Fakulta zemědělská
a technologická
Faculty of Agriculture
and Technology

Jihočeská univerzita
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Autoreferát dizertační práce

Monitoring mikroklimatických podmínek v intenzivních chovech hospodářských zvířat s technologií nucené a přirozené ventilace

Autor práce: Ing. Radim Kuneš

Školitel: doc. RNDr. Petr Bartoš, Ph.D.

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Abstrakt

Dizertační práce se zabývá problematikou mikroklimatických podmínek, zejména monitoringem emisí amoniaku a metanu, v intenzivních chovech s technologií přirozené a nucené ventilace. Jsou diskutovány přístupy pro odhad emisí amoniaku z intenzivních chovů prasat, které jsou definovány zákonem o integrované prevenci a omezování znečištění, vycházející se Závěrů o BAT podle směrnice Evropského parlamentu a rady č. 2010/75/EU o průmyslových emisích. Pro potřeby odhadu emisí amoniaku z intenzivních chovů prasat pomocí metody výpočtu měřením koncentrace amoniaku a výkonu ventilace byla vytvořena metodika pro provádění experimentálních měření. Z provedeného monitoringu byla diskutována problematika počtu a rozložení monitorovacích dnů na přesnost odhadu emisí amoniaku z výkrmu prasat. Bylo ověřeno, že vybrané monitorované kategorie intenzivních chovů prasat splňují limity BREF pro emise amoniaku. V práci byla diskutována potřeba revize stanovených emisních faktorů pro odhad emisí amoniaku.

V aktuálním návrhu revize směrnice Evropského parlamentu a rady č. 2010/75/EU o průmyslových emisích je uvedeno, že do oblasti působnosti budou spadat všechny zemědělské podniky zabývající se chovem skotu, prasat a drůbeže s kapacitou větší než 150 dobytčích jednotek, byla práce rozšířena i o problematiku chovů skotu. Jednalo se zejména o návrh obecné metodiky pro odhad emisí amoniaku a metanu z intenzivních chovů skotu pomocí metody výpočtu měřením koncentrace amoniaku, metanu a výkonu ventilace. K návrhu metodiky bylo použito počítačových simulací a modelů pro určení parametrů proudění vzduchu ve stáji.

Klíčová slova: emise; amoniak; metan; BREF; BAT; IPPC.

Abstract

The dissertation thesis deals with the issue of microclimatic conditions, especially monitoring ammonia and methane emissions in intensive farms with natural and forced ventilation technology. Approaches for estimating ammonia emissions from intensive pig farms, as defined by the Integrated Pollution Prevention and Control Act, based on the BAT Conclusions under Directive 2010/75/EU of the European Parliament and the Council on Industrial Emissions, are discussed. A methodology for carrying out experimental measurements was developed to estimate ammonia emissions from intensive pig farms using the calculation method by measuring ammonia concentration and ventilation performance. From the monitoring conducted, the issue of the number and distribution of monitoring days on the accuracy of estimating ammonia emissions from fattening pigs was discussed. It was verified that the selected, monitored categories of intensive pig farms meet the BREF limits for ammonia emissions. The need to revise the established emission factors for estimating ammonia emissions was discussed. In the current proposal for revision of Directive 2010/75/EU of the European Parliament and the Council on industrial emissions, it is stated that all cattle, pig, and poultry farms with a capacity greater than 150 livestock units will be included in the scope, the work was extended to include cattle farms. In particular, it involved the proposal of a general methodology for estimating ammonia and methane emissions from intensive cattle farms using a calculation method measuring ammonia and methane concentrations and ventilation performance. Computer simulations and models were used to design the methodology to determine the airflow parameters in the barn.

Keywords: emissions; ammonia; methane; BREF; BAT; IPPC.

Úvod

Spotřeba masa a dalších živočišných produktů zaznamenala v posledních desetiletích velký nárůst. Snahy zemědělců o uspokojení trhu zvyšují požadavky na intenzifikaci živočišné výroby. Ta je v České republice (ČR) směřována zejména do oblasti chovů drůbeže, prasat a dojnic. Intenzifikace chovů je dále podporována díky novým moderním chovným technologiím, které využívají nejnovějších poznatků zejména v oblasti automatizace a řízení. Intenzifikace výroby však na druhé straně klade také zvýšené požadavky na řízení mikroklimatických podmínek uvnitř stáje, aby v nich bylo zajištěno vhodné životní prostředí pro chovaná zvířata i obsluhu, která se v prostorách pohybuje.

