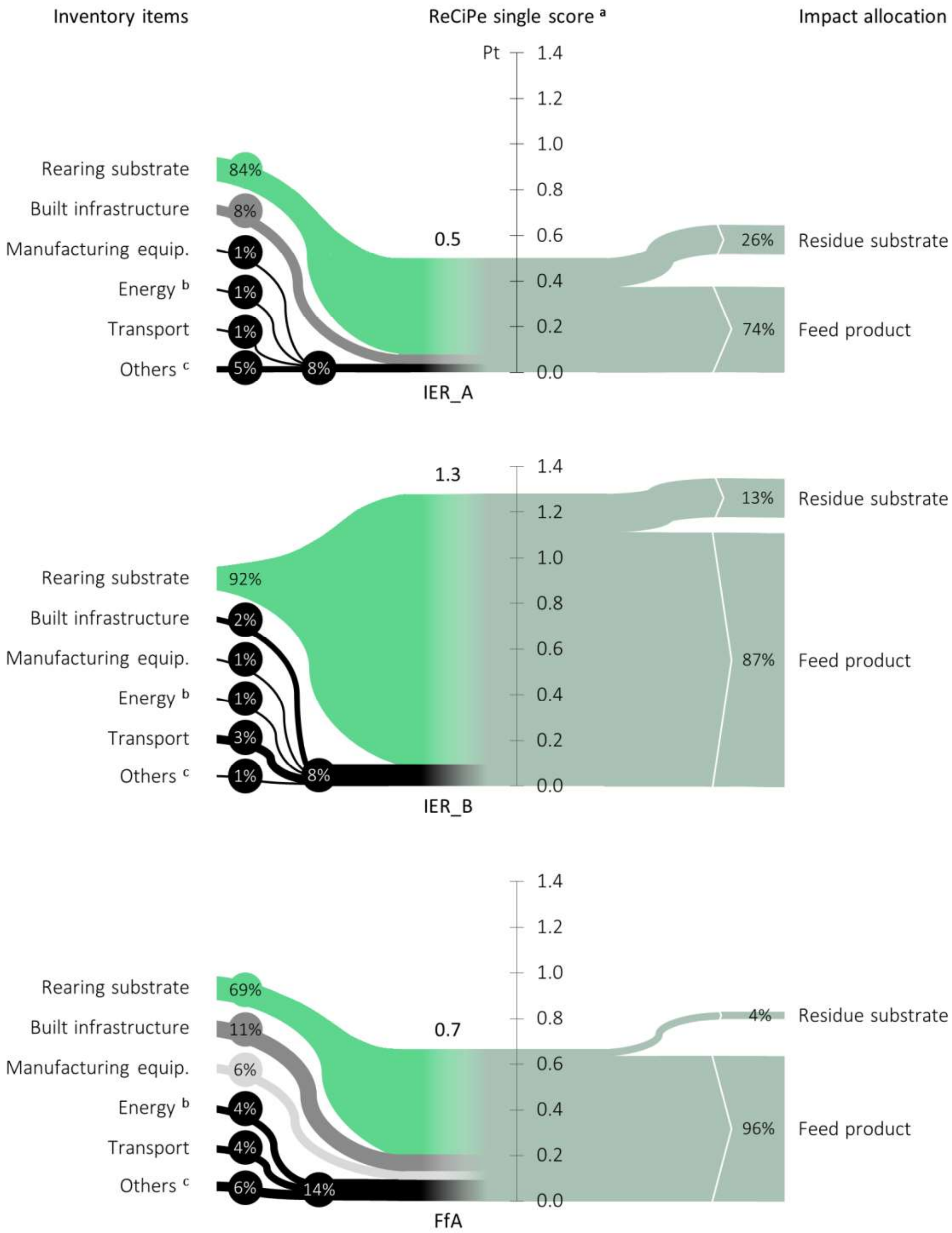

Figure 1. Environmental characterisation of different insect based feed (IBF) production systems. Comparison of the IER_A, IER_B and FfA system by estimated impacts associated with the provision of 1 kg IBF and co-produced quantities of residue substrate to a generic market in West Africa. Breakdown of ReCiPe single score results by contributions of relevant inventory items and partitioning to co-produced IBF and residue substrates through economic allocation, calculated accordingly to their share in revenues. All data presented are subject to rounding.

[a] ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) expressed in impact points (Pt); [b] Impacts related to the burning of natural gas (i.e., killing and drying of larvae). [c] Merger of inventory items that contribute less than 5% to the overall impact and costs in each impact category.

Rearing substrates, constituting the largest mass flow in the IBF production systems, are the major contributors to the ReCiPe single scores in all three IBF systems (Figure 1). The environmental loads of rearing substrates are economically allocated and thereby a function of market demand/price and the environmental impact of the substrate producing systems (see section 2.1.1). The highest substrate related impacts are found in the IER_B system. The use of 22.8 kg sheep manure and 14.2 kg ruminant blood contribute a total of 1.2×10^{0} Pt to the single score, which constitutes 92% of all process induced impacts (Figure 1 and Table 2). When comparing the IBF systems by impacts of rearing substrates, the 40 kg chicken manure used in the IER_A production process is of the lowest environmental load, contributing a total of 4.2×10^{-1} Pt to the single score results (84% of the process impact). The sparing use of rearing substrates in the FfA system benefits the system's environmental performance. The mixture of 8.9 kg brewery waste (3.8×10^{-1} Pt) and 6.3 kg chicken manure (6.6×10^{-2} Pt) contributes a total of 4.4×10^{-1} Pt to the estimated single score results (Figure 1 and Table 2). Adding the impact of sawdust (1.6×10^{-2} Pt), which is used as a bedding material for the purging of larvae (emptying gut content prior to pupation), substrate related impacts in the FfA system total 4.6×10^{-1} Pt, which constitutes about 69% of the system's single score results (Figure 1 and Table 2).

Impacts associated with the sourcing of substrates (i.e., transportation) are of lower relevance but are notably different between the three systems. The sourcing of ruminant blood increases transport related impacts in the IER_B system up to 4.6×10^{-2} Pt, i.e., about 3% of the total single score results. The transport of brewery waste in the FfA system adds a total of 2.3×10^{-2} Pt to the system's single score results (Figure 1 and Table 2). Impacts associated with the sourcing of wearable materials (i.e., inventory items that require regular replacement) add little to system's single score results. Regular trips to a nearby market (10 km proximity) via motorbike add 6.1×10^{-4} Pt to the single score results of the IER systems and, because of a higher demand for nondurable auxiliary equipment and more frequent gas bottle exchange (Roffeis et al., 2017), this adds 3.9×10^{-3} Pt to the single score results of the FfA system (Figure 1 and Table 2).

The higher consumption of propane gas in the FfA system (i.e., gas bottle exchange) is due to climatic conditions of coastal West Africa, where high relative air humidity and precipitation levels do not allow for sun drying of larvae. Instead, the FfA system uses a gas oven to dry the larvae, which increases the consumption of propane gas and process related impacts, i.e., 2.5×10^{-2} Pt per 1 kg IBF and 7.1 kg residue substrate (Table 2). The IER systems, operating in the tropical savanna climate of Bamako, only burn propane gas to support the occasional killing of larvae when exposure to sun is not possible (e.g., precipitation, cloud coverage) (Roffeis et al., 2017). This lowers the unit input of propane gas and reduces the energy-related impacts (5.0×10^{-3} Pt) in the IER systems (Figure 1 and Table 2).

Another relevant contributor to the system's single score results are impacts related to the production infrastructure, i.e., inputs of built infrastructure and manufacturing equipment. In the IER_A and IER_B system, impacts associated with the production infrastructure explain 9% (4.5×10^{-2} Pt) and 3% (4.5×10^{-2} Pt) of the total process impacts, respectively (Figure 1 and Table 2). Due to a more elaborate process, the FfA system shows considerably higher impacts relating to production infrastructure. The input of built infrastructure and manufacturing equipment add impacts of 7.5×10^{-2} and 3.8×10^{-2} Pt to the system's single score results, which total 17% of the process-induced impacts (Figure 1 and Table 2).

When systems are compared by allocated impacts, i.e., partitioned in function to their relative share in revenues (FU_B), the differences between the IBF models are more pronounced (Figure 1). Allocated with 87% of the process associated impacts, the IBF product of the IER_B system arrives at the highest impact. i.e., with 1.1 Pt (1.1×10^{0} Pt) per kg IBF. The IBF product of the FfA system, attributed 96% of the process-induced impacts, ranks second with 0.6 Pt (6.4×10^{-1} Pt). In the IER_A system, the IBF product is allocated 74% of the process impacts, which results in the lowest impact per kg IBF of 0.4 Pt (3.7×10^{-1} Pt) (Figure 1 and Table 2).

3.2. Sensitivity analysis

As demonstrated in section 3.1, the impacts of IBFs are largely determined by economic allocation, affecting both the environmental loads of manures (rearing substrate) and the impacts allocated to co-produced residue substrates (see section 2.1.1). To analyse how price assumptions underlying the economic allocation influence the assessment results, a sensitivity analysis was conducted in which impacts are recalculated under the condition of varying prices of organic fertilizer (manures and residue substrates). To better distinguish between the effects following from changes in the environmental load of manures (input flows) and the impact allocation to residue substrate (output flows), the sensitivity analysis is conducted in two consecutive scenarios. In the first scenario (Scenario A), changes in fertilizer prices are assumed to affect the impact allocation between co-products of IBF production only. In the subsequent scenario (Scenario B), price variations of organic fertilizer are applied to both the impact allocation between co-products of sheep and broiler production (meat and manure) and IBF production (feed and residue substrate).

Figure 2 illustrates the variability of the LCIA results in Scenario A, corresponding to fertilizer prices of (F1) zero economic value (i.e., manure and residue substrate are considered a true waste stream); (F2) 7.85 EUR/ t (-50% BSL, where BSL is the baseline assuming a customary market price for organic fertilizer of 15.70 EUR/ t) and (F3) 23.55 EUR/ t (+50% BSL). As the assumed price variations only affect the revenues of residue substrates, increases in fertilizer prices are met by a decrease in impacts allocated to the system's IBF products (Figure 2). Due to a relatively high output of residue substrates (28.0 kg/ kg IBF), changes are most pronounced in the IER_A system. Here, an increase of fertilizer prices from zero economic value (F1'A) to 23.55 EUR/ t (F3'A) causes a variation in single score results of +34% and -10% compared to the BSL price (Figure 2 and Table A4).

