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Eggs or meat? Environmental impact and efficiency assessment of chicken protein production with potential of *Hermetia illucens* use in feed

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ABSTRACT

This study presents a life cycle assessment (LCA) comparing laying hen to broiler chicken production. Sustainability and protein conversion efficiency are considered. The protein-to-protein conversion was calculated per 1t of feed protein consumed by birds and per 1 kg of protein in end products for human consumption. Additionally, a part of the commercial feed was replaced by live black soldier fly larvae, reared on Gainesville diet, and fruit and vegetable waste (FVW). Results of the LCA showed significant differences in integrated impacts between different production systems and different chicken feeds but not between different insect feeds. The most environmentally friendly scenario is insect (FVW) fed broiler. In protein conversion efficiency (PCE) assessment, laying hen production achieved better PCE than broiler chicken when protein quality is considered. Main influencing factors on results were feed production, composition, and protein content. Due to many assumptions made, results should be viewed critically.

1. Introduction

The food sector is facing a challenging future. According to UN DESA (2019), the world's population is expected to rise from 7.7 billion people in 2019 to 9.7 billion people in 2050. Since food supply is already a problem in low- to middle-income countries, the FAO predicts that there must be a 70% increase in food production by 2050 to ensure the food market (Dzepe et al., 2021). Especially in protein demand, which includes mostly animal protein, there will be an immense increase (Bengtsson and Seddon, 2013). However, not only the demand for animal protein, but also the sustainability associated with it poses a problem. The livestock sector alone accounts for about 14.5% of total greenhouse gas emissions. This is largely made up of cattle milk and meat (65%), pig meat (9%) and chicken meat and eggs (8%) (FAO, 2021). According to OECD-FAO (2019), chicken meat is expected to increase by 40 Mt by 2028, representing about half of the total increase in meat production within that year, which indicates that efficiency should be improved.

In poultry farming, the feed production is especially climate-intensive. Above all feed processing requirements, the feed ingredient production has the most damaging effect on the environment (Bengtsson and Seddon, 2013; González-García et al., 2014; López-Andrés et al., 2018). Due to this large impact, it should be investigated whether the feed can be produced more sustainably or whether the feed can be converted more efficiently by the poultry species. The ability to convert feed efficiently into a product depends on the poultry breed or commercial hybrid. Over the past 60 years, commercial chicken have been selected into different two hybrid lines, for meat (broiler chicken) and for egg (laying hens) production (Hoy, 2009). Due to the different metabolic processes, laying hen and broiler chicken have a different efficiency to convert nutrients into eggs or meat.

Replacing feed ingredients with other nutrient-supplying products could also improve sustainability. As a potential alternative protein source, insects have shown to be promising in recent years (Halloran et al., 2016). Insects are of particular interest because they have a very good feed conversion efficiency, can synthesize high-quality-protein

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body mass starting from substrate low-quality-protein. Furthermore, insects can be produced using waste streams as substrate and small areas as farm (Halloran et al., 2014; Oonincx and de Boer, 2012; van Huis et al., 2013). Among all edible insects, the black soldier fly larvae (BSFL) (*Hermetia illucens*) has established itself in the food and feed sector due to its harmlessness, ease of handling and high protein and fat content (Alvarez, 2012; El-Hack et al., 2020). Also, amino acid profile of BSFL is comparable to common fed protein sources such as fish meal (El-Hack et al., 2020). In the fall of 2021, processed animal protein (PAP) was authorized for the first time under European legislation for use in pig and chicken feed (IPIFF, 2021). The potential of insects to be used as feed has also been investigated in several studies (Bejaei and Cheng, 2018; Wang et al., 2007). Thus, in broiler feed, BSFL meal was not associated with a negative effect on meat quality and animal health (Dzepe et al., 2021; Pieterse et al., 2019; Schiavone et al., 2019). When feeding insect meal to laying hens, there were minor negative effects, such as a reduction in egg size or an increase in liver size (Brah et al., 2017; Mwaniki et al., 2020). Also, whole BSFL are applicable as poultry feed both in live and dried form (Balolong et al., 2020; Colombino et al., 2021; Irawan et al., 2019) and can additionally improve birds ́ welfare (Bellezza Oddon et al., 2021; Ipema et al., 2020; Star et al., 2020).

Previous LCA studies assessed the sustainability of different poultry husbandry conditions and compared the use of different protein sources in feed (Bengtsson and Seddon, 2013; Costantini et al., 2021; Pelletier, 2008), as well as estimated protein conversion of laying hens and broiler chicken (Alexander et al., 2016). There are quite a few studies (Biasato et al., 2016; Dörper et al., 2020; Star et al., 2020) integrating insects in poultry feed to define the efficiency of feed transformation and influence of insects on animal wellbeing and product quality. Since insects have proven in recent years to be a potential alternative and more sustainable source of protein (Hexeberg Rustad, 2016; Maiolo et al., 2020; Oonincx and de Boer, 2012) than conventional proteins like soy or fishmeal, insect integration is intended to improve environmental impact of poultry production. At the same time, protein conversion rates of BSFL to chicken and meat combined with sustainability assessment was never performed. Current LCA is intended to fill the existing gap of estimating the most sustainable and efficient poultry protein production based on feed protein input and type of husbandry system. The objective of this study was a comparative life cycle assessment (LCA) of protein conversion efficiency (PCE) of the two poultry protein production systems: laying hens and broiler chicken. The study is parted into two parts dealing with protein conversion efficiency and sustainability assessment.

2. Method

2.1. Goal and scope

Protein conversion efficiency analysis relied on the model of protein transformation, which calculated 1 t of feed protein fed per converted edible biomass protein (eggs and meat). Even though it's usually not highly valued or even used in human consumption, laying hens meat was assumed to be used in the same way as broiler meat. For the alternative insect scenario 100 kg of feed protein were replaced by BSFL. Since not only in poultry but also in insect production the feed has the highest influence on sustainability, two different feeds were compared for insect production. One was Gainesville diet (GVD) (Hogsette, 1992) and the other one was composed of fruit and vegetable waste (FVW).