Intenzifikace živočišné výroby nutně vede ke zvýšení produkce emisí nejenom uvnitř chovné haly, ale také v jejím blízkém okolí, kam jsou tyto látky přirozeně uvolňovány. Intenzivní chov hospodářských zvířat je z pohledu ochrany ovzduší definován jako stacionární antropogenní zdroj emisí, které primárně ovlivňují prostředí stáje. Těmito emisemi můžou být například plynné látky jako je amoniak (NH_3), oxid uhličitý (CO_2), metan (NH_4), či sirovodík (H_2S), popřípadě pachové látky jako celek, prachové částice (zejména frakce $PM_{2,5}$ a PM_{10}) či hlukové emise. Z legislativního pohledu jsou monitorovány zejména emise (NH_3, NH_4), které snižují kvalitu chovných podmínek či jinak ovlivňují okolní životní prostředí.

Prakticky veškerá snaha k omezení NH_3 a NH_4 je směřována k uvedenému odvětví zemědělské produkce. Stále se vyvíjejí a ověřují nové chovné technologie, které by tyto emise snížily. Jako klíčová se v tomto směru jeví snaha co nejlépe porozumět jednotlivým faktorům, které uvolňování emisí do prostředí ovlivňují. Celkové emise produkované z intenzivních chovů hospodářských zvířat závisí na mnoha faktorech jako konstrukce budovy, režim větrání, mikroklima stáje, technologie chovu a výživy, klimatické podmínky, stáří, počet a kategorie ustájených zvířat, výživa, etologické projevy a mnoho dalších.

Evropská komise se snaží pomocí preventivních opatření snížit produkci emisí a odpadů zavedením směrnice Evropského parlamentu a rady č. 2010/75/EU o průmyslových emisích (integrované prevenci a omezování znečištění) – (dále jen směrnice IED). Tato směrnice je v ČR implementována zákonem o integrované prevenci a omezování znečištění. V příloze č. 1 zákona o integrované prevenci jsou vymezeny činnosti, na které se působnost zákona vztahuje. Intenzivní chovy drůbeže a prasat s prostorem pro více než 40 000 kusů drůbeže, 2 000 kusů prasat na porážku s hmotností nad 30 kg, nebo 750 kusů

prasnic jsou zařazeny v kategorii 6.6. Chovatelům provozující chovy přesahující uvedené kapacity vzniká povinnost splnění podmínek pro vydání integrovaného povolení.

Evropská komise si vytyčila za cíl omezit produkci zejména NH_3 a NH_4, a to v návaznosti na Zelenou dohodu „Green Deal". Evropská komise se snaží postupně zpřísňovat požadavky kladené na chovy hospodářských zvířat, aby mohla tohoto svého cíle dosáhnout. Proto byl dne 5. dubna 2022 ve Štrasburku předložen návrh revize směrnice IED, který výrazně upravuje předchozí směrnici v ohledu na intenzivní chovy, kdy výrazně snižuje prahovou kapacitu pro chovy spadající do působnosti této směrnice a rozšiřuje jí o chovy skotu.

Výzkum a vývoj realizovaný pro potřeby této dizertační práce vychází z konkrétních zadání funkčních úkolů Ministerstva zemědělství ČR (MZe ČR) dlouhodobě realizovaných na Fakultě zemědělské a technologické Jihočeské univerzity v Českých Budějovicích (FZT JU). Cílem těchto aktivit je zajištění silné pozice ČR při vyjednávání v rámci Evropské unie (EU) tak, aby byly chráněny zájmy našich chovatelů hospodářských zvířat. Dizertační práce se zabývá monitoringem emisí NH_3 z intenzivních chovů prasat, emisí NH_3 a NH_4 z intenzivních chovů dojnic a sledováním mikroklimatických podmínek. V jejím rámci byla formulována metodika pro stanovení emisí NH_3 v intenzivních chovech prasat s nucenou ventilací vzduchu a její experimentální ověření v provozních podmínkách. Dále bylo realizováno porovnání naměřených emisí se závaznými limity vycházejících ze směrnice IED a legislativy ČR, a také s emisními faktory, které slouží pro stanovení roční produkce ze zemědělských provozů. Jelikož se v aktuálním návrhu revize IED uvažuje o rozšíření zájmových chovů o kategorii skot, práce reflektuje na tuto problematiku provedením pilotního monitoringu emisí NH_3 a NH_4 v chovech dojnic a jejich porovnání s aktuálními emisními faktory, které slouží pro odhad vyprodukovaných emisí.