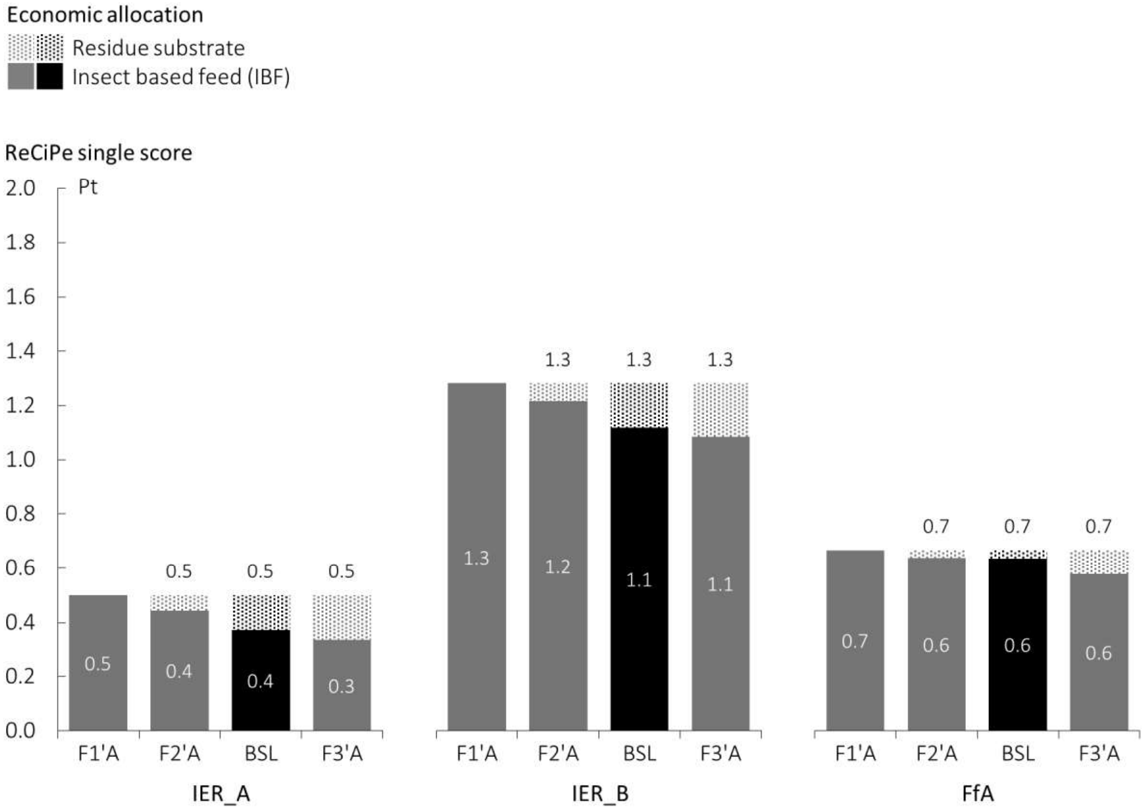

Figure 2. Economic impact allocation under conditions of varying fertilizer prices applied to co-products of insect based feed (IBF) production only (Scenario A). Comparison of the allocated impacts (ReCiPe single score results) of IBFs from the IER_A, IER_B and FfA systems at a market price of organic fertilizer of (F1'A) zero economic value (i.e., chicken and sheep manure and residue substrates are considered a true waste stream); (F2'A) 7.85 EUR/ t (-50% BSL (-50% BSL, where BSL is the baseline assuming a customary market price for organic fertilizer of 15.70 EUR/ t) and (F3'A) 23.55 EUR/ t (+50% BSL). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

The FfA system, co-producing 7.1 kg residue substrate/ kg IBF, shows the lowest responsiveness towards changes in fertilizer prices. Here, impacts allocated to the IBF product range from 0.7 Pt/ kg

(F1'A) to 0.6 Pt/ kg (F1'A), corresponding to a variation in single score results of +5% and -9% compared to the BSL price (Figure 2).

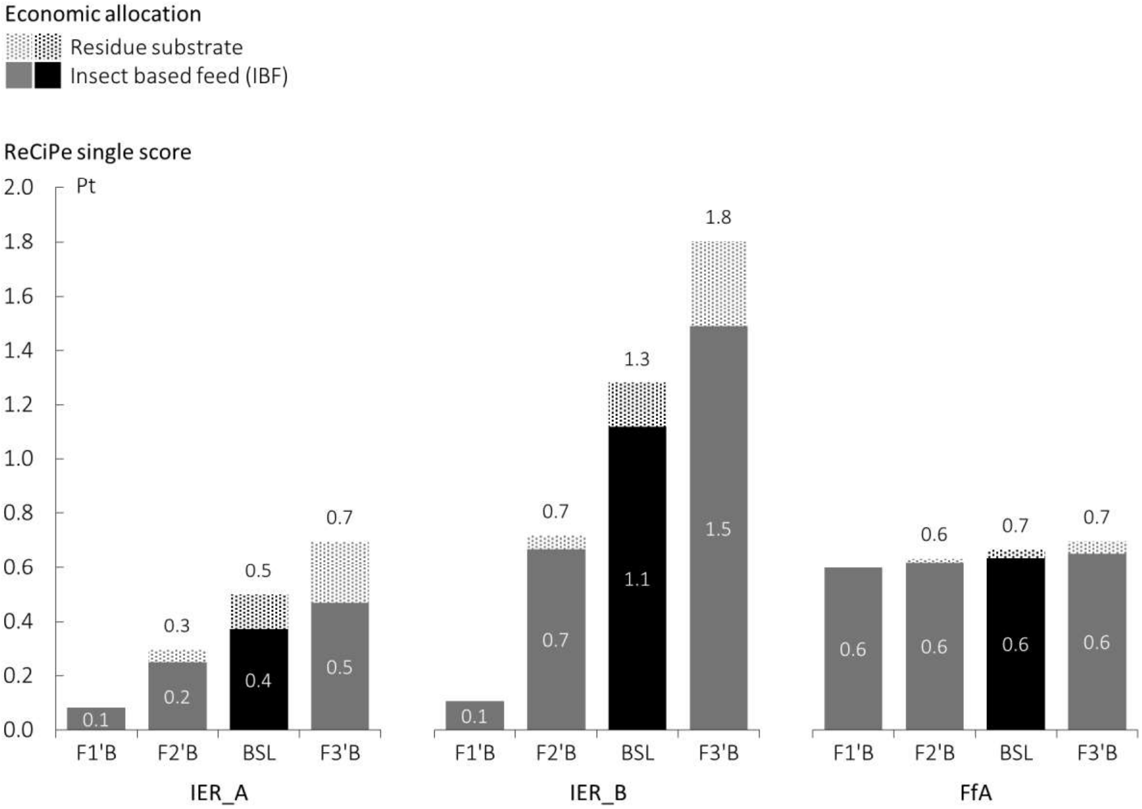

Figure 3. Economic impact allocation under conditions of varying fertilizer prices applied to co-products of insect based feed (IBF) production and livestock production (Scenario B). Comparison of the allocated impacts (ReCiPe single score results) of IBFs from the IER_A, IER_B and FfA systems at a market price of organic fertilizer of (F1'B) zero economic value (i.e., chicken and sheep manure and residue substrates are considered a true waste stream); (F2'B) 7.85 EUR/ t (-50% BSL, where BSL is the baseline assuming a customary market price for organic fertilizer of 15.70 EUR/ t) and (F3'B) 23.55 EUR/ t (+50% BSL). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

The outcome of the assessment changes considerably if price variations are applied to both the impact allocation between co-products of sheep and broiler production (meat and manure) and IBF production (feed and residue substrate) (Figure 3). In contrast to Scenario A, the allocated impacts of IBFs markedly increase in response to increasing fertilizer prices (Figure 2 and 3). Underlying this relationship are changes in the allocated impacts of manures, which increase correspondingly to their share in revenues generated in the broiler and sheep producing operation (Appendix A, Table A2). Similar to the IBF systems, the extent to which impacts of manures increase is closely related to the systems' conversion efficiency, i.e., unit output of manure per kg sheep and broiler. Due to a comparatively low feed conversion efficiency of sheep, increases in the environmental load are particularly pronounced for sheep manure (Appendix A, Table A1-A2), resulting in an upsurge of the process related impacts in the IER_B system. However, as the variations in fertilizer prices affect both the impacts (i.e., revenues) of manures (sheep and chicken) and residue substrates (IBF), the way impacts of IBF respond is also a function of the system's conversion efficiency. Owing to a comparatively low conversion efficiency, the IBF product of the IER_A system shows the highest variation in impacts. An increase of fertilizer prices from 0 EUR/ t (F1'B) to 23.55 EUR/ t (F3'B) causes a variation in single score results of -78% and +26% compared to the BSL price, respectively (Figure 3). In the F3'B scenario (23.55 EUR/ t fertilizer) almost 33% (0.2 Pt) of the process-induced impacts of the IER_A system is allocated to the residue substrate (Figure 3). The impact of the IBF product from the IER_B system shows a similar variation, although the increase from F1'B to F3'B is less pronounced due to a higher conversion efficiency, i.e., less input of manure and output of residue substrate per kg IBF produced (Figure 3).

The lowest relative changes in impacts are seen in the FfA system. Since chicken manure constitutes a minor component of the substrate mixture, the increases in fertilizer prices are of little relevance to the system's overall single score results. Adding to this is the comparatively low output of residue substrate (Table 1), which contracts associated revenues and lessens variations in the impacts in response to changing fertilizer prices. An increase of fertilizer prices from 0 EUR/ t (F1) to 23.55 EUR/ t causes a variation in single score results of -6% and +2% compared to the BSL price, respectively (Figure 3).

3.3. Comparison of IBF and conventional protein feeds

To analyse environmental advantages of current IBF production designs, allocated impacts (FU_B) are compared with Peruvian fishmeal, cottonseed meal and soybean meal as summarized in Figure 4.

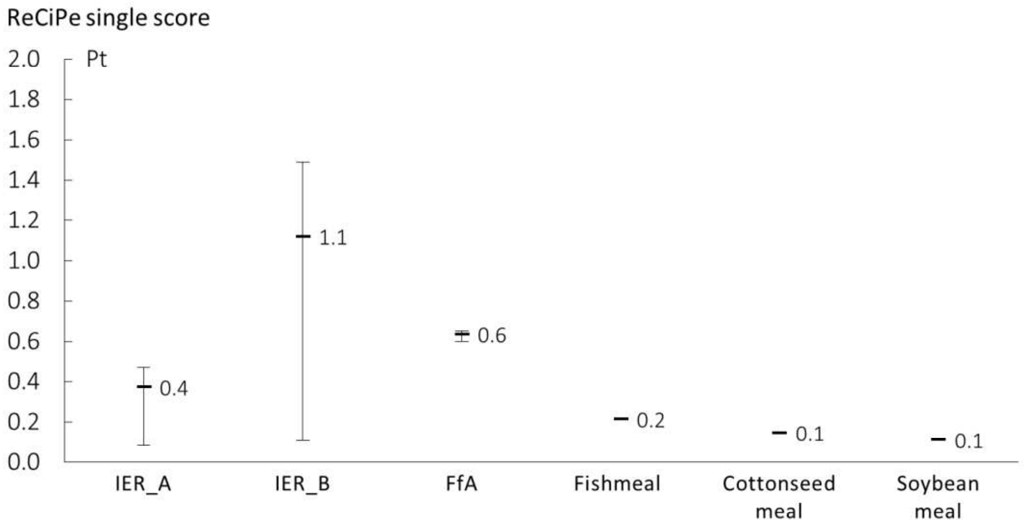

Figure 4. Environmental performance of insect based feeds (IBFs) and conventional feeds. Comparison of the impacts (ReCiPe single score results) of IBFs from the IER_A, IER_B and FfA system with those of conventional feeds. ReCiPe single scores results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per 1kg dried feed (≤ 10% water). Impact allocation between IBF and residue substrate calculated accordingly to their share in revenues (economic allocation). All data presented are subject to rounding. Error bars represent the range of impacts according to the findings of the sensitivity analysis (section 3.2).