The LCA was developed using a modular and attributional approach (Brander et al., 2009; Spykman et al., 2021). The underlying data was calculated in the software SimaPro 8.5.2.0 (PRé Sustainability B.V., Amersfoort, The Netherlands) and followed the standard LCA approach (ISO 14,040, 2006 and ISO 14,044, 2006). Background data were taken from the *ecoinvent 3.4* (ecoinvent, Zurich, Switzerland) and *Agri-footprint 4.0* (Blonk Consultants, Gouda, The Netherlands) database. The methodology of the life cycle impact assessment was IMPACT 2002+ (Jolliet et al., 2003).

2.2. Functional unit

In order to assess the protein content of eggs and meat, two functional units were considered. The first functional unit (FU1) – protein conversion ratio, aimed to assess the amount of poultry protein, produced by a certain mass of feed protein. In this study, a feed protein input of 1 t was assumed. For further assessment of sustainability, a second functional unit (FU2) was considered, which estimates the production of 1 kg of poultry protein.

2.3. System boundaries

This study followed the cradle to slaughterhouse gate (or egg production gate) perspective with further extensions of waste treatments and considered therefore the whole chain of poultry production. The main systems included are feed production, hatchery, poultry and egg production and slaughterhouse. Although meat and eggs were assessed based on protein content, the isolation of protein was not considered as a process step in this LCA since the purpose of the study was to assess the environmental impact of edible proteins that can be ingested through food originating from chicken, and not of protein isolate originating from chicken. Background processes such as electricity or litter production were included in the system boundaries. All waste streams were treated by relevant waste treatments. Fig. 1 represents all the processes considered in the system boundaries.

2.4. Scenarios

In this study, six different scenarios were considered, three of laying hens (A-C) and three of broiler chicken farming (D-F). Scenario A represents the laying hens production using 1 t of feed protein from commercial poultry feed. In scenarios B and C 100 kg of the commercial laying hen feed was replaced by protein of BSFL: Gainesville diet was fed to the insects in scenario B and fruit and vegetable waste in scenario C. For broiler chicken production scenario D represents the conventional production with use of 1 t commercial poultry feed protein. In "Scenario E Gainesville diet" fed larvae protein replaced 100 kg of feed protein and fruit and vegetable waste fed larvae protein in scenario F.

Protein replacement rates of up to 100% of protein with BSFL are identified as possible (Balolong et al., 2020), but rates of about 5 to 15% are more common in studies (Ipema et al., 2020; Ruhnke et al., 2018). Therefore, feeding of BSFL protein in the rate of 10% was assumed (Balolong et al., 2020; Ipema et al., 2020; Ruhnke et al., 2018).

2.5. Data collection and quality

Data used in this study are based on literature. Mainly, Dekker et al. (2011) (The Netherlands) was used for laying hen production and González-García et al. (2014) (Portugal) for broiler chicken production. The data were partly adapted and extended by additional literature. Although, production takes place in different European countries it was assumed that Germany is the country of overall production. Spykman et al. (2021) served as the basis for insect production. Therefore, climate differences and location dependencies were adjusted to be similar for both production systems. However, in real cases production might differ. For background processes, such as electricity generation or waste treatments, the *ecoinvent 3.4* (ecoinvent, Zurich, Switzerland) database was used; for feed ingredients, the *Agri-footprint* 4.0 database (Blonk consultants, Gouda, The Netherlands) was partly used. Moreover, transport routes, capital goods and cleaning agents were not considered in this study. Background processes used from database were localized for Germany or Switzerland as specific as possible.

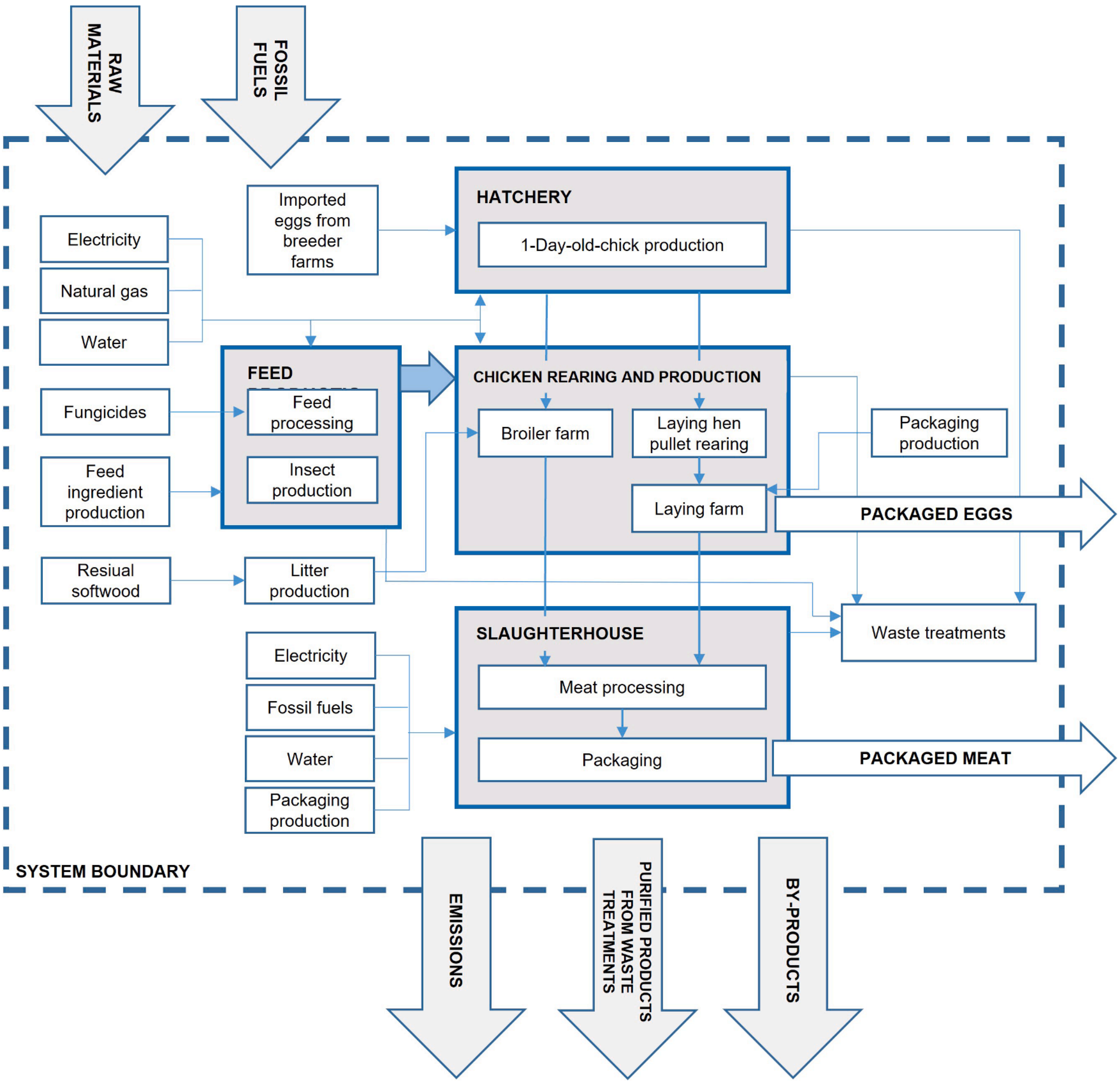

Fig. 1. System boundaries of study presenting the main processes, background processes and input and output flows as well as packed eggs and packed meat as main output.