1 Přehled publikací

Autor dizertační práce se rozhodl prezentovat výsledky výzkumných aktivit jako ucelený přehled publikací, které jsou uvedeny v této kapitole. Na tyto publikace se bude ve většině případů odkazovat v níže uvedené části autoreferátu dizertační práce. Vědecké publikace jsou zveřejněny v periodikách s impakt faktorem a prezentují aktivity, které vedly ke splnění cílů a ověření stanovených výzkumných hypotéz. Autor se k tomuto řešení rozhodl z důvodu zpřehlednění uvedené problematiky a časové posloupnosti prováděných vědecko-výzkumných aktivit. Mimo jiné, každá ze čtyř publikací prošla recenzním řízením (článek oponovali zpravidla 3–4 oponenti), celkem publikace citují 317 zdrojů, v období od roku 2021 až 2024 byly 11x citovány podle databáze Web of Science a autor dizertační práce je vždy na prvním či druhém místě mezi autory publikace.

Některé výstupy z vědecko-výzkumných aktivit byly publikovány také v rámci funkčních úkolů pro MZe ČR.

A Review: Comparison of Approaches to the Approval Process and Methodology for Estimation of Ammonia Emissions from Livestock Farms under IPPC

Radim Kunes *, Zbynek Havelka [ID], Pavel Olsan [ID], Lubos Smutny, Martin Filip, Tomas Zoubek [ID], Roman Bumbalek, Bojana Petrovic [ID], Radim Stehlik [ID] and Petr Bartos

Department of Technology and Cybernetics, Faculty of Agriculture and Technology, University of South Bohemia, Studentska 1668, 37005 Ceske Budejovice, Czech Republic
*   Correspondence: kunesr@fzt.jcu.cz

Abstract: Ammonia (NH_3) emissions have a negative impact on the welfare of breeding animals, human health, and the environment. These influences of modern intensive agriculture have led to numerous protocols, national regulations, and European Directives. Following previous regulatory measures, the Commission Implementing Decision European Union (EU) 2017/302 on 15 February 2017 has established best available technique (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and the Council, for the intensive rearing of poultry and pigs. This applies to intensive poultry and pig producers with a capacity of over 40,000 poultry, 750 sows, or 2000 fattening pigs. Due to the application of this directive, air emissions have been reduced by between 40% and 75% over the last 15 years. The integrated permit monitors the entire environmental burden of the farm on its surroundings (air pollution, water, soil pollution, waste production, energy use). This review aims to provide a critical overview of how member states (including the United Kingdom) are approaching the implementation of IPPC (Integrated Pollution Prevention and Control) and the conclusions of BAT in their legislation and related documents, and how they monitor NH_3 emissions from intensive livestock farming. The data for this review were obtained from 2019 to 2020.

Keywords: air pollution; NH_3; BREF; BAT; IPPC

1. Introduction

Intensive livestock production produces nitrogen in various forms. The production of NH_3 emissions results in a deterioration of human health and exposure to health risks, and impacts the surrounding ecosystems and biodiversity [1–3]. The release of nitrates into surface waters contributes to their eutrophication, while groundwater contamination threatens to reduce its quality [4]. According to [5], excess nitrates in the soil could lead to the production of nitrous oxide emissions.

In the EU, the share of agriculture in NH_3 emissions is about 94% of total anthropogenic emissions [6], of which 75% of NH_3 emissions come from livestock production [7]. From all livestock categories, concerning the whole manure handling cycle (housing, storage, application), cattle are the largest source of NH_3 emissions (53%), followed by pigs (25%), poultry (15%), and other animal categories (7%) [8].

Therefore, the livestock industry is in a difficult situation, as it should ensure a high level of production and the improvement of its impact on the environment. Increased human concern for the sustainable development of agriculture, together with the increase in the number of animals and the size of farms, has led to the introduction of strict environmental legislation throughout the EU.

1.1. EU Legislation

In 1991, the EU presented Council Directives concerning the usage of nitrate fertilizers (91/676/EEC), intending to reduce water pollution by agricultural sources using nitrates. Therefore, the nitrates' concentration limits in groundwater and surface water were set to 50 mg·L^{-1} [9,10]. This Directive is one of the most critical European regulations, as it reduces the effects of careless use of fertilizers on the environment and increases nitrogen use efficiency. The Directive about nitrates defines "vulnerable zones", and establishes spatial and time limits on their application, setting the maximum amount of organic nitrogen (170 kg·ha^{-1}·year^{-1}) which can be applied to the soil. According to a report from the European Commission, this Directive has had specific positive effects. In 2012–2015, 13.2% of groundwater monitoring stations exceeded the nitrate concentration limit. This is a slightly improved result compared to the previous reporting period of 2008–2011, when 14.4% of stations exceeded the same threshold [11].