The comparison of IBF products and conventional feeds by ReCiPe single scores yields ambiguous results. At the baseline price, i.e., economic impact allocation at customary fertilizer price of 15.70 EUR/ t, the impacts of IBFs compare unfavourably with conventional feeds. Ranging between 0.1 Pt (soybean meal) and 0.2 Pt (fishmeal) per kg feed, the impacts of conventional feeds are considerably lower than the one of the lowest IBF product, i.e., IER_A system (0.4 Pt/ kg IBF). However, conclusions shift under the assumption of low fertilizer prices (i.e., represented by the error bars in Figure 4). When manures and residue substrates are considered true waste streams (i.e., zero economic value), the impact of IBFs from the IER systems drop to 0.1 Pt/ IBF, which is comparable to cottonseed meal and soybean meal (both 0.1 Pt/ kg feed) and compares favourably to the impacts of fishmeal (0.2 Pt/ kg feed). The impact of IBFs from the IER_A system remains comparable to fishmeal up to a fertilizer price of 7.85 EUR/ t (0.2 Pt/ kg IBF) (Figure 4).

4. DISCUSSION

To facilitate understanding, the results are discussed in schematic order, starting with the environmental impacts of the IBF systems and thereafter addressing findings of the sensitivity analyses and benchmarking of IBF against conventional feeds.

4.1. Life cycle impact assessment (LCIA)

The LCIA analysis unveiled marked differences between the IBF models. A comprehensive impact contribution analysis demonstrated that differences are mainly explained by systems' conversion efficiencies and the specific environmental loads of rearing substrates. Roffeis et al. (2017) established that conversion efficiencies are largely determined by the biophysical properties of rearing substrates (i.e., energy density, protein and fibre content), providing efficiency advantages to the FfA and IER_B system using mixtures of more than one rearing substrate. The environmental loads of rearing substrates, on the other hand, are the result of economic allocation and thereby a function of market demand/price and the environmental impact of the substrate producing systems (see section 2.1.1). What attracts attention, however, is that the economies of high conversion efficiencies are seemingly offset by the environmental burden of higher quality substrates used to improve the conversion efficiency of the systems (Roffeis et al., 2017). This somewhat inverse relationship between conversion efficiency and environmental impact is best illustrated by the IER systems. The use of chicken manure as a sole rearing substrate constrains the conversion efficiency of the IER_A system, showing effect in a high unit input of rearing substrate and surplus of co-produced quantities of residue substrates. The main reasons for this are a lower nutritional quality of the chicken manure (low calorific value and protein content) and the fact that chicken manure was sourced as a dried product (i.e., not fresh), which negatively affects its suitability as rearing substrate (Kenis et al., 2018b; Oonincx et al., 2015; Roffeis et al., 2017). However, as the environmental load of chicken manure (1.0×10^{-2} Pt/ kg) is considerably lower than sheep manure (5.2×10^{-2} Pt/ kg), impacts related to rearing substrates are lowest in the IER_A system (Appendix E). Here, the differences in the environmental loads of chicken and sheep manure are causal to the impact of sheep and broiler production. The production of broilers is of lower environmental impact and associated with smaller quantities of co-produced manures (Appendix A, Table A1). Given that impacts of the livestock producing systems were also economically allocated, the impact of the chicken manure is considerably lower than sheep manure (Appendix A, Table A1). The ruminant blood (IER_B system) is of little relevance to the revenues of the slaughtering process and therefore of low environmental load (5.5×10^{-4} Pt/ kg) and insignificant contribution to the overall impact of the system (Appendix E).

The continuity between substrate utility value and environmental impact is also apparent in the FfA system. The brewery waste used is rich in valuable proteins, dietary fibre and calories, which enhances the system's conversion efficiency (Kenis et al., 2018b; Lynch et al., 2016). However, its nutritional properties also make brewery waste a popular feedstuff for ruminant and monogastric livestock and, depending on regional demand, an important source of income for brewery operations that trade the co-produced residue as feed. The utility value is reflected in the environmental load of the brewery waste (4.2×10^{-2} Pt/ kg), which accounts for 82% of the substrate related impacts in the FfA system (Table 2 and Appendix E).

While the use of substrate combinations appears to benefit the system's conversion efficiency, it also imposes additional sourcing (i.e., transportation) efforts. Proximity to markets and the interlinkage with local value chains greatly affects the environmental and socioeconomic performance of an insect production system. Impacts related to the transport of ruminant blood (IER_B system), sourced from a slaughterhouse at 10 km proximity using a commercial vehicle (3.5 t), accounts for 3% of single score results in the IER_B system. In the FfA system, the sourcing of brewery waste by truck (7.5 t) from a brewery in 20 km proximity make up almost 4% of the process-induced impact. Although proximity to substrate providing facilities is performance-critical, the environmental efficiency of transportation also depends on the water content of the rearing substrates. This not only shapes the frontiers of environmentally sound sourcing strategies, it also explains the environmental advantages of a direct integration of insect production systems into substrate providing operations, as seen in the case of the IER_A system.

Other factors influencing the systems conversion efficiency and environmental performance are larval development time and inoculation practices, i.e., the method by which eggs or larvae are added to the rearing substrates (Roffeis et al., 2017). The larvae of *H. illucens* have a longer larval development phase and reach a higher individual mass than *M. domestica* (Kenis et al., 2018a, 2014). This enables a more effective penetration and mixing of the rearing substrates and a greater degree of feeding resulting in a more efficient substrate conversion in the FfA system (Roffeis et al., 2017). In addition there are operational advantages of artificial inoculation versus natural oviposition which include the ability to adjust stocking densities according to substrate quality and quantity to achieve consistent production outputs; this improves the efficiency and manageability of process flows in the FfA system (Kenis et al., 2014; Roffeis et al., 2017). However, artificial substrate inoculation has environmental disadvantages as the maintenance of two interlinked production units (i.e., egg- and larvae production unit) increases the relative inputs of production infrastructure (i.e., built infrastructure and manufacturing equipment) and intermediate production factors, such as consumables and supplies, space and water (Roffeis et al., 2017). In the FfA system the impacts related to the use of production infrastructure and consumables and supplies amount to 1.3×10^{-1} Pt/ kg (22% of the process impacts), which is ca. 2.7 and 3.7 times higher than related impacts in the IER_A and IER_B system, respectively (Table 2 and Annex C, Table C3 – C6). The slight differences between the IER_A and IER_B systems basically align to the findings of the LCI analysis (Roffeis et al., 2017), showing that a decrease in conversion efficiency is directly mirrored by an increase in the occupation of built infrastructure (Table 2 and Annex C, Table C3 – C6).

The trade-off relationship between conversion efficiency and environmental performance is more pronounced when systems are compared by allocated impacts of the IBF product. The lower conversion efficiency of the IER_A system reciprocates in a higher output of residue substrate, which in turn increases the revenues from residue substrate and decreases the share of impacts being allocated to the IBF product. The FfA system, showing the highest conversion efficiency, profits the least from the trade of residue substrates, as larger shares of process induced impacts (about 96%) are allocated to the IBF product (section 3.1).

4.2. Sensitivity analysis

The sensitivity analysis showed a strong deviation of the impacts of IBFs in response to variations in fertilizer prices (i.e., manure and residue substrate) underlying the economic impact allocation between co-products of livestock production (i.e., IBF production and sheep and broiler production). Under the assumption that fertilizer prices only affect the revenues of IBF production (i.e., share of revenues from residue substrates), an increase in fertilizer prices caused a reduction of impacts economically allocated to the systems' IBF products in function of the systems' conversion efficiency, i.e., unit output of residue substrate per kg IBF (Figure 2). However, as market changes apply to all links in a local value chain, variations in fertilizer prices also affect the environmental loads coming along with the input of manures (section 3.2). Taking this rationale into account changed the outcome of the assessment results. The increase of fertilizer prices caused a substantial increase in the environmental loads of manures economically allocated from the sheep and broiler producing systems (Appendix A, Table A2). In cases where the inputs of manures surpass the quantities of co-produced residue substrates (IER systems), allocated impacts of IBFs exhibited a marked increase in response to increasing fertilizer prices (Figure 3).

However, as the tested allocation scenarios affected both the impact of manures and the share of impacts being allocated to the residue substrates, the extent to which impacts of IBF deviated was also closely related to the system's conversion efficiencies. Due to lower conversion efficiencies, the impacts of the IER_A and IER_B system responded most sensitively towards variations in fertilizer prices. The increase of fertilizer prices was followed by a marked increase in process impacts and, to a lesser extent, allocated impacts of the IBF products. In both systems, the allocated impacts of IBF products were lowest when organic fertilizers are considered true waste stream, i.e., zero economic value. This nullified the environmental burden of manures (input flows) and the share of impacts allocated to residue substrates (output flows), which, when totalled, reduces the impacts of IBFs from the IER systems to a single point score of 0.1 Pt/ kg IBF (allocated with 100% of the process-induced impacts). The FfA system responded less sensitively to changes in fertilizer prices, as substrate related impacts are mainly due to inputs of brewery waste (i.e., about 82% of substrate-related impacts). As chicken manure is a minor component in the substrate mixture of the FfA system (Table 1), the increase in process impacts was offset by an increasing share of impacts being allocated to the residue substrates, causing a slight reduction in the allocated impacts of the IBF in response to increasing fertilizer prices (Figure 3).