2.6. Allocation

Due to the application of the attributional approach, side streams arising in the value chain must be allocated with a relevant environmental impact. This was achieved based on economic values and the mass produced in the corresponding module. Occurring side products were thereby manure in poultry production, frass in insect production, organic slaughterhouse waste and eggs and meat for laying hen module assembling.

2.7. Inventory

The life cycle inventory determines the quantity of all input and output flows considered in the system boundaries (ISO, 2006). Detailed data, calculations and assumptions made in this study are given in the electronic supplementary materials (Appendix 1–11). This life cycle inventory analysis was created according to the principle of the modular LCA approach. In this approach, the analyzed product system will be divided into modules, which can ultimately be combined into a value chain (Steubing et al., 2016). The modules themselves can represent individual process units or life cycle phases and are expanded with background data. There is no difference to a conventional LCA regarding the handling of the data and the results are also equivalent (Rebitzer, 2005). Modules considered in this study are: M1 - feed processing; M2 – insect production; M3 – hatchery; M4 – poultry production; M5 – egg packaging production and M6 – slaughterhouse.

Laying hen and broiler chicken production differs in terms of husbandry conditions. Broiler chicken were kept from the day of hatching to their 34th day of life in barn husbandry with the aim to gain body weight. In laying hen production, the hens were re-stalled to rearing farms after hatching. Pullets were kept for 18 weeks till they reach sexual maturity and were then transported to egg production farms. 77 weeks after hatching, the laying hens were slaughtered. The housing method was the cage rearing with 4 to 5 hens per cage (Dekker et al., 2011). One hen produces 338 eggs per lifetime (Dekker et al., 2011) with a weight of ca. 60 g per egg (Heuel et al., 2021; Irawan et al., 2019; Mwaniki et al., 2020). Produced eggs were packaged in eggboxes with 10 eggs per box. Packaging material was linerboard (Estrada-González et al., 2020). Occurred manure in both laying hens and broiler chicken production was sold as fertilizer (Dekker et al., 2011; González-García et al., 2014).

Different feeds were assumed for laying hen and broiler production. Feed for broilers was based on allegations of González-García et al. (2014) as well as feed processing. Dekker et al. (2011) serves as a basis for laying hen feed and differs between laying hens and pullets. The laying hen feed consists of 14.68% crude protein (on a dry matter basis) and the pullet feed of 13.9%. Broiler chicken feed consists of 19.93% crude protein. The respective feed intake per bird's lifetime is 5.3 kg per pullet (0.31 kg per week), 42 kg per laying hen (0.7 kg per week) and 2.9 kg per broiler (0.58 kg per week).

In the hatchery fertile eggs were imported from special breeder farms. Since male laying hens are of no economic interest, they were killed immediately after hatching (Buhl, 2016). These dead chicks were sold as animal feed for zoos or home use. Other residues such as infertile eggs (10% of incubated eggs) or egg shells were disposed in biogas plants (Wüthrich Geflügel AG, 2021). One hatched chick has a weight of 40 g (Michalczuk et al., 2011). Data for the hatchery is based on Dekker et al. (2011).

Broiler chicken reach a final body weight of 1.70 kg and laying hens of 1.72 kg (Dekker et al., 2011; González-García et al., 2014). In the slaughterhouse the chicken were killed, processed into cuts, and packaged. Occurred slaughter residues were sold for further processing as animal feed. Data for slaughtering is based on González-García et al. (2014).

In insect production BSFL were reared with Gainesville diet (50% wheat bran, 30% alfalfa, 20% corn meal) until their 5th day of life. After that 3.5% of larvae were kept for maintaining the breed stock. Remaining larvae were fattened with Gainesville diet or fruit and vegetable waste. Since FVW is a waste product, no environmental impact was considered for production. Produced BSLF fed with Gainesville diet consisted of 16.29% crude protein and fruit and vegetable waste fed larvae consisted of 10.35% crude protein on fresh matter basis. Production residues like frass and dead flies were sold as fertilizer (Spykman et al., 2021).

All modules are finally assembled by scaling factors for the use of 1 t of feed protein. Based on the poultry feed intake and the protein content of the feed, the number of birds that can consume 1 t of feed protein was calculated. This resulted in a total of 144 laying hens and 1730 broilers. By using the meat gain, the egg yield and the respective protein content, the amount of final product produced was calculated. Chicken meat consists of 22% and eggs of 13% crude protein (Naber, 1979; Schiavone et al., 2007). To calculate the amount of net protein, the protein content of 1-day-old chicks was subtracted (15%) protein in body (Shaarani et al., 2006). For further evaluation of protein efficiency, protein conversion efficiency was calculated by dividing the feed protein used by the net protein produced.

2.8. Protein quality

To assess protein conversion efficiency, in laying hen production, egg and meat protein were aggregated. But since they are different proteins with different quality, the direct comparison of the two poultry productions is not appropriate. Therefore, the produced amount of protein should be extended by the protein quality. The quality of protein can be determined by several methods. Since 2013, FAO has recommended the Digestible Indispensable Amino Acid Score (DIAAS) as the preferred method (FAO, 2013). In this method, protein quality is determined by amino acid sequence and digestibility, which is measured in growing pigs at the end of the small intestine (Burd et al., 2019). The DIAAS gives values in percent but can also be over 100%. As hundred percent, three age depending reference proteins are considered, which represent the required amino acid need of human body in the best possible way (FAO, 2013). A DIAAS of 116.4% is given for the whole chicken egg and 108.2% for chicken skin and meat (Ertl et al., 2016). Thus, the protein quality of chicken meat is slightly lower than that of chicken egg. To correct and better evaluate the amount of protein produced in this study, the protein quality is multiplied by the protein content.