In 1999, the Gothenburg Protocol of the Convention of Long-Range Transboundary Air Pollution (CLRTAP) set national emission ceilings for a series of gases, including nitrogen oxides (NO_2) and NH_3, which by 2010 would have resulted in a reduction in NH_3 emissions of 17% compared to 1990. This was followed in 2001 by implementing the Gothenburg Protocol in the EU as the National Emission Ceilings Directive 2001/81/EC (NECD). Each EU country set a maximum level of emissions to be met by 2010. This goal has been achieved by 23 of the 27 EU countries. For the above reason, EU countries must report the NH_3 emissions produced. In 2012, the Gothenburg Protocol was modified and subsequently predicted a reduction in NH_3 emissions of 6% in 2020 compared to 2005 [12].

In 1996, EU member states agreed on the preparation for implementing the best available techniques (BAT), according to the Council Directive (96/61/EC) concerning IPPC. A reference document, BREF, was developed [13] and addressed the main issues in implementing the IPPC Directive. In addition to the NH_3 issue, the BREF also dealt with odours, particulate matter, and other gases produced by agriculture and industry. This document had been amended several times until the Commission Implementing Decision (EU) 2017/302 of 15 February 2017 established best available techniques (BAT) conclusions under Directive 2010/75/EU for the intensive rearing of poultry or pigs. This Directive established rules for the licensing of industrial activities with the general objective of environmental protection. One of the defined sectors is intensive livestock farming (farms with more than 40,000 places for poultry, 2000 for fattening pigs or 750 for sows), in which producers must have an operating license granted that describes the total environmental impact of the husbandry. This includes air, water, soil pollution, waste production, and resource use (water consumption and energy efficiency). An operating license is only issued if the farmer demonstrates the appropriate use of non-excessive BAT, listed and described in the official BREF [14–17].

1.2. Emission Estimation Methodologies

The issue of NH_3 emissions is complex and depends on many factors (animal categories, housing technology, climate, and microclimate conditions) [18].

Due to this reason, an effort has been made for the most accurate determination of the resulting emissions from agricultural holdings. Reliable estimates of NH_3 emissions in EU countries are essential to identify the effectiveness of mitigation strategies at national and regional levels. To determine the level of NH_3 emissions from intensive livestock farming, methodologies have been developed to calculate these emissions based on data from operating conditions.

Estimation can be performed by using emission factors to calculate NH_3 emissions, such as the number of animals, the occupancy during the year, and the emission factor for each category. The emission factor is determined based on scientific knowledge and varies according to the category of animals. The calculations consider each cycle of manure production and handling (stables, storage, and landspreading). Technologies used to reduce

NH_3 emissions are also considered. The emission factor is derived from measurements designed and performed according to a national or an international protocol [19,20].

Estimation of NH_3 emission is performed by measuring the NH_3 concentration and the ventilation rate. National or international standards are used as measurement methodologies. To estimate annual emissions, six 24 h measurements are required. The annual average is calculated as a mean over all sampling days. These are spread over the breeding cycle according to the category of animals:

- Stable emission production (laying hens)—measurements are recommended once every two months during one year;
- Linear emission production (fattening pigs)—three measurements in the first breeding cycle and three measurements in the second breeding cycle;
- Exponential emission production (broilers)—one measurement in the first breeding cycle, two measurements in the second breeding cycle, and three measurements in the last breeding phase [17].

Another possible approach is an estimation made by using a mass balance based on the excretion and the total (or ammoniacal) nitrogen present at each manure management stage. The methodology found in the European Monitoring and Evaluation Programme/European Environmental Agency (EMEP/EEA) air pollutant emission inventory guidebook 2016 (Part B: Sectoral guidance chapters 3. Agriculture-3.B Manure management 2016) can be used and is very widespread in EU countries. This method is especially suitable for countries with specific emission factors set. For the calculation, the methodology uses different algorithms. For livestock categories that make a minor contribution to NH_3 emissions, a Tier 1 algorithm could be used, since it considers the total NH_3-N emission factors for different categories of animals, including the total manure handling process (housing, storage, and landspreading). For livestock categories where NH_3 emission production is an essential source, the Tier 2 algorithm can be used. Calculation of the total NH_3 emissions is based on total NH_3 nitrogen (TAN). The method includes 15 steps to determine NH_3 emission, and the authors of this work recommend it as the most appropriate method. The Tier 3 algorithm has been recommended for countries with sufficient data to apply a specific emission factor. Additionally, it uses emission models to estimate the production of emissions [21].