While the findings of the sensitivity analysis highlight the ambiguity of the LCIA results, they also demonstrate the influence of socioeconomic conditions on the environmental performance of the IBF systems. The environmental loads of substrates are calculated as a function of their utility values at a given time and within a specific geographical context. Here the utilization of true waste streams, i.e., products or mass flows of no economic value and environmental load, has proven most favourable. However, the idea of valorising true waste streams (zero economic value) poses a contradiction in itself, as the economic value of yet unused material flow would necessarily increase if IBF production offers an opportunity for their commercial exploitation. In other words, true waste streams are likely to vanish if technological progress enables their reuse within a circular economy (Geissdoerfer et al., 2017). The environmental impacts of possible rearing substrates are further subject to present production and consumption patterns, which can vary immensely between geographical contexts and in time. Taking West Africa as an example, it seems likely that the economic value (and thereby environmental loads) of organic residues will rise in the near future alongside all products in agricultural value chains in response to projected increases in food demand and decreases in soil fertility (Hollinger and Staatz, 2015; Palazzo et al., 2016). Against this background, any recommendations on suitable rearing substrates require caution. Instead, prospective insect farmers should develop individual implementation strategies based upon careful consideration of local production and consumption patterns placing particular importance on substrate availability. This is especially important, as the implementation of IBF production would raise regional demand (i.e., utility value) for the substrate of choice.

4.3. Comparison of IBF and conventional protein feeds

The comparison with conventional feeds points to environmental disadvantages of current IBF production systems, especially in relation to plant based feeds. The differences between IBF and plant based feeds are best explained by the contrasting mechanisms of nutrition in insects and plants. Soy and cotton are photoautotroph and thus at the first level of the trophic pyramid (i.e., primary production). Given that approximately 10% of the original energy of the sun is passed from one to another level, the production of proteins and calories through plants is generally more resource-efficient. In contrast, insects and anchoveta used for the production of fishmeal are chemoheterotroph organisms (decomposer and consumer), which ingest or absorb organic carbon to grow and maintain their life. As decomposers (or consumers), they only utilize a fraction of the original energy, land, water and resources used to build the organic material they are feeding on. Whilst this line of argumentation is often put forward in support of vegetarianism, it also holds true for feeds, as is exemplified by the notable differences between plant- and animal based feeds (i.e., IBF and fishmeal).

Ecologic causalities also provide an indirect explanation for the differences between IBF and fishmeal. The impacts of using wild-caught anchoveta for the production of fishmeal are considerably lower than the impact contribution of rearing substrates in the production of IBF. What appears counterintuitive, is largely rooted in methodological peculiarities. Although the ReCiPe method accounts for relevant abiotic stress factors, such as climate change or acidification processes, it does not capture impacts relating to the use of biotic resources, such as damages on marine ecosystems caused by an overuse of small pelagic fishes for fishmeal production (Avadí and Fréon, 2013; Burgess et al., 2013; Goedkoop et al., 2008; Saarikoski et al., n.d.; Sanchirico et al., 2008). The serviceability of biotic resources, such as wild fish, relies on complex interactions between biotic and abiotic entities and the quantification of their formation and renewal rates remains one of the major challenges in ecology (Edwards and Abivardi, 1998; Salles, 2011). As the LCA community lacks consensus on how to address these constraints (Avadí and Fréon, 2013; Langlois et al., 2014; Woods et al., 2016), the utilization of naturally grown resources, such as anchoveta or naturally occurring flies, are considered as an ecosystem service that comes free of any environmental charge (Avadí and Fréon, 2013; Goedkoop et al., 2008; Sanchirico et al., 2008). As a matter of cause, substrate related impacts in the fishmeal system are reduced to the environmental impacts associated with the fishing activities (Fréon et al., 2017) providing disproportionate advantages over the IBFs systems, which, in contrast, use energy, materials, land, technological equipment and labour to grow biomass themselves (insect larvae). In other words, what is the marine food web for the fishmeal system, is the rearing process in IBF production. Advantages of using ecosystem services also come to the fore when comparing the environmental performances of the FfA and IER systems. Though not necessarily attributable to methodological shortfalls in the ReCiPe method, the use of natural oviposition, i.e., an ecosystem service free of environmental charge, clearly benefits the environmental performance of the IER systems. The FfA system, in contrast, maintained separate adult colonies to facilitate substrate inoculation artificially, which increases the unit input of production infrastructure causing sizeable disadvantages to the environmental performance of the FfA system (see section 3.1.).

Other factors compromising the environmental performance of IBFs are the comparatively low scale of production and the technical immaturity of current system designs. As a highly automated and industrial production process, the fishmeal system benefits greatly from economies of scale. The maximized capacity utilization of large-scale processing infrastructure and means of transportation causes a relative depreciation in respective unit inputs, which directly translates into a favourable environmental and economic performance (Fréon et al., 2017). The IBF systems, on the other, represent novel production designs that are not yet properly geared towards the competitive constraints in a globalized economy. One consequence of this absence of rationalization force is that manufacturing equipment and built infrastructure are not used to their full capacity (low economies of scale), resulting in a generally high impact contribution of production infrastructure, consumables and supplies. However, the extent to which this finding can be generalized requires further investigation. The influence of economies of scale on the systems' environmental performance should be of particular ongoing interest given that upscaling is one of the key measures taken in the commercial optimisation of novel product systems.

However, as is the case with any LCA study, readers need to consider the presented results within the context of limitations. Most importantly with respect to the comparative assessment, readers should be aware that the impacts of conventional feeds correspond to generic product systems, which do not include, for instance in the case of imported Peruvian fishmeal, impacts related to transportation from a port of discharge to a generic market in West Africa. Whilst the relative contribution of impacts associated with the transport by transoceanic tankers or large-scaled transport lorries is generally small when calculated per unit product transported (economies of scale), this general rule might not be applicable to the West African context. The interplay of timeworn transport vehicles and a poorly maintained road infrastructure, makes transportation in West Africa particularly resource- and time consuming (Teravaninthorn, 2009). As a consequence, Peruvian fishmeal at a generic market in West Africa could be of much higher impact than the one considered in the comparative assessment. Further, it ought to be noted that a comparison of the environmental performances of feeds by mass output does not take into account the differences in the nutritional performance of feed products. Given the differences in amino acid patterns, fatty acids and calories and fibres of the compared feedstuffs, it is likely that the comparative assessment would yield different outcomes when system's performances are compared based on more appropriate measures, such as livestock-specific ileal digestibility (protein turnover per protein intake) of compared feedstuffs.

5. CONCLUSIONS

This study demonstrates that the impact of IBF production is largely determined by the environmental impact of rearing substrates in the geographical context of tropical West Africa. To ensure environmental soundness, prospective insect farmers should opt for the utilization of substrates that are available in sufficient volume and, in an optimal case, not yet harnessed in other value chains, as any market competition in use is paralleled with an increase in environmental load. In this context, the use of waste streams, i.e., products of low economic value, has proven most favourable. A direct integration of insect production systems into substrate providing operations offers further improvements, as it helps to reduce impacts related to the transportation of substrates.

The LCIA results also suggest that in Western Africa the use of natural oviposition is environmentally preferable to artificial inoculation. Though artificial inoculation has the edge over natural oviposition in terms of conversion efficiency and process planning, the interplay between egg and larvae production involved a sequence of complex operation steps, causing a high itemization and surpluses in impacts related to the use of production infrastructure and consumables and supplies. This provided advantages for the simplistic setups used in the production of *M. domestica* under conditions of natural oviposition. The production in a closed system (i.e., artificial inoculation), on the other hand, shows greater potential for improvement through economies of scale, as the additional input of production infrastructure and consumables and supplies are to a greater extent output-independent. However, to better leverage economies of scale effects, system designs should implement measures of automation and more specialised rearing equipment (e.g., improvement of harvesting techniques).

A comparison with conventional feeds yielded ambiguous results. Although results vary under conditions of low fertilizer prices, the comparative assessment with conventional feeds at a generic market in West Africa points towards environmental disadvantages of current IBF production designs, especially in reference to plant based feeds. Disparities between IBF and conventional feeds were mainly attributable to economies of scale and trophic differences. Provided larvae are reared on low-value waste streams, the impacts of IBFs from the IER_A system were comparable to fishmeal. The results of the comparative assessment also point to methodological limitation of the ReCiPe characterisation method, which does not account for the impacts related to the use of biotic resources. As a consequence, the utilization of naturally grown resources, such as wild anchoveta, was treated as an ecosystem service of no environmental charge, providing disproportionate advantages to the fishmeal system.

While the sensitivity analysis demonstrated the possibilities to influence the assessment outcomes through methodological choices, it also bears testament to the vagueness of the LCIA results. The ex-ante assessment of the IBF production models required assumptions and approximations in the foreground and background inventory data, as well as the use of proxy data to determine environmental characterization factors and applicable market dynamics. Given these multiple sources of model uncertainty, the results are inevitably afflicted with uncertainty. Therefore, the derived findings and recommendations must be interpreted and communicated with due care. Furthermore, results are highly site-specific and do not allow to general conclusions on IBF production to be drawn.

Nevertheless, this study illustrates how an ex-ante LCA assessment facilitates valuable feedback to guide development activities and design processes towards environmental sound production patterns. This study shall further serve as a reference point for scientific discussions and as an inspiration for future research in the domain of eco-design and life cycle management.

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APPENDIX A

Table A1. Biophysical and economic characteristics of co-products from sheep and broiler production. Comparison of sheep and broiler production by co-products’ mass, dry matter content (DM) and revenues (converted to a value in Euros (EUR)). All data presented are subject to rounding.

Livestock systems	Mass output	DM content	Revenue (BSL) [a]	Data sources
Functional outflows	kg	%	EUR	
Broiler production				
Broiler at slaughterhouse	2.0	31	5.79	[1-2]
Chicken manure	17.5	90	0.27	[1, 3]
Sheep production				
Sheep at slaughterhouse	18.3	27	69.55	[1, 4]
Sheep manure	367.3	75	5.77	[1, 3, 5]

[a] Revenues of co-products according to baseline scenario (BSL), i.e., customary market prices as surveyed in West Africa in the third and fourth quarters of 2015 (see supplementary material S1). Data sources: [1] - (Roffeis et al., 2017); [2] - (Shen et al., 2015); [3] (da Silva et al., 2017), [4] - (Paladines et al., 1964), [5] - (Fasae et al., 2009).

Table A2. Economic relationship (revenues) of co-products from sheep and broiler production. Calculation of impact allocation factors based on co-product’s shares in revenues corresponding to fertilizer prices of (BSL) 15.70 EUR/ t, i.e., customary market prices applied in baseline scenario; (F1) zero economic value (i.e. considered a true waste stream); (F2) 7.85 EUR/ t; and (F3) 23.55 EUR/ t. All data presented are subject to rounding.