2.9. Life cycle impact assessment method

To examine the sustainability of input and output flows shown in life cycle inventory, a life cycle impact assessment was carried out in SimaPro 8.5.2.0 (PRé Sustainability B.V., Amersfoort, The Netherlands) software. The underlying environmental impact assessment method is IMPACT 2002+ (Jolliet et al., 2003). This method represents a practicable realization of a midpoint/damage approach which can show integrated single scores. It combines all life cycle inventory results across 14 midpoint categories into the four damage categories resources, climate change, ecosystem quality and human health (Humbert et al., 2012).

Furthermore, Monte Carlo simulation analysis was conducted to examine uncertainties of resulting impact (Raychaudhuri, 2008). The analysis was carried out with 1000 runs for midpoint and damage categories as well as single scores of all scenarios. The environmental categories ionizing radiation and ozone layer depletion were identified as not resilient and therefore excluded from further results and assessment. Remaining categories to assess were therefore carcinogens (C), non--carcinogens (NC), respiratory inorganics (RIO), terrestrial ecotoxicity (TE), terrestrial acidification/nutrification (TA), land occupation (LO), global warming potential (GWP) and non-renewable energy (NRE).

3. Results

3.1. Protein conversion efficiency

Fig. 2 shows the protein conversion efficiency of laying hens (scenario A to C) and broiler chicken (scenario D to F) production. Thereby, both the mass based PCE and the PCE corrected by protein quality are shown. The corrected PCE does not represent a real PCE of laying hens and broiler chicken but clarifies that the efficiency is influenced by the nutritional relevance of the protein produced. To calculate the PCE, 144 laying hens and 1730 broiler chicken consumed 1 t of feed protein. Since in the scenarios where insects replaced a part of the feed protein, the total amount of protein fed did not vary either, it therefore did not affect the efficiency of production in this study.

By feeding 1 t of feed protein, a net protein amount of 416.79 kg was produced in laying hen production, which resulted in a PCE of 2.4, and a net protein amount of 446.34 kg was produced in broiler chicken production, which resulted in a PCE of 2.24. Thus, protein is converted more efficiently in broiler chicken production. However, since laying hen protein consists of egg and meat protein, the difference in quality must also be considered. Since egg protein (DIAAS 116.4) is of higher quality than meat protein (DIAAS 108.2) (Ertl et al., 2016), the PCE was corrected accordingly by multiplying the net protein content with DIAAS value. Thus, the calculated net protein quantity is corrected to 485.15 kg of laying hen production and 482.94 kg of broiler chicken production. Protein conversion efficiency is therefore corrected to 2.06 in laying hen production and to 2.07 in broiler chicken production. Accordingly, under the influence of protein quality, it is not possible to state a significant difference in efficiency.

3.2. Feed requirement

Since different feeds were used for laying hens and broiler chicken to provide 1 t of feed protein, the total feed requirements differ. For laying hen production, in contrast to broiler chicken production with an input of 5017.56 kg, a higher feed input of 6854.34 kg is necessary. For each of the scenarios (B, C, E, F) that integrate insects in the feed, the commercial feed input is the same for laying hens (6172.84 kg) and broiler chicken (4515.81 kg). However, the insects required to obtain the total protein content of 1 t varies. For scenario B and E 613.87 t of GVD fed larvae and for scenario C and F 966.18 t of FVW fed larvae must be fed to poultry. Overall, laying hen production consumed less feed when GVD was fed to larvae than when only commercial feed was consumed and used more feed when FVW is fed to larvae. For broiler chicken production, the use of insects increased feed requirement in both cases.

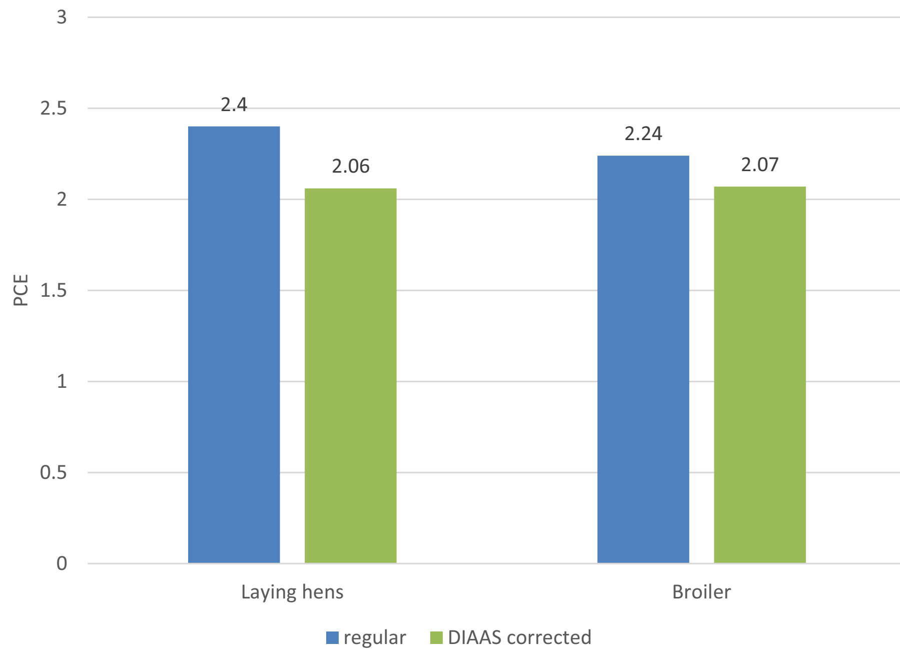

Fig. 2. Protein conversion efficiency (PCE) of laying hen and broiler production, presenting regular PCE as well as protein quality corrected PCE; PCE - 1 t of feed protein fed per converted edible biomass protein.