The methodologies mentioned above provide approaches for correctly estimating the emissions produced. However, EU countries also use country-specific methods, and the final result is more accurate for overall estimated emissions. Annual updates of the NH_3 emissions produced should assess compliance with the agreed commitments, identify the main sources of emissions, and evaluate their impact on the environment.

2. Implementation of IPPC and the Approach to Monitoring NH_3 Emissions in EU Countries

The following chapter summarizes the basic information on how member states implement IPPC in their legislation and how they approach the monitoring of NH_3 emissions in intensive farms under IPPC.

2.1. Austria

Competent authorities for environmental protection in Austria are diverse. The state and provinces have legal and administrative powers. However, the powers of the state prevail. Some facilities covered by the IPPC, mainly intensive livestock farming, fall under provincial law-permit issued by the regional administration [22,23].

Permission is granted indefinitely, but compliance is checked regularly [24]. After ten years, the licensee must check the current status of the BAT and, if needed, take the necessary measures immediately and notify the competent authorities of the change in the BAT [25]. Non-compliance with the required conditions may result in the closure of the farm and the imposition of a sanction up to €2180 [26].

Austria has tried to implement the IPPC Directive as part of an overall reform to standardize and centralize the regulatory framework for permits. However, the reform failed to introduce an environmental law, so Austria continued implementing the IPPC Directive by amending sector-specific legislation [25]. The primary and most comprehensive framework for production permits is the Commercial Law. The application of the BAT conclusions is contained in the Law on Waste Management. The EMEP/EEA Tier 1 methodology is used to estimate emissions [27,28].

2.2. Belgium

The primary responsibility for environmental policy and legislation in Belgium belongs to the three autonomous regions: the Flemish region, Brussels, and the Wallonia Region. This means that implementation of the IPPC Directive is the exclusive competence of individual regions (without the involvement of the state), but also that this legislation is different in all three regions. Each region implements the IPPC and provides an operational licensing agenda [29,30].

I.   Flemish Region

The IPPC Directive has been implemented by the Regulation (Law on Regional Parliament) on Environmental Licensing (as amended), supplemented by some administrative regulations, which state in detail the procedure and conditions for issuing license permits (Vlarem II, Vlarem III)—in Annex I, the Regulation Vlarem III states a list of the facilities that must apply for a permit. The list is taken from Directive 2010/75/EU of the European Parliament and the Council [30–34].

The competent authority issues the permit, in this case, the Flemish government or municipality. There are three categories of equipment when issuing permits:

- For installations with low environmental impact, it is sufficient to inform about the construction in advance;
- For medium environmental impact installations, the local government issues the permit (municipality);
- Installations with a significant impact on the environment are issued the permit by the provincial government [30].

All IPPC installations are classified in the C category. The competent authority decides on the duration of the permit.

II.   Wallonia Region

The IPPC Directive has been implemented by the Environmental Licensing (as amended) and implementing regulations. When issuing integrated permits, installations differ according to their environmental impact, as in the event of the Flemish region [30,35]. The EMEP/EEA Tier 2 methodology is used to estimate emissions [36].

III.   Brussels Region

The IPPC Directive has been implemented by the Environmental Licensing Regulation (as amended) and its implementing regulations [37].

There is a unique situation in the Brussels region, in which, in the event of refusal to issue an environmental permit by the government of the Brussels region, an appeal may be lodged against the so-called "Milieucollege—Collège de l'environnement". The Commission is composed of five independent experts who will review the decision of the Brussels government and may issue a permit [30].

The Brussels Environment Agency primarily issues the permit. There are four different categories (IA, IB, II, III) in the Brussels region that are distinguished according to the impact of their activities on the environment when issuing an integrated permit. Category IA installations are subject to environmental impact assessment requirements and permits, category IB is subject to simplified management of environmental impact assessment and permit requirements, category II is subject to an environmental permit issued by

the competent municipality, and category III installations only have to announce their activities [30].

2.3. Bulgaria

Bulgaria is implementing the IPPC Directive through the environmental protection law, which is published in the Official Gazette 91/2002, as last amended by the Official Gazette 98/2014. At the national level, it implements EU Directive 2010/75/EC, which came into effect on 7 January 2014 and introduces an integrated permit system. The integrated permit is issued by the Director of the Executive Environment Agency (Executive Environment Agency), which must include mandatory environmental protection measures and be based on the concept of BAT. The EMEP/EEA Tier 1 methodology is used to estimate emissions [38,39].