Livestock systems	BSL [a]		F1’B		F2’B		F3’B		Data sources
Functional outflows	EUR	(%)	EUR	(%)	EUR	(%)	EUR	(%)	
Broiler production									
Broiler at slaughterhouse	5.79	(95)	5.79	(100)	5.79	(98)	5.79	(93)	[1], SD [b]
Chicken manure	0.27	(5)	0.00	(0)	0.14	(2)	0.41	(7)	[1], SD [b], AS [c]
Sheep production									
Sheep at slaughterhouse	69.55	(92)	69.55	(100)	69.55	(96)	69.55	(89)	[1], SD [b]
Sheep manure	5.77	(8)	0.00	(0)	2.88	(4)	8.65	(11)	[1], SD [b], AS [c]

[a] Economic allocation factors of baseline scenario (BSL) also applies to scenario F1’A – F3’A, i.e., variable fertilizer prices are assumed to affect revenues of residue substrates from IBF production only. [b] Surveyed data: market information and prices gathered upon surveys on-site in the third and fourth quarters of 2015 (see supplementary material S1). [c] Assumptions concerning the variation of fertilizer prices, i.e. revenues of manures. Data sources: [1] - (Roffeis et al., 2017).

Table A3. Biophysical and economic characteristics of co-products from IBF production. Comparison of the IER_A, IER_B and FfA system by co-products’ mass, dry matter content (DM) and revenues (converted to a value in Euros (EUR)). All data presented are subject to rounding.

Livestock systems	Mass output	DM content	Revenue (BSL) [a]	Data sources
Functional outflows	kg	%	EUR	
IER_A				
IBF	1.0	90	1.28	[1], BeP [b]
Co-product	28.0	90	0.44	[1], SD [c]
IER_B				
IBF	1.0	90	1.74	[1], BeP [b]
Co-product	16.0	90	0.25	[1], SD [c]
FfA				
IBF	1.0	90	2.37	[1], BeP [b]
Co-product	7.1	90	0.11	[1], SD [c]

[a] Revenues of co-products according to baseline scenario (BSL). [b] Breakeven price (i.e., cost price) of IBF, calculated as production costs less the hypothetical revenues from residue substrates sold at a customary market price of organic fertilizer. [c] Surveyed data: market information and prices gathered upon surveys on-site in the third and fourth quarters

of 2015 (see supplementary material S1). Data sources: Data sources: [1] - (Roffeis et al., 2017); [2] - (Shen et al., 2015); [3] (da Silva et al., 2017), [4] - (Paladines et al., 1964), [5] - (Fasae et al., 2009).

Table A4. Economic relationship of co-products from insect based feed (IBF) production under consideration of variable fertilizer prices effecting revenues of co-produced residue substrates only (Senario A). Calculation of impact allocation factors based on co-product's shares in revenues (calculated as breakeven prices) corresponding to fertilizer prices of (BSL) 15.70 EUR/ t, i.e., customary market prices applied in baseline scenario; (F1) zero economic value (i.e. considered a true waste stream); (F2) 7.85 EUR/ t; and (F3) 23.55 EUR/ t. All data presented are subject to rounding.

Livestock systems	**BSL**		**F1'A**		**F2'A**		**F3'A**		**Data sources**
Functional outflows	EUR	(%)	EUR	(%)	EUR	(%)	EUR	(%)	
IER_A									
IBF	1.28	(74)	1.09	(100)	1.18	(84)	1.37	(67)	[1], BeP[a]
Co-product	0.44	(26)	0.00	(0)	0.22	(16)	0.66	(33)	[1], SD[b], AS[c]
IER_B									
IBF	1.74	(87)	1.63	(100)	1.68	(93)	1.79	(83)	[1], BeP[a]
Co-product	0.25	(13)	0.00	(0)	0.13	(7)	0.38	(17)	[1], SD[b], AS[c]
FfA									
IBF	2.37	(96)	2.38	(100)	2.37	(98)	2.36	(93)	[1], BeP[a]
Co-product	0.11	(4)	0.00	(0)	0.06	(2)	0.17	(7)	[1], SD[b], AS[c]

[a] Breakeven price (i.e., cost price) of IBF, calculated as production costs less the hypothetical revenues from residue substrates. [b] Surveyed data: market information and prices gathered upon surveys on-site in the third and fourth quarters of 2015 (see supplementary material S1). [c] Assumptions concerning the variation of fertilizer prices (residue substrates). Data sources: [1] - (Roffeis et al., 2017)

Table A5. Economic relationship (revenues) of co-products from insect based feed (IBF) production under consideration of variable fertilizer prices effecting both cost of manures and revenues of co-produced residue substrates (Scenario B). Calculation of impact allocation factors based on co-product's shares in revenues (calculated as breakeven prices) corresponding to fertilizer prices of (BSL) 15.70 EUR/ t, i.e., customary market prices applied in baseline scenario; (F1) zero economic value (i.e. considered a true waste stream); (F2) 7.85 EUR/ t; and (F3) 23.55 EUR/ t. All data presented are subject to rounding.

Livestock systems	**BSL**		**F1'B**		**F2'B**		**F3'B**		**Data sources**
Functional outflows	EUR	(%)	EUR	(%)	EUR	(%)	EUR	(%)	
IER_A									
IBF	1.28	(74)	1.09	(100)	1.18	(84)	1.37	(67)	[1], BeP[a]
Co-product	0.44	(26)	0.00	(0)	0.22	(16)	0.66	(33)	[1], SD[b], AS[c]
IER_B									
IBF	1.74	(87)	1.63	(100)	1.68	(93)	1.79	(83)	[1], BeP[a]
Co-product	0.25	(13)	0.00	(0)	0.13	(7)	0.38	(17)	[1], SD[b], AS[c]
FfA									
IBF	2.37	(96)	2.38	(100)	2.37	(98)	2.36	(93)	[1], BeP[a]
Co-product	0.11	(4)	0.00	(0)	0.06	(2)	0.17	(7)	[1], SD[b], AS[c]

[a] Breakeven price (i.e., cost price) of IBF, calculated as production costs less the hypothetical revenues from residue substrates. [b] Surveyed data: market information and prices gathered upon surveys on-site in the third and fourth quarters of 2015 (see supplementary material S1). [c] Assumptions concerning the variation of fertilizer prices (residue substrates). Data sources: [1] - (Roffeis et al., 2017)

APPENDIX B

Correspondingly to the sensitivity analysis on economic impact allocation, an impact allocation on the basis of physical relationship is conducted for two scenarios; allocating impacts between co-products of IBF production only (scenario A), and impact allocation applied to both co-products of sheep and chicken production and IBF production (scenario B). The results of the analysis are summarized in Figure B1 (scenario A) and B2 (scenario B). The physical relationships between co-products underlying the calculation of allocation factors are presented in Table B1 and B2.

Table B3. Biophysical relationship of co-products from sheep and broiler production. Calculation of impact allocation factors based on co-products' mass fractions and share in energy output. All data presented are subject to rounding.

Livestock systems	**DM content ^{a}**	**Energy ^{b}**	**Mass output**		**Energy output**		**Data sources**
Functional outflows	%	MJ*kg^{-1}	kg	(%)	MJ	(%)	
Broiler production							
Broiler at slaughterhouse	31	21.6	2.0	(10)	43.1	(17)	[1-2]
Chicken manure	90	11.9	17.5	(90)	208.5	(83)	[1, 3]
Sheep production							
Sheep at slaughterhouse	27	23.9	18.3	(5)	435.5	(9)	[1, 4]
Sheep manure	75	11.4	367.3	(95)	4189.7	(91)	[1, 3, 5]

^{a} Dry matter (DM) content of co-products as sourced. ^{b} Energy content of co-products expressed in MJ per kg fresh matter (i.e. DM content as sourced). Data sources: [1] - (Roffeis et al., 2017); [2] - (Shen et al., 2015); [3] (da Silva et al., 2017), [4] - (PALADINES et al., 1964), [5] - (Fasae et al., 2009).

Table B2. Biophysical relationship of co-products from insect based feeds (IBF) production. Calculation of impact allocation factors based on co-products' mass fractions and share in energy output. All data presented are subject to rounding.

IBF systems	**DM content ^{a}**	**Energy ^{b}**	**Mass output**		**Energy output**		**Data sources**
Functional outflows	%	MJ*kg^{-1}	kg	(%)	MJ	(%)	
IER_A							
IBF	90	22.9	1.0	(3)	22.9	(25)	[1-2]
Co-product	90	2.4	28.0	(97)	67.3	(75)	[1, 3]
IER_B							
IBF	90	22.9	1.0	(6)	22.9	(37)	[1-2]
Co-product	90	2.4	16.0	(94)	38.4	(63)	[1, 3]
FfA							
IBF	90	24.1	1.0	(12)	24.1	(59)	[1, 4]
Co-product	90	2.4	7.1	(88)	16.9	(41)	[1, 3]

^{a} Dry matter (DM) content of co-products at plant gate. ^{b} Energy content of co-products expressed in MJ per kg fresh matter (i.e. DM content at plant gate). Data sources: [1] - (Roffeis et al., 2017); [2] - (Heuzé and Tran, 2015); [3] - (Teotia and Miller, 1974); [4] - (Tran et al., 2015).

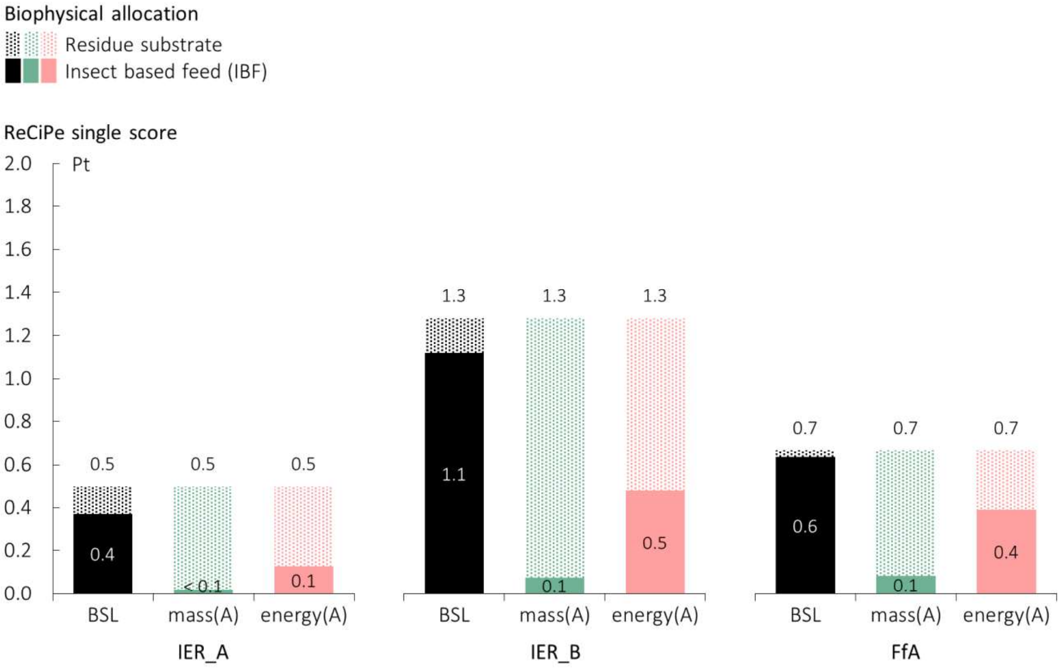

Figure B1. Impact allocation on the basis of biophysical relationships between functional outflows applied to co-products of insect based feeds (IBFs) production only (scenario A). Partitioning of the process related impacts (ReCiPe single score) of the IER_A, IER_B and FfA system by economic allocation (black bars (BSL), i.e. baseline), mass allocation (green bars) and impact allocation by energy content (red bars). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