3.3. Life cycle assessment

The results of the impact assessment are presented in Table 1 as midpoint categories and single scores for the functional units FU1 and FU2. For laying hen production, the midpoint categories terrestrial ecotoxicity (FU1: 2.7 · 10^6 to 2.45 · 10^6 kg TEG soil), global warming potential (FU1: 1.05 · 10^4 kg CO_2-eq) and land occupation (FU1: 1.05 · 10^4 to 9.5 · 10^3 m^2 org arable) achieved the highest environmental impacts. For broiler chicken, it is global warming potential (FU1: 1.3 · 10^4 to 1.75 · 10^4 kg CO_2-eq), respiratory inorganics (FU1: 9.94 to 9.24 kg PM2.5-eq) and land occupation (FU1: 1.1 · 10^4 to 1 · 10^4 m^2 org arable). Thereby, the laying hen production shows twice as high values in TE as in the broiler chicken production. In the category RIO, broiler production shows values about 60% higher than in layer production. Also, in contrast to broiler chicken, laying hens show about twice as high values in the category NC and half as high values in the category C. Other environmental categories show comparable values in all scenarios. Also, regarding the two different functional units, the results of the individual impact categories are in a comparable proportion to each other.

Single scores of impact assessment are presented per scenario and midpoint category (Table 1; Fig. 3; Fig. 4). The results were checked for significance by IMPACT 2002+ method with 95% confidence interval. The overall environmental impacts of FU1 range from 4.38 Pt to 4.92 Pt and for FU2 from 9.57 mPt to 11.8 mPt, with Scenario F achieving the

Table 1
Life cycle impact assessment results according to the IMPACT 2002+ method, comparison of scenario A to F per midpoint and damage category for FU1 and FU2 and share of modules per scenario of single scores; FU1 - poultry protein produced by the use of 1 t of feed protein; FU2 – production of 1 kg poultry protein; A - conventional laying hen production (LHP); B - LHP with GVD fed BSFL in feed; C - LHP with FVW fed BSFL in feed; D - conventional broiler chicken production (BP); E - BP with GVD fed BSFL in feed; F - BP with FVW fed BSFL in feed.

		Midpoint category							Damage category					
	unit	A	B	C	D	E	F	unit	A	B	C	D	E	F
FU1														
Carcinogens	t C_2H_3Cl eq	0.05	0.048	0.049	0.086	0.081	0.083	Pt	0.02	0.02	0.02	0.03	0.03	0.03
Non-carcinogens	t C_2H_3Cl eq	1.19	1.103	2.16	0.58	0.56	0.54	Pt	0.47	0.44	0.427	0.23	0.22	0.21
Respiratory inorganics	kg $PM_{2.5}$ eq	6.5	6	12	10	10	9	Pt	0.62	0.59	0.579	0.98	0.92	0.91
Terrestrial ecotoxicity	kt TEG soil	2.71	2.53	2.48	1.24	1.22	1.16	Pt	1.56	1.46	1.432	0.71	0.7	0.67
Terrestrial acid/nutri	t SO_2 eq	0.35	0.34	0.33	0.29	0.28	0.27	Pt	0.03	0.03	0.025	0.02	0.02	0.02
Land occupation	m^2org.arable	10,100	9900	9550	11,200	10,600	10,200	Pt	0.84	0.78	0.759	0.89	0.84	0.81
Global warming	t CO_2 eq	10.71	10.41	10.65	12.89	12.5	12.74	Pt	1.08	1.05	1.076	1.3	1.26	1.29
Non-renewable energy	GJ primary	45.1	48.1	5.1	5.8	6.15	6.45	Pt	0.3	0.32	0.336	0.38	0.41	0.43
Total single score								Pt	4.92	4.68	4.651	4.55	4.4	4.37
FU2														
Carcinogens	g C_2H_3Cl eq	121	114	117	118	178	180	μPt	47.6	45.1	46.2	74	70.2	71.2
Non-carcinogens	kg C_2H_3Cl eq	2.86	2.64	2.6	1.27	1.22	1.17	mPt	1.13	1.04	1.02	0.5	0.48	0.46
Respiratory inorganics	g $PM_{2.5}$ eq	15.1	14.2	14	21.8	20	20	mPt	1.49	1.4	1.39	2.15	2	1.99
Terrestrial ecotoxicity	kt TEG soil	6.49	6.07	5.95	2.7	2.66	2.54	mPt	3.75	3.5	3.43	1.56	1.53	1.47
Terrestrial acid/nutri	g SO_2 eq	849	803	780	627	609	587	μPt	64.9	61	59.2	47.6	46.2	44.6
Land occupation	m^2org.arable	25.33	23.61	22.88	24.36	23.06	22.38	mPt	2	1.88	1.82	1.94	1.83	1.78
Global warming	kg CO_2 eq	25.6	25	26	28.2	27.4	27.9	mPt	2.59	2.52	2.52	2.85	2.76	2.81
Non-renewable energy	MJ primary	108.22	115.32	122.44	127.07	135.03	141.53	mPt	0.71	0.252	0.81	0.836	0.889	0.931
Total single score								mPt	11.8	2.52	11.16	9.95	9.63	9.57

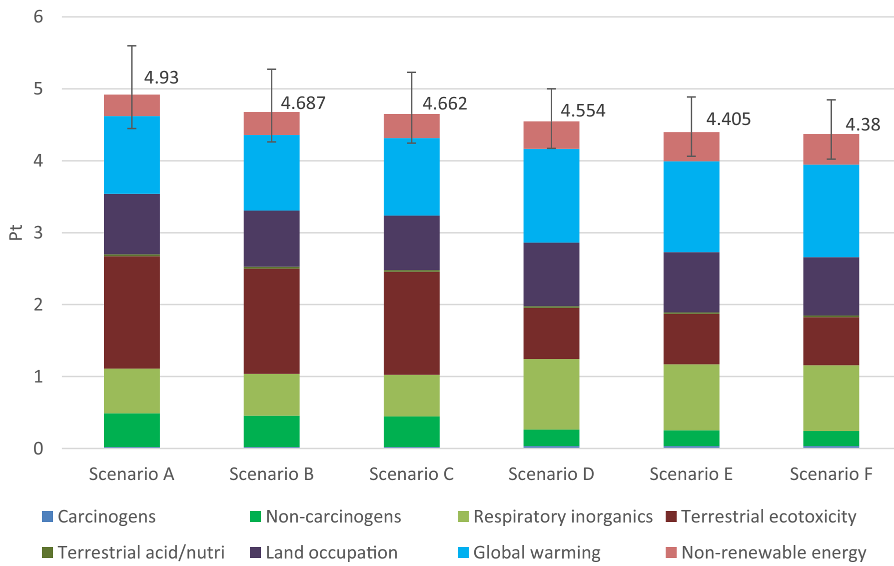

Fig. 3. Life cycle impact assessment results for FU1 (use of 1 t of feed protein), comparison of scenario A to F as single score in Pt per impact category; kPt - average environmental impact caused by one person in Europe during one year; A - conventional laying hen production (LHP); B - LHP with Gainesville diet (GVD) fed black soldier fly larvae (BSFL) in feed; C - LHP with fruit and vegetable waste (FVW) fed BSFL in feed; D - conventional broiler chicken production (BP); E - BP with GVD fed BSFL in feed; F - BP with FVW fed BSFL in feed.