The integrated permission is issued for an indefinite period, except in cases where the environmental regulations set a specific deadline for the facility's closure. The licensee is obliged to inform the Ministry of Environmental and Water Protection and the Executive Environment Agency of any changes in working conditions. In the case of performing activities without a license, the licensee in question may be fined up to €25,000 [40].

Bulgaria has set up an extensive database of information on emissions from all sources of pollutants divided into 11 groups according to the emission source. One of these groups is agriculture and natural resources. Emissions of 14 harmful substances, including NH_3, are monitored. The MOEW (Ministry of the Environment and Water), the Bulgarian branch of the EEA (European Environment Agency), RIEW (Regional Inspectorates of Environment and Water), and NSI (National Statistical Institute) are responsible for organizing data collection [41].

2.4. Croatia

The implementation of the IPPC Directive into the Croatian legal system has been performed by Regulation NN 114/2008-Regulation on the procedure for setting integrated environmental protection requirements [42]. The establishments listed in Annex I must also apply for an integrated permit for this regulation (parameters are identical to European Directive 2010/75/EU). The transfer of European legislation 2010/75/EU took place in the Act on Environmental Protection NN 80/2013 of 21 June 2013. The EMEP/EEA Tier 2 methodology is used to estimate emissions [43,44].

The competent authority issues the permit (Department for Integrated Environmental Protection of the Ministry of Environmental Protection and Energy). In the event of a violation of the conditions of the integrated license, the licensee faces a fine of up to €120,000 [43].

2.5. Czech Republic

In the Czech Republic, intensive poultry and pig farming has been defined by the Law on Integrated Prevention No. 76/2002 Coll. in Annex No. 1 in category 6.6. This law is based on Directive 2010/75/EU of the European Parliament and the Council on industrial emissions. Intensive farm owners whose capacities exceed the above limits must apply for an integrated permit under the Integrated Prevention Act. It is a demanding administrative process that requires comprehensive knowledge, especially in legislation and technology. The Czech Inspectorate issues inspections and permits for Environmental Protection. The review of integrated permits will, among other things, examine how emissions of pollutants into the environment are monitored. The BAT conclusions set minimum requirements for NH_3 emission limits that institutions must meet. The provider can determine NH_3 emissions either by calculation according to the Methodological Instruction of the Ministry of the Environment (BAT 25C), or with measurement under BAT 25B, if required by the situation in operation. However, the permitting authority cannot order the measurement of NH_3 emissions, as follows from the methodological instruction of the Ministry of the Environment, which the permitting authorities have used in the review of issued integrated

permits, in the following four years. In practice, the calculation of NH_3 emissions according to BAT 25C, as stated in the BAT conclusions according to Directive 2010/75/EU of the European Parliament and the Council for intensive poultry or pig farming, is mainly used [17,45].

2.6. Denmark

Environmental laws in Denmark are based mainly on EU law and, to some extent, on international treaties. All EU directives have been transposed and incorporated into Danish law. The primary document is the Environmental Protection Act (LBK No. 1121 of 9 March 2018) [46]. The Environmental Protection Act contains the 2013 Industrial Emissions Directive (IED), which implements the IPPC Directive [47,48]. This Directive provides that all industrial production, agricultural production, and waste treatment processes are subject to the approval of the competent authority. It introduces a requirement for more frequent use of BAT techniques and provides for more frequent inspections of licensed installations. The most common BAT reference document in Denmark is the BREF for pig and poultry farming—there are approximately 1200 farms in Denmark [48,49].

The Environmental Protection Act is based on the principle of decentralization. This means that the administration and application of most regulations are in the hands of the municipalities that issue the permit. An integrated licensing system is enshrined in part of the Environmental Protection Act. The categories subject to approval are listed in Appendix 1 and 2 of Act No. 1458 of 12 December 2017, namely, 6.6 Livestock [50].

Since 2007, livestock farms have been subject to a comprehensive environmental permit system, which the Law provides on Livestock No. 1020 of 7 June 2018. The Act stipulates (Chapter 3, §16a.) that without prior permission, a local council may not have established livestock operations with an NH_3 emission higher than 3500 kg $NH_3 \cdot$animal place$^{-1} \cdot$year^{-1}. They use their own emission factors to estimate NH_3 emissions [51].

2.7. Estonia

In Estonia, the European IPPC Directive is being implemented with the help of:
- The Air Protection Act (RT I, 7 June 2015, 1), valid from 30 September 2004, partially since 27 November 2004 [52];
- The Industrial Emissions Act (RT I, 4 July 2017, 1) valid from 1 June 2013 [53].