Allocating impacts between functional outflows by mass fractions or relative energy content changes the outcome of the comparative assessment considerably (Figure B1). When biophysical impact allocation is applied to co-products of IBF production only (scenario A), the impacts allocated to IBF are considerably reduced. Owing to the high mass fraction of co-produced residue substrates (Table B2), the highest reductions are seen for an impact allocation by mass fractions (Figure B1). Here, allocated impacts of IBF range between <0.1 Points/ kg IBF (IER_A system) and 0.1 Points/ kg IBF (IER_B and FfA system). The share of impacts allocated to IBF increase when impacts are allocated based on the relative energy contents of co-products. The IBF from the IER_A system shows with 0.1 Points/ kg the lowest impact. The IBF from the FfA and IER_B system rank second and third, carrying 37% (0.4 Points / kg IBF) and 59% (0.5 Points/ kg IBF) of the process induced impacts, respectively (Table B2 and Figure B1).

The outcome of the comparative assessment changes yet again when biophysical impact allocation is applied to both livestock production (sheep and broiler production) and IBF production (scenario B). As can be gathered from Table B1, an allocation of impacts by mass fractions or relative energy content causes an upsurge in impacts allocated to the manures, which in turn increases the overall impacts of systems by a multiple (Table B2 and Figure B2). Similar to scenario A, an allocation by mass fractions results in a relative reduction of impacts allocated to the IBF products. Here, the IBF from the FfA system is calculated with lowest impact of

0.2 Points/ kg IBF, followed by the IER_A and IER_B system with 0.3 Points and 0.9 Points per kg IBF, respectively (Table B2 and Figure B2). The allocation of impacts by co-products' relative energy contents, on the other hand,

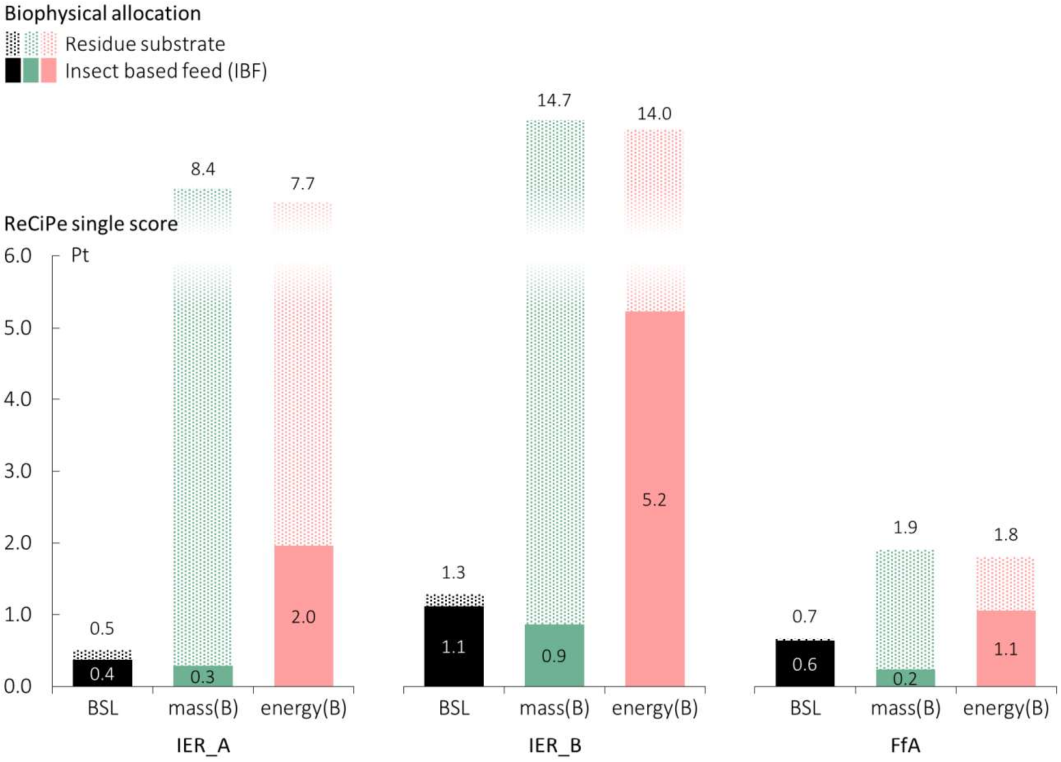

Figure B2. Impact allocation on the basis of biophysical relationships between functional outflows applied to both livestock production (sheep and broiler production) and insect based feed (IBF) production (scenario B). Partitioning of the process related impacts (ReCiPe single score) of the IER_A, IER_B and FfA system by economic allocation (black bars (BSL), i.e. baseline), mass allocation (green bars) and impact allocation by energy content (red bars). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

The allocation of impacts by co-products' relative energy contents, causes a relative incr5ease in the impacts allocated to the IBF products. As was the case for mass allocation, an impact allocation by energy content increases the environmental loads of manures and thus overall single score results of the IBF systems. However, given that the calorific values of co-produced residue substrates are low, the impact allocation between IBF and residue substrate is more even. Depending on the system's conversion efficiency, IBF products are allocated with 25% (IER_A system) to 59% (FfA system) of the process impacts, causing a substantial increase in the single scores of IBFs as compared to the BSL (Table B2 and Figure B2).

However, the principles underlying the differences in performances of the IBF systems cast doubt on the appropriateness of an impact allocation based on biophysical relationships. Given that manures and residue substrates are allocated with the largest proportion of the process induced impacts, it is questionable whether co-products mass fractions and relative energy contents are fitting measures for the causative factors in livestock production (i.e. meat and IBF).

APPENDIX C

Table C4. Production equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the IER_A production model as presented in Roffeis et al. (2017). Inventory flows associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). All Results presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Material flow**	
Inventory items		No.	days	*day^{-1}	*kg IBF^{-1}
PRIMARY FACTORS					
Wheelbarrow	p	2	2282.8	8.8×10^{-4}	2.9×10^{-4}
Colander	p	1	9131.3	1.1×10^{-4}	3.7×10^{-5}
Mechanical scale	p	1	9131.3	1.1×10^{-4}	3.7×10^{-5}
Plastic tray	p	5	365.3	1.4×10^{-2}	4.6×10^{-3}
Metal tray	p	3	1826.3	1.6×10^{-3}	5.5×10^{-4}
Small sieve	p	2	1826.3	1.1×10^{-3}	3.7×10^{-4}
Plastic bucket (20 l)	p	1	1404.8	7.1×10^{-4}	2.4×10^{-4}
Broom	p	1	1074.3	9.3×10^{-4}	3.1×10^{-4}
Shovel	p	2	1014.6	2.0×10^{-3}	6.6×10^{-4}
Dust pan	p	1	1826.3	5.5×10^{-4}	1.8×10^{-4}
Hand broom	p	1	1074.3	9.3×10^{-4}	3.1×10^{-4}
INETERMEDIATE FACTORS					
Used PP bag (2.25 m2)	p	8	365.3	2.2×10^{-2}	7.3×10^{-3}
Sponges	p	12	30.4	3.9×10^{-1}	1.3×10^{-1}
Rubber gloves	p	3	7.0	4.3×10^{-1}	1.4×10^{-1}
Disposable nitrile gloves	p	30	12.2	2.5×10^{0}	8.2×10^{-1}
General purpose cleaner	kg	-	-	1.3×10^{-2}	4.2×10^{-3}

Table C5. Production equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the IER_B production model as presented in Roffeis et al. (2017). Inventory flows associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). All Results presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Material flow**	
Inventory items		No.	days	$*day^{-1}$	$*kg\ IBF^{-1}$
PRIMARY FACTORS					
Wheelbarrow	p	2	2282.8	8.8×10^{-4}	2.9×10^{-4}
Colander	p	1	9131.3	1.1×10^{-4}	3.7×10^{-5}
Mechanical scale	p	1	9131.3	1.1×10^{-4}	3.7×10^{-5}
Plastic Barrel (40 l)	p	5	1461.0	3.4×10^{-3}	1.1×10^{-3}
Plastic tray	p	5	365.3	1.4×10^{-2}	4.6×10^{-3}
Metal tray	p	3	1826.3	1.6×10^{-3}	5.5×10^{-4}
Small sieve	p	2	1826.3	1.1×10^{-3}	3.7×10^{-4}
Plastic bucket (20 l)	p	1	1404.8	7.1×10^{-4}	2.4×10^{-4}
Broom	p	1	1074.3	9.3×10^{-4}	3.1×10^{-4}
Shovel	p	2	1014.6	2.0×10^{-3}	6.6×10^{-4}
Dust pan	p	1	1826.3	5.5×10^{-4}	1.8×10^{-4}
Hand broom	p	1	1074.3	9.3×10^{-4}	3.1×10^{-4}
INETERMEDIATE FACTORS					
Used PP bag (2.25 m2)	p	5	365.3	1.4×10^{-2}	4.6×10^{-3}
Sponges	p	12	30.4	3.9×10^{-1}	1.3×10^{-1}
Rubber gloves	p	3	7.0	4.3×10^{-1}	1.4×10^{-1}
Disposable nitrile gloves	p	30	12.2	2.5×10^{0}	8.2×10^{-1}
General purpose cleaner	kg	-	-	1.1×10^{-2}	3.5×10^{-3}