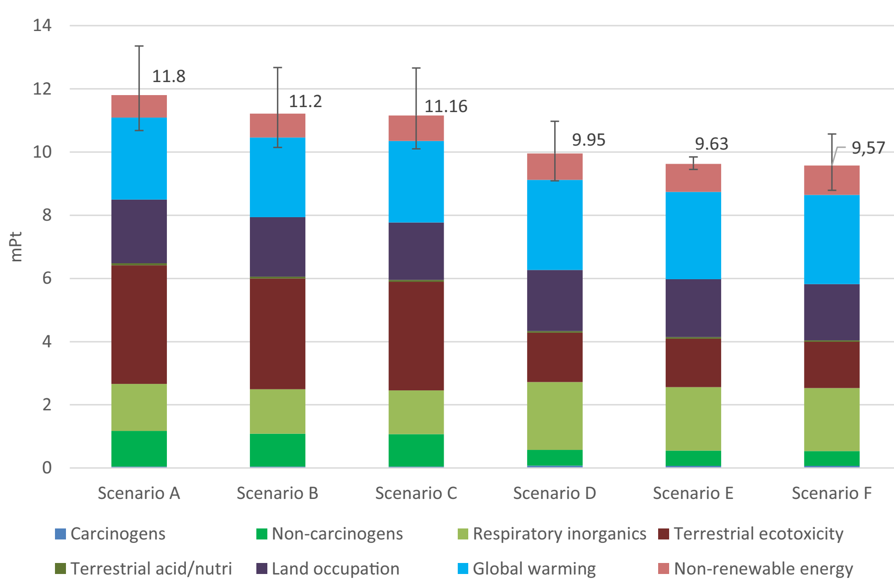

Fig. 4. : Life cycle impact assessment results for FU2 (1 kg produced chicken protein), comparison of scenario A to F as single score in Pt per impact category; kPt - average environmental impact caused by one person in Europe during one year; A - conventional laying hen production (LHP); B - LHP with Gainesville diet (GVD) fed black soldier fly larvae (BSFL) in feed; C - LHP with fruit and vegetable waste (FVW) fed BSFL in feed; D - conventional broiler chicken production (BP); E - BP with GVD fed BSFL in feed; F - BP with FVW fed BSFL in feed.

best single score of 4.38 Pt (FU1) and 9.57 mPt (FU2). Overall, the conventional scenario of broiler chicken production (D) is significantly more sustainable than corresponding scenario of conventional laying hen production (A). Also, all insect integrating scenarios of broiler chicken production (E, F) are significantly more sustainable than those of laying hen production (B, C). Furthermore, for both laying hens and broiler chicken, the scenario in which the BSFL were fed FVW (C and F) tends to be the most sustainable per production system, followed by the scenario in which the BSFL were fed GVD (B and E). However, the difference between scenarios B and C and between E and F is not significant. The significantly least sustainable scenarios per production system are the conventional productions with feeding of commercial feed (scenario A and D). However, since laying hen production has the highest overall environmental impact, Scenario A is the most environmentally damaging with a single score of 4.92 Pt (FU1) and 11.8 mPt (FU2). Furthermore, the share of the individual modules in the total environmental impact of the scenarios was assessed (Table 2). It shows that feed processing (M1) has by far the highest share in all scenarios with 78% to 95%.

Table 2
Share of modules per scenario of single scores; A - conventional laying hen production (LHP); B - LHP with GVD fed BSFL in feed; C - LHP with FVW fed BSFL in feed; D - conventional broiler chicken production (BP); E - BP with GVD fed BSFL in feed; F - BP with FVW fed BSFL in feed.

Modul share of single scores	unit	A	B	C	D	E	F
M1 - Feed processing	%	95.1	89.9	90.36	83.89	78.05	78.5
M2 - Insect production	%	/	4.96	4.46	/	5.29	4.74
M3 - Hatchery	%	0.32	0.34	0.34	2.43	2.51	2.52
M4 - Chicken production	%	2.59	2.71	2.73	11.99	12.39	12.47
M5 - Egg packaging	%	1.87	1.96	1.98	/	/	/
M6 - Slaughterhouse	%	0.12	0.13	0.13	1.69	1.76	1.77

4. Discussion

4.1. Life cycle assessment

4.1.1. Midpoint categories

When assessing the midpoint category impacts of the IMPACT 2002+ impact assessment method, feed ingredient production (M1) was identified as the main cause of environmental pollution in all the categories considered. This was also reported by serval studies (González-García et al., 2014; Katajajuuri, 2007; López-Andrés et al., 2018). In this study wheat production was the most environmentally damaging in the TA, TE, RIO, LO and NC categories, soybean expeller in the GWP, LO and C categories and grain maize production in the NRE category for laying hen production. In broiler chicken production, soybean meal production was the most environmentally damaging in the NRE, GWP, LO, RIO, and C categories, and wheat production was the most environmentally damaging in the TE, TA, and NC categories.

The production of wheat mainly affected the TE, TA, RIO, and NC categories through field cultivation, harvesting, fertilizer and glyphosate production, and straw treatment. In the TA and RIO categories, transport routes also contributed to the environmental impact, as they emitted sulfur and nitrogen oxides as well as particulate matter, leading to soil acidification and health impacts (Groneberg et al., 2009; Reif, 2010; Ulrich, 1986). The LO category is affected by cultivation on extensive areas, leading to the destruction of pristine land and the loss of biodiversity (Gasparri et al., 2016).