According to Section 19, paragraph 3, a Government Regulation was issued with a list of partial activities requiring an integrated permit to operate facilities (RT I, 25 September 2018, 4), valid from 14 June 2013. According to this Regulation, the holdings requiring an integrated permit correspond exactly to the holdings under Directive 2010/75/EU [54].

The Environment Council issues the permit, issued for an indefinite period. The application is submitted through the environmental information system and is confirmed by a digital signature. In the case of non-compliance, the farm may be closed, and a fine of up to €32,000 may be imposed. The EMEP/EEA Tier 1 and 2 methodologies are used to estimate emissions. In Estonia, sampling from regional sources and analysis of pollutants (including NH_3) is performed by the Air Quality Management Department of the Estonian Center for Environmental Research. The measurement results are further published by the Environmental Agency of the Republic of Estonia [54–56].

2.8. Finland

Directive 2010/75/EU of the European Parliament and the Government has been implemented in Finland by the Law on Environmental Protection No. 527/2014 of 27 June 2014 [57]. Annex I of this law lists the installations for which a permit is required. The list of facilities follows the European directive.

The State Environmental Permit Authority has issued the permit based on an authorization from Decree No. 713/2014. The Center for Trade, Transport, and Environment monitors compliance with the requirements of the integrated permit. The issued per-

mit is valid for an indefinite period. Own emission factors are used to estimate NH_3 emissions [58].

2.9. France

France implements Directive 2010/75/EU in its legal order by Decree No. 2013-375 of 2 May 2013, modifying the classification tables of installations covered by the integrated permit from the Environmental Protection Act defined in Article R511-9 of this Act (Annex 3—pig farms are in category No. 2102; poultry farms are in category No. 2111). Intensive livestock farming was classified in category 3660 and complied with the European IPPC Directive. Own methods are used to estimate NH_3 emissions [59,60].

The Directive 2010/75/EU covers approximately 3400 holdings (approximately 50% of the holdings covered by this Directive). Most of them are located in the Brittany region. In France, farms produce about 75% of total NH_3 emission [61].

In the case of non-compliance with emission and air pollution limits, the owner is threatened with imprisonment for two years and a fine of €75,000 [62].

2.10. Germany

Germany implements and applies the Directive through its Industrial Emissions Directive Implementation Act and two Decrees of national law from 2 May 2013. The amendments were first made to the Pollution Control Laws, the Water law, and the Recycling law. These modifications have led to an amendment to the Regulation on equipment requiring approval [63–67].

Currently, there is a legal framework regulating emissions from livestock production facilities in general. In addition, there are specific regulations for livestock farming in critical areas, such as near residential areas. The emission reduction measures to be taken are particular and may vary according to the location of the building and the size of the livestock facilities. The choice of equipment or their combination for reducing emissions then depends only on the owner's choice, who must meet the limits. Own emission factors are used to estimate NH_3 emissions [68].

Building new facilities or expanding existing facilities over the stated limit (Table 1) requires only a construction permit or simplified management of the IPPC permit according to §19, without public participation. If the IPPC farm size values are exceeded, the issue is addressed through the Emissions Act, and automatically, the approval process must include public participation. It is controlled by the Technical Instructions on Air Quality Control (TA-Luft). TA-Luft requires the authorities to confirm that future NH_3 emissions from the planned project will not have negative local effects on the environment. For this purpose, it specifies minimum distance from vulnerable ecosystem requirements for animal housing facilities [68].

Table 1. Threshold capacities for integrated permits in Germany [69].

Livestock Category	Breeding Size for Simplified IPPC Procedures (pc)	Breeding Size for Full IPPC Procedures (pc)
Fattening pigs (>30 kg)	1500	2000
Sows (including piglets < 30 kg)	560	750
Piglets (10–30 kg)	4500	6000
Laying hens	15,000	40,000
Pullets	30,000	40,000
Broilers	30,000	40,000
Turkeys	15,000	40,000

The legal basis for the control of NH_3 emissions from livestock is:

- Federal Law on Emission Control and its transposed legislation TA-Luft adopted pursuant to §48 BlmSchG;
- Environmental Impact Assessment Act;
- Habitats Directive (Council Directive 92/34/EEC) of 21 May 1992 in connection with the Nature Conservation Act, in particular §34 and §36, which implement the Habitats Directive in national law [68].