Table C6. Production equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the FfA production model as presented in Roffeis et al. (2017). Inventory flows associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). All Results presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Material flow**	
Inventory items		No.	days (d)	$*day^{-1}$	$*kg\ IBF^{-1}$
PRIMARY FACTORS					
Mechanical scale	p	1	9131.3	1.1×10^{-4}	4.6×10^{-5}
Fine scale (electronic)	p	1	3043.8	3.3×10^{-4}	1.4×10^{-4}
Wheelbarrow	p	1	4565.6	2.2×10^{-4}	9.2×10^{-5}
Trolley (rearing trays)	p	6	9131.3	6.6×10^{-4}	2.7×10^{-4}
Steel frame (adult cage)	p	2	9131.3	2.2×10^{-4}	9.2×10^{-5}
Mosquito mesh	m^2	80	269.1	3.0×10^{-1}	1.2×10^{-1}
Cotton sheet	m^2	1	365.3	2.0×10^{-3}	8.2×10^{-4}
Metal rearing tray	p	54	913.1	5.9×10^{-2}	2.5×10^{-2}
Rubber band	kg	0	91.5	2.3×10^{-3}	9.5×10^{-4}
Emergence box (pupa)	p	2	1095.8	1.8×10^{-3}	7.6×10^{-4}
Hatching vessel (larvae)	p	60	1095.8	5.5×10^{-2}	2.3×10^{-2}
Plastic bowl	p	27	3043.8	8.9×10^{-3}	3.7×10^{-3}
Plastic Barrel (40 l)	p	1	1461.0	6.8×10^{-4}	2.9×10^{-4}
Plastic bucket (20 l)	p	1	1404.8	7.1×10^{-4}	3.0×10^{-4}
Water spray bottle	p	1	122.0	8.2×10^{-3}	3.4×10^{-3}
Sieve	p	3	1826.3	1.6×10^{-3}	6.9×10^{-4}
Forceps (egg collection)	p	1	9131.3	1.1×10^{-4}	4.6×10^{-5}
Common water glass	p	8	365.3	2.2×10^{-2}	9.2×10^{-3}
Broom	p	1	1074.3	9.3×10^{-4}	3.9×10^{-4}
Shovel	p	2	1014.6	2.0×10^{-3}	8.2×10^{-4}
Dust pan	p	1	1826.3	5.5×10^{-4}	2.3×10^{-4}
Hand broom	p	1	1074.3	9.3×10^{-4}	3.9×10^{-4}
INETERMEDIATE FACTORS					
Batteries	p	8	45.7	1.8×10^{-1}	7.3×10^{-2}
Sponges	p	14	30.5	4.6×10^{-1}	1.9×10^{-1}
Rubber gloves	p	2	30.5	6.6×10^{-2}	2.7×10^{-2}
Disposable nitrile gloves	p	6	1.0	6.5×10^{0}	2.7×10^{0}
General purpose cleaner	kg	-	-	2.3×10^{-2}	9.8×10^{-3}

Table C4. Environmental characterization of the manufacturing equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the IER_A production model. Impacts (ReCiPe single score results) associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Impact**	**Data base**	
Inventory items		No.	days	[Pt]	Foreground	background
PRIMARY FACTORS						
Wheelbarrow	p	2	2282.8	4.4×10^{-4}	LCI [a]	ID [b]
Colander	p	1	9131.3	1.7×10^{-3}	"	"
Mechanical scale	p	1	9131.3	3.5×10^{-4}	"	"
Plastic tray	p	5	365.3	2.2×10^{-4}	"	"
Metal tray	p	3	1826.3	2.2×10^{-4}	"	"
Small sieve	p	2	1826.3	2.1×10^{-4}	"	"
Plastic bucket (20 l)	p	1	1404.8	2.4×10^{-5}	"	"
Broom	p	1	1074.3	2.9×10^{-5}	"	"
Shovel	p	2	1014.6	1.6×10^{-4}	"	"
Dust pan	p	1	1826.3	1.3×10^{-5}	"	"
Hand broom	p	1	1074.3	3.4×10^{-5}	"	"
INETERMEDIATE FACTORS						
Used PP bag (2.25 m2)	p	8	365.3	5.7×10^{-4}	"	"
Sponges	p	12	30.4	6.0×10^{-6}	"	"

Rubber gloves	p	3	7.0	8.3×10^{-4}	" | "
Disposable nitrile gloves	p	30	12.2	2.3×10^{-5}	" | "
General purpose cleaner	kg	-	-	2.0×10^{-3}	" | "

[a] Life cycle inventory data as published by Roffeis et al. (2017). [b] Impact data (ReCiPe single scores) extracted from the LCA database ecoinvent 3.1 using SimaPro® (Goedkoop et al., 2008; Weidema et al., 2013).

Table C5. Environmental characterization of the manufacturing equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the IER_B production model. Impacts (ReCiPe single score results) associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). ReCiPe single score results (ReCiPe V 1.11; World **|** egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Impact**	**Data base**	
Inventory items		No.	days	[Pt]	Foreground	background
PRIMARY FACTORS						
Wheelbarrow	p	2	2282.8	4.4×10^{-4}	LCI [a]	ID [b]
Colander	p	1	9131.3	1.7×10^{-3}	"	"
Mechanical scale	p	1	9131.3	3.5×10^{-4}	"	"
Plastic Barrel (40 l)	p	5	1461.0	7.8×10^{-4}	"	"
Plastic tray	p	5	365.3	2.2×10^{-4}	"	"
Metal tray	p	3	1826.3	2.2×10^{-4}	"	"
Small sieve	p	2	1826.3	2.1×10^{-4}	"	"
Plastic bucket (20 l)	p	1	1404.8	2.4×10^{-5}	"	"
Broom	p	1	1074.3	2.9×10^{-5}	"	"
Shovel	p	2	1014.6	1.6×10^{-4}	"	"
Dust pan	p	1	1826.3	1.3×10^{-5}	"	"
Hand broom	p	1	1074.3	3.4×10^{-5}	"	"
INETERMEDIATE FACTORS						
Used PP bag (2.25 m2)	p	5	365.3	3.4×10^{-4}	"	"
Sponges	p	12	30.4	6.0×10^{-6}	"	"
Rubber gloves	p	3	7.0	5.0×10^{-4}	"	"
Disposable nitrile gloves	p	30	12.2	2.3×10^{-5}	"	"
General purpose cleaner	kg	-	-	1.7×10^{-3}	"	"

[a] Life cycle inventory data as published by Roffeis et al. (2017). [b] Impact data (ReCiPe single scores) extracted from the LCA database ecoinvent 3.1 using SimaPro® (Goedkoop et al., 2008; Weidema et al., 2013).

Table C6. Environmental characterization of the manufacturing equipment (primary factors of production) and consumables & supplies (intermediate factors of production) employed in the FfA production model. Impacts (ReCiPe single score results) associated with the production of 1 kg IBF calculated for a time horizon of 50 years (18262.5 days). ReCiPe single score results (ReCiPe V 1.11; World | egalitarian perspective) are expressed in impact points (Pt) per kg IBF. All data presented are subject to rounding.

Life cycle inventory (LCI)	**Unit**	**Amount**	**Lifespan**	**Impact**	**Data base**
Inventory items		No.	days (d)	[Pt]	Foreground | background
PRIMARY FACTORS					
Mechanical scale	p	1	9131.3	4.4×10^{-4}	LCI [a] | ID [b]
Fine scale (electronic)	p	1	3043.8	4.9×10^{-4}	" | "
Wheelbarrow	p	1	4565.6	2.8×10^{-4}	" | "
Trolley (rearing trays)	p	6	9131.3	4.9×10^{-3}	" | "
Steel frame (adult cage)	p	2	9131.3	6.8×10^{-4}	" | "
Mosquito mesh	m^2	80	269.1	8.5×10^{-3}	" | "
Cotton sheet	m^2	1	365.3	4.2×10^{-4}	" | "
Metal rearing tray	p	54	913.1	2.3×10^{-2}	" | "
Rubber band	kg	0	91.5	1.9×10^{-4}	" | "
Emergence box (pupa)	p	2	1095.8	2.1×10^{-4}	" | "
Hatching vessel (larvae)	p	60	1095.8	3.6×10^{-4}	" | "
Plastic bowl	p	27	3043.8	7.1×10^{-3}	" | "
Plastic Barrel (40 l)	p	1	1461.0	2.1×10^{-5}	" | "
Plastic bucket (20 l)	p	1	1404.8	3.0×10^{-5}	" | "
Water spray bottle	p	1	122.0	3.2×10^{-4}	" | "
Sieve	p	3	1826.3	2.6×10^{-4}	" | "
Forceps (egg collection)	p	1	9131.3	1.1×10^{-5}	" | "
Common water glass	p	8	365.3	1.2×10^{-6}	" | "
Broom	p	1	1074.3	3.7×10^{-5}	" | "
Shovel	p	2	1014.6	2.0×10^{-4}	" | "
Dust pan	p	1	1826.3	1.7×10^{-5}	" | "
Hand broom	p	1	1074.3	4.3×10^{-5}	" | "
INETERMEDIATE FACTORS					
Batteries	p	8	45.7	2.6×10^{-4}	" | "
Sponges	p	14	30.5	6.7×10^{-5}	" | "
Rubber gloves	p	2	30.5	2.4×10^{-4}	" | "
Disposable nitrile gloves	p	6	1.0	2.8×10^{-3}	" | "
General purpose cleaner	kg	-	-	4.6×10^{-3}	" | "

[a] Life cycle inventory data as published by Roffeis et al. (2017). [b] Impact data (ReCiPe single scores) extracted from the LCA database ecoinvent 3.1 using SimaPro® (Goedkoop et al., 2008; Weidema et al., 2013).

APPENDIX D

The life cycle impact assessment (LCIA) of the IBF production processes (FU_A) by ReCiPe characterisation factors at mid- and endpoint level are summarized in Table D1 (Goedkoop et al., 2008). To avoid suggesting a false level of accuracy, assessment results are presented in scientific notation rounded to one decimal place.

Table D1. Environmental characterisation (ReCiPe V 1.11; World | egalitarian perspective) of insect based feed (IBF) production processes. Comparison of the IER_A, IER_B, and FfA system by life cycle impacts associated with the provision of 1 kg IBF (≤ 10% water) and co-produced quantities of residue substrate to a generic market in West Africa (FU_A), reported for ReCiPe impact categories at midpoint level (18 impact categories), and ReCiPe damage categories and ReCiPe single score at endpoint level (Goedkoop et al., 2008). All Results presented are subject to rounding.