In the production of soybean meal and expeller, the GWP category was largely determined by transport routes and land occupation. NRE was consumed through transportation, heat production to process the soybeans, field processing, harvesting, and fertilizer. The carcinogens category is affected by the combustion of natural gas to generate heat for processing the soybeans, as well as the use of fertilizers such as potassium, single and triple superphosphates. Harvesting operations result in particulate matter, which affects the RIO category. Soybean production also results in immense LO, as much land is used for cultivation and thus virgin land is cleared.

Grain maize production affects the NRE category through transportation, field operations, harvesting, production of finished products, heat generation, and generation of electricity, as these production steps involve the mining of uranium to produce nuclear energy, as well as the consumption of natural gas and petroleum.

4.1.2. Single scores

Overall, laying hen production single scores are significantly higher than for broiler chicken production. Thus, conventional broiler chicken production (Scenario D) has a -7.6% lower single score than conventional laying hen production (Scenario A).

In midpoint category assessment, feed production (M1) has the influence in overall environmental impact (Scenario A: 95.1%; scenario D: 83.9%). Especially, the different feed compositions, which are based on the literature data of Dekker et al. (2011) and González-García et al. (2014) are responsible for the higher single score in laying hen production. The broiler chicken feed is composed of six different ingredients, of which the main components are soybean meal (35.9%), wheat and corn (23.4% each). The feed for laying hens consists of five ingredients, of which the main ingredients are corn (42%), wheat (22%), soybean expeller (17%) and sunflower expeller (8%). Since these different ingredients are produced differently, they have different environmental effects. In addition, it should be noted that the ingredients of the laying hen feed soybean expeller and sunflower expeller were taken from the *Agri-footprint 4.0* database (Agri-footprint, Netherlands) and not from the *ecoinvent 3.4* database (ecoinvent, Switzerland), like other background data. This may lead to further differences in environmental impact. Finally, the composition is important not only in terms of production, but also in terms of the protein content of the feed. Since the protein content of laying hen feed with 13.9% for pullets and 14.68% for egg production is lower than that of broiler feed with 19.93%, there is an increased demand for feed (see 3.2). Since more raw material is required to produce 1 t of feed protein, the environmental impact of laying hen production is higher.

But not only the feed production, but also the other modules of the production are involved in the environmental impact. It is noticeable that the modules M3, M4 and M6 have a higher share in the broiler chicken production than in the laying hen production (Table 2). For hatchery (M3) and slaughterhouse (M6) significantly higher quantity of birds (Broiler chicken: 1730; Laying hens: 144), which consume 1 t of feed protein, is responsible for the higher share in broiler chicken production since more resources were therefore consumed. The higher proportion in M4 (poultry production) can also be explained by a larger number of birds, but also by using litter for keeping the broilers in barn conditions. Laying hens were kept in cages and therefore do not require any litter. Ingredient production and processing impacts were therefore not considered. But it also should be noted that while the production of broilers chicken requires more birds, the production of laying hens, due to its longer life, has a higher overall environmental impact per bird. In addition, manure management was handled differently. For example, broiler chicken production involves the application of manure to the field as a fertilizer, as opposed to laying hen production. This leads to additional emissions into the water of NO_3^- and PO_4^{-3}.

In addition, the conventional production of laying hens and broiler chicken could be improved by using live BSFL in the feed (Scenario B, C, E, F). The use of Gainesville diet fed insect larvae reduced the environmental impact of laying hen production by -5% and BSFL fed with fruit and vegetable waste by -5.5%. In broiler chicken production, BSFL fed with GVD reduced the impact by -3.3% and those fed with FVW by -3.8%. The main reason for the lower environmental impact of the insect larvae fed with fruit and vegetable waste is that FVW is considered a waste stream and therefore has no environmental impact. However, it is noticeable that the use of BSFL fed with FVW reduces the environmental impact of production by only -0.5% compared to BSFL fed with Gainesville diet. This is because the FVW diet has no environmental impact but is also less nutritious than GVD. Thus, less BSFL can be produced with the same feed input than with GVD (Spykman et al., 2021). Accordingly, there is a higher demand for electricity, water and heat to produce 1 kg of BSFL. In addition, electricity also has a high impact on the environmental impact of insect production. For example, in the production of larvae fed with GVD, feed accounts for 58% and electricity for 30%.

4.2. Protein conversion efficiency

Results show that broiler chicken can convert a higher amount of protein than laying hens from the same feed protein input. However, the protein produced by laying hens is of higher quality for human consumption and if protein quality is included in the evaluation of protein conversion efficiency, no significant difference in efficiency can be observed.

Differences in the amount of protein produced are mainly due to the difference in the metabolic process to produce eggs and poultry meat. But other factors can also influence the PCE. Especially in this study, the protein content of the feed and the feed intake can significantly influence the result since the calculation of the protein quantity is based on these parameters.

Similar feed intake values from the literature are in a range of 0.525 kg to 0.943 kg per week for broiler chicken and 0.525 kg to 0.826 kg per week for laying hens (Boggia et al., 2010; Cesari et al., 2017; Edeh et al., 2020; Mattila et al., 2011; Pelletier, 2008; Wiedemann and McGahan, 2011). Common data of protein content in feed found in literature range from 14.58% to 18.4% for laying hens and 19.93% to 21.6% for broiler chicken (Ijaiya and Eko, 2009; Mwaniki et al., 2020; Ocio et al., 1979; Ruhnke et al., 2018; Wang et al., 2007). Therefore, values used in this study are comparably low (Broiler: 19.93%; Laying hens: 14.58%) and can strongly influence the result if were set higher. Assuming a FI of 0.943 kg per week for broiler production instead of 0.580 kg per week, the calculated protein content would decrease from 446.34 kg to 228.76 kg and the PCE would increase from 2.24 to 4.37. If the protein content of the laying hen feed were increased from the relatively low 14.58%, fewer hens could consume the protein amount of 1 t and thus produce less protein.

Another factor influencing protein conversion efficiency can be the age at which the birds are kept. Whereas broiler chicken were fattened for only five weeks of life, during which they achieve maximum weight gain, laying hens lose laying performance from the 8th week, which then decreases continuously until slaughter (Brade et al., 2008). Another point is that laying hens must first become sexually mature to lay eggs. Thus, they were kept for the first 18 weeks life without achieving any product yield. Also, energy conversion depends on age, weight and body size (Holtmeier, 1995). Thus, it can be assumed that an adult bird, due to its higher body mass, needs more feed for basic maintenance than a chick. The different efficiency of converting feed into poultry protein also depends on the breed. For example, there are slow-growing broilers that consume more feed to produce meat (Quentin et al., 2004). Also, there are breeds that are bred for meat production as well as egg production (Siekmann et al., 2018). Also, the housing system plays a role in the performance of the poultry. For example, if birds are not kept under optimal conditions, laying performance decreases (Englmaierová et al., 2014). Also, more movement, such as in free-range systems, leads to an increased energy demand (Brade et al., 2008).