Life Cycle Impact	**Unit**	**IBF production models**		
Characterisation factor (abbr.)		IER_A	IER_B	FfA
MIDPOINT LEVEL [a]				
Climate change (GWP).	kg CO_2 eq	4.5×10^{0}	$1.2\times10^{+1}$	5.5×10^{0}
Ozone depletion (ODP)	kg CFC-11 eq	2.0×10^{-3}	2.4×10^{-3}	3.6×10^{-3}
Terrestrial acidification (TAP)	kg SO2 eq	1.2×10^{-1}	6.9×10^{-1}	6.6×10^{-2}
Freshwater eutrophication (FEP)	kg P eq	1.7×10^{-3}	7.7×10^{-3}	1.8×10^{-3}
Marine eutrophication (MEP)	kg N eq	4.0×10^{-2}	1.2×10^{-1}	3.2×10^{-2}
Human toxicity (HTP)	kg 1.4-DB eq	3.8×10^{0}	5.8×10^{0}	6.6×10^{0}
Photochemical oxidant form. (POFP)	kg NMVOC	1.9×10^{-2}	3.9×10^{-2}	2.7×10^{-2}
Particulate matter form. (PMFP)	kg PM10 eq	2.2×10^{-2}	8.8×10^{-2}	1.7×10^{-2}
Terrestrial ecotoxicity (TETP)	kg 1.4-DB eq	3.1×10^{-2}	2.3×10^{-2}	1.0×10^{-1}
Freshwater ecotoxicity (FETP)	kg 1.4-DB eq	1.3×10^{-2}	1.4×10^{-2}	2.3×10^{-2}
Marine ecotoxicity (METP)	kg 1.4-DB eq	3.1×10^{0}	5.9×10^{0}	4.5×10^{0}
Ionising radiation (IRP)	kg U235 eq	5.1×10^{-1}	3.7×10^{-1}	5.6×10^{-1}
Agricultural land occupation (ALOP)	m2a	5.5×10^{0}	$6.1\times10^{+1}$	7.5×10^{0}
Urban land occupation (ULOP)	m2a	3.3×10^{-1}	6.5×10^{-1}	4.0×10^{-1}
Natural land transformation (NTLP)	m2	2.9×10^{-3}	7.7×10^{-3}	2.1×10^{-3}
Water depletion (WDP)	m3	9.6×10^{0}	8.5×10^{0}	$1.1\times10^{+1}$
Mineral depletion (MDP)	kg Fe eq	2.8×10^{-1}	5.0×10^{-1}	5.5×10^{-1}
Fossil depletion (FDP)	kg oil eq	9.6×10^{-1}	1.2×10^{0}	1.5×10^{0}
ENDPOINT LEVEL [b]				
Human Health (HH)	DALY	2.4×10^{-5}	6.7×10^{-5}	2.9×10^{-5}
Ecosystems (ES)	species.yr	2.4×10^{-7}	1.2×10^{-6}	3.1×10^{-7}
Resources (RS)	$	1.8×10^{-1}	2.4×10^{-1}	3.0×10^{-1}
Human Health (HH)	Points	3.0×10^{-1}	8.5×10^{-1}	3.6×10^{-1}
Ecosystems (ES)	Points	4.8×10^{-2}	2.4×10^{-1}	6.2×10^{-2}
Resources (RS)	Points	1.5×10^{-1}	2.0×10^{-1}	2.4×10^{-1}
ReCiPe single score [c]	**Points**	$\mathbf{5.0\times10^{-1}}$	$\mathbf{1.3\times10^{0}}$	$\mathbf{6.6\times10^{-1}}$

[a] ReCiPe impact categories assessed at midpoint level. [b] ReCiPe damage categories at endpoint level. [c] ReCiPe single score at endpoint level expressed in impacts points (Pt) per kg IBF and co-produced quantities of residue substrates.

The characterisation results at midpoint level show sizeable differences between the IBF system (Table D1). When compared with one another, the IER_B ranks highest in most of the 18 ReCiPe impact categories. Particular disadvantages are observable in global warming potential (GWP) terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), particular matter formation potential (PMFP), marine ecotoxicity potential (METP), as well as impacts of agricultural- and urban land occupation (ALOP and ULOP) and natural land transformation (NTLP). The FfA system ranks highest in ozone depletion potential (ODP), human toxicity potential (HTP), terrestrial- and freshwater ecotoxicity (TETP and FETP), and water-, mineral- and fossil depletion potential (WDP, MDP and FDP). Although assessed with the lowest conversion efficiency (Roffeis et al., 2017), the IER_A system compares favourable in most of the 18 midpoint categories (Table D1).

The aggregation into endpoint indicators arrives at more balanced results. By measure of damage to human health (HH), i.e. an aggregate of the results for GWP, HTP, POFP, PMFP and IRP, the the co-production of IBF and residue substrates in the IER_B system shows with 6.7×10^{-5} DALY (Disability-Adjusted Life Years) the highest damage (Table D1). The FfA and IER_A systems follow by clear margin with 2.4×10^{-5} DALY, and 2.9×10^{-5} DALY/ kg IBF, respectively (Table D1). A similar ranking is found in the estimated damage to ecosystems (ES), which is calculated in function of midpoint categories relating to terrestrial interventions (i.e. GWP, FEP, TETP, FETP, METP AOLP, ULOP and NLP). The IER_B system is assessed with highest damage to ES with 1.2×10^{-6} species·yr (loss of species during a year), followed with in sizeable distance by the FfA system with 3.1×10^{-7}, and the IER_A system with 2.4×10^{-7} species·yr/ kg IBF. The damage to resource availability (RS) aggregates the results for MDP and FDP. Correspondingly, the FfA system is calculated with the highest damage of 3.0×10^{-1} \$/ kg IBF, shortly followed by the IER_B and IER_A system with 2.4×10^{-1} \$, and 1.8×10^{-1} \$/ kg IBF, respectively (Table D1).

The aggregated ReCiPe single score results are largely explained by impacts relating to damages of HH. Performances in regarded damage category contribute with 61%, 66% and 54% to the total single score results of the IER_A, IER_B, and FfA system, respectively (Table D1). Whilst the Egalitarian perspective gives highest weight to ES damages, the system's performances in pertaining midpoint categories are of low relevance to the single score results. Impacts related to ES damages explain 10% and 19% of the ReCiPe single score in the IER_A and IER_B systems, and 9% of the single score results in the FfA system (Table D1). When compared by damages to RS, i.e. an aggregate of the system's MDP and FDP, the differences between the IBF production processes are less pronounced. Damages to RS associated with the production of 1kg IBF and co-produced quantities of residue substrate range from 1.5×10^{-1} Pt (IER_A system) to 2.4×10^{-1} Pt (FfA system) (Table D1).

APPENDIX E

Table E1. Environmental characterisation of rearing substrates used in the production of insect based feeds (IBFs). Comparison of sheep and chicken manure, brewery waste, and ruminant blood by life cycle impacts of 1 kg (dry matter content as sourced), reported for ReCiPe impact categories at midpoint level (18 impact categories), and ReCiPe damage categories and ReCiPe single score at endpoint level (Goedkoop et al., 2008). All Results presented are subject to rounding.

Life Cycle Impact	**Unit**	**Rearing substrates IBF production**			
Characterisation factor (abbr.)		Ruminant blood	Brewery waste	Chicken manure	Sheep manure
MIDPOINT LEVEL [a]					
Climate change (GWP).	kg CO_2 eq	5.0×10^{-3}	3.6×10^{-1}	4.7×10^{-1}	9.7×10^{-2}
Ozone depletion (ODP)	kg CFC-11 eq	9.1×10^{-11}	2.3×10^{-8}	8.5×10^{-9}	4.3×10^{-9}
Terrestrial acidification (TAP)	kg SO2 eq	3.2×10^{-4}	3.7×10^{-3}	3.0×10^{-2}	2.7×10^{-3}
Freshwater eutrophication (FEP)	kg P eq	3.5×10^{-6}	1.1×10^{-4}	3.3×10^{-4}	3.7×10^{-5}
Marine eutrophication (MEP)	kg N eq	5.6×10^{-5}	2.7×10^{-3}	5.3×10^{-3}	9.9×10^{-4}
Human toxicity (HTP)	kg 1.4-DB eq	2.3×10^{-3}	4.3×10^{-1}	2.1×10^{-1}	7.3×10^{-2}
Photochemical oxidant form. (POFP)	kg NMVOC	1.6×10^{-5}	1.7×10^{-3}	1.5×10^{-3}	4.1×10^{-4}
Particulate matter form. (PMFP)	kg PM10 eq	3.9×10^{-5}	9.5×10^{-4}	3.7×10^{-3}	4.4×10^{-4}
Terrestrial ecotoxicity (TETP)	kg 1.4-DB eq	1.0×10^{-5}	1.1×10^{-2}	9.4×10^{-4}	7.4×10^{-4}
Freshwater ecotoxicity (FETP)	kg 1.4-DB eq	6.6×10^{-6}	2.2×10^{-3}	6.1×10^{-4}	3.2×10^{-4}
Marine ecotoxicity (METP)	kg 1.4-DB eq	2.4×10^{-3}	3.0×10^{-1}	2.3×10^{-1}	6.2×10^{-2}
Ionising radiation (IRP)	kg U235 eq	1.5×10^{-4}	4.2×10^{-2}	1.4×10^{-2}	1.2×10^{-2}
Agricultural land occupation (ALOP)	m2a	2.8×10^{-2}	5.0×10^{-1}	2.6×10^{0}	1.2×10^{-1}
Urban land occupation (ULOP)	m2a	2.4×10^{-4}	1.3×10^{-2}	2.2×10^{-2}	3.7×10^{-3}
Natural land transformation (NTLP)	m2	3.4×10^{-6}	7.6×10^{-5}	3.1×10^{-4}	6.2×10^{-5}
Water depletion (WDP)	m3	3.5×10^{-3}	7.2×10^{-1}	3.3×10^{-1}	2.1×10^{-1}
Mineral depletion (MDP)	kg Fe eq	1.9×10^{-4}	2.5×10^{-2}	1.8×10^{-2}	4.2×10^{-3}
Fossil depletion (FDP)	kg oil eq	4.8×10^{-4}	1.0×10^{-1}	4.5×10^{-2}	2.1×10^{-2}
ENDPOINT LEVEL [b]					
Human Health (HH)	DALY	2.9×10^{-8}	1.8×10^{-6}	2.7×10^{-6}	5.1×10^{-7}
Ecosystems (ES)	species.yr	5.4×10^{-10}	2.1×10^{-8}	5.0×10^{-8}	5.1×10^{-9}
Resources (RS)	$	9.2×10^{-5}	1.9×10^{-2}	8.6×10^{-3}	3.8×10^{-3}
Human Health (HH)	Points	3.7×10^{-4}	2.3×10^{-2}	3.4×10^{-2}	6.3×10^{-3}
Ecosystems (ES)	Points	1.1×10^{-4}	4.2×10^{-3}	1.0×10^{-2}	1.0×10^{-3}
Resources (RS)	Points	7.5×10^{-5}	1.5×10^{-2}	7.0×10^{-3}	3.1×10^{-3}
ReCiPe single score [c]	**Points**	$\mathbf{5.5\times10^{-4}}$	$\mathbf{4.2\times10^{-2}}$	$\mathbf{5.2\times10^{-2}}$	$\mathbf{1.0\times10^{-2}}$

[a] ReCiPe impact categories assessed at midpoint level, egalitarian perspective (World, ReCiPe V 1.11). [b] ReCiPe damage categories at endpoint level, egalitarian perspective (World, ReCiPe V 1.11). [c] ReCiPe single score at endpoint level, egalitarian perspective (World, ReCiPe V 1.11).

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