4.3. Limitations

The possibility of divergence between the results of this study and the potential of similar future experimental studies is increased by many simplifications and assumptions made. Because of the choice of attributional approach, only the sustainability of the system itself and not the resulting effects on market were considered. The underlying data were based exclusively on literature data and the use of databases. Accordingly, it can be assumed that assumptions have already been made previously, which reduce the data quality. In addition, not all background processes used from the database were specific to the real process and the locality of the background processes was not always appropriate. Furthermore, background processes for some feed ingredients were not taken from the *ecoinvent 3.4* database (ecoinvent, Switzerland), but from the *Agri-footprint* 4.0 database (Agri-footprint, Netherlands) (see 4.1.2). However, since the production of the feed has by far the greatest influence on the environmental impact, this can lead to distortions in the results. Another point is the allocation used in this study, which is based on prices for small quantities of goods from the Internet. However, since prices for large-scale production are often cheaper than for private use, the prices used are not necessarily applicable to a large-scale broiler chicken production. Additionally, this study assumes that conventional feed and BSFL are interchangeable without negative influences. However, some studies showed that insects in laying hen feed can lead to decrease in egg size and increase in liver size (Brah et al., 2017; Mwaniki et al., 2020). Accordingly, a lower egg and meat yield could occur in the real-life applications. Also, positive effects of insects in feed could lead to a change in yield. Furthermore, the real-life applicability of this study is limited. For example, conventional cage rearing has not been allowed in Europe since 1 January 2012. Also, housing in enriched cages (small group husbandry) is to be prohibited by the end of 2025 (Bundesministerium für Ernährung und Landwirtschaft, 2019). In addition, the killing of male chicks due to inefficiency is to be banned in Germany from the end of 2021 (Bundesministerium für Ernährung und Landwirtschaft, 2021). Furthermore, the rearing of animals (insects) intended for human consumption on waste streams is not permitted according to Regulation (EC) No 1069/2009(European Parliament and Council, 2009).

5. Conclusion

The aim of this study was the comparative life cycle assessment and protein conversion efficiency assessment of laying hens and broiler chicken with the alternative scenario of supplementing the feed with BSFL (fed with Gainesville diet (GVD) or fruit and vegetable waste (FVW)). Six scenarios of feeding 1 t of feed protein to poultry (A: conventional laying hen production (LHP); B: LHP with GVD fed BSFL; C: LHP with FVW fed BSFL; D: conventional broiler chicken production (BP); E: BP with GVD fed BSFL; F: BP with FVW fed BSFL) which converted it into food biomass (eggs and meat).

Results of life cycle assessment showed higher environmental impacts in laying hen production (11.8 mPt per kg protein) than in broiler chicken production (9.95 mPt per kg protein). This was predominantly due to the composition of the feed. In addition, the environmental impact per bird is higher in layer production than in broiler chicken production due to the longer life cycle. Scenarios that supplemented BSFL in the feed improved production in both cases (laying hen: 11.2 mPt per kg protein; broiler chicken: 9.63 mPt per kg protein), with fruit and vegetable waste fed BSFL performing slightly, but not significantly, better (laying hen: 11.16 mPt per kg protein; broiler chicken: 9.57 mPt per kg protein), as no environmental impact was attributed to the production of the waste. Considering the midpoint categories, the highest environmental impacts in laying hen production were mainly in the categories terrestrial ecotoxicity (6493.64 kg TEG soil per kg protein), global warming potential (25.69 kg CO_2-eq per kg protein) and land occupation (25.33 m^2 org arable per kg protein) and in broiler chicken production in the categories global warming potential (28.22 kg CO_2-eq per kg protein), respiratory inorganics (0.02 kg PM2.5-eq per kg protein) and land occupation (24.36 m^2 org arable per kg protein). The reason for these different impacts was the different composition of the feed used, as well as the different total amount of feed necessary to provide 1 t of feed protein (laying hens: 6854.34 kg; broiler chicken: 5017.56 kg). The category terrestrial ecotoxicity achieved almost twice as high impacts in laying hen production than in broiler chicken production. This was mainly due to the production of wheat (field cultivation, harvesting, fertilizer and glyphosate production, and straw treatment), since more of this crop was used than in broiler chicken production, and also due to the different composition of the feed. In broiler chicken production, respiratory inorganics had about 60% higher environmental impact than in laying hen production. Here, the production of soybean meal (harvesting operations) (ecoinvent 3.4 database) was decisive, since in laying hen production soybean expeller (Agri-footprint 4.0 database) was used to a lesser extent.

In the protein conversion efficiency assessment, by feeding 1 t of feed protein, a PCE of 2.24 for broiler chicken and of 2.4 for laying hens could be calculated. Thus, broiler chicken can be identified as more efficient in protein conversion. However, since in laying hen production the two products (eggs and meat) were aggregated, the result is not sufficiently reliable due to the different metabolic processes and protein structures. For this reason, the amount of protein produced was corrected by the DIAAS (value for protein quality assessment), which changes the PCE of laying hens to 2.06 and of broiler chicken to 2.07. Thus, no significant difference can be assumed in this observation.

Overall, the comparability with other studies is given, but the results should be viewed critically since this work is based exclusively on literature values and thus many assumptions were made. Therefore, sensitivity analyses are recommended. In summary, the results were mainly influenced by the production and composition of the feed, so in real applications, improvements in cultivation techniques, crop yield as well as optimal composition of the feed should be achieved. Besides, the insect inclusion into feed should improve feed sustainability.

CRediT authorship contribution statement

Wiebke Heines: Formal analysis, Methodology, Investigation, Writing – original draft. **Dusan Ristic:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision. **Sandra Rosenberger:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Carl Coudron:** Resources, Validation. **Francesco Gai:** Resources, Validation, Project administration, Funding acquisition. **Achille Schiavone:** Resources, Validation. **Sergiy Smetana:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Supplementary materials

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