2.11. Great Britain

The implementation of the IPPC Directive into the legal system of the United Kingdom of Great Britain and Northern Ireland has been effected by the Pollution Prevention and Control Act of 1999 [70]. The implementation of European Directive 2010/75/EU took place individually in each country:

I.   Scotland

Regulation on the change of pollution prevention and control 2014 [71].

II.   Northern Ireland

Pollution Prevention and Control Regulation for industrial emissions 2013—Industrial Emissions [72].

III.   Britain and Wales

Pollution Prevention and Control Regulation 2019 [73].

2.12. Greece

The implementation of Directive 2010/75/EU in Greece has been effected with the help of Joint Ministerial Decision 36060/1155/E.103/2013-Official Gazette of the Government No. 1450/B/14-6-2013 in the Law on Environmental Protection No. 1650/1986. Ministerial Decision 36060/1155/E.103/2013 defines the works covered by the integrated permit in Annex I and amends them following EU legislation. Licenses are allocated according to the amendments to the law 4014/2011 (Official Gazette 290/A/2011). The EMEP/EEA Tier 1 methodology is used to estimate emissions. The competent environmental authority issues the permit. The application shall be submitted together with the EIA documentation. In the event of non-compliance, the farm may be closed, and the owner may be fined between €1000 and €60,000 [74–76].

2.13. Hungary

Hungary has incorporated the IPPC Directive into its legal system by Government Decree No. 193/2001—implementing rules for integrated environmental permitting and subsequently, No. 314/2015—environmental impact assessment and approval procedure for integrated environmental permits, according to the law LIII 1995 on general rules for environmental protection. Government Decree No. 314/2015 in Annex 2, category 11-Intensive livestock production lists the farms that fall under the IPPC Directive and must apply for an integrated permit. These farms fully comply with European Directive 2010/75/EU. The Environmental Office issues the permit [77–79].

The permit is usually issued for at least ten years. If an installation has previously had a problem with environmental pollution or was applying for a permit for the first time, the permit may be issued for a period of five years.

In the event of an installation owner without a valid permit, the competent authorities may restrict, suspend, or stop the operation of the installation. Simultaneously, a fine of €140–280 per day is imposed, depending on the degree of environmental risk. The EMEP/EEA Tier 1 and 2 methodologies are used to estimate emissions [79,80].

2.14. Ireland

The implementation of the IPPC Directive in Ireland has been performed with the assistance of:

- The Waste Management Act 1996;
- The Planning and Development Act 2000;
- The Environmental Protection Agency Act 1992 [81–83].

The implementation was effected with the help of the statutory instrument SI. No. 137/2013. Annex I, category 6 of the Environmental Protection Law, which defines the intensive farms that must apply for an integrated permit following part IV [84].

The Environmental Protection Agency (EPA), which issues integrated permits, is also responsible for monitoring them. The license can be inspected at any time after issue, but no later than three years. The license shall be terminated if the breeding has not started operating within three years of its issuance or if the breeding has ceased in the last three years [83].

Ireland's basic approach to establishing intensive farms is to locate them at a sufficient distance from residential and odour-sensitive areas. These distances are determined based on an odour dispersion model. The EMEP/EEA Tier 2 methodology is used to estimate emissions [85].

TEAGASC finances measurement of pollutant emissions from livestock farms in Ireland; the Irish National Institution for Agriculture and Food Development provides integrated research, advice, and training services to the agri-food industry and rural communities. The LowAmmo project was set up for precise measurement and focuses on critical knowledge gaps in Irish NH_3 emissions. This project (LowAmmo) includes measuring, modeling, and reducing emissions of NH_3 from large livestock farms [82,86,87].

2.15. Italy

The IPPC Directive was introduced into Italian law by Legislative Decree No. 372 of 4 August 1999 on the implementation of Directive 96/61/EC on integrated pollution prevention and control, and later by the Legislative Decree No. 59 of 18 February 2005. The legislative decrees have been amended several times, and the most significant change was Legislative Decree No. 152 of 3 April 2006, which incorporated Directive 2001/80/EC into its legislation. This Regulation is supplemented by Legislative Regulation No. 46 of 4 March 2014, following European Union Directive 2010/75/EU. Following these amendments, Annex VIII, Part II of Regulation 152/06 lists the activities that require applying for an integrated permit. In agriculture, the conditions are identical to those set out in Directive 2010/75/EU. Three authorities issue the permit:

- The Ministry of Agriculture;
- The Ministry of the Environment;
- Local authorities.

It is issued for 5 or 8 years, using values for fulfillment of the criteria [88–91].

Non-compliance with emission and air pollution limits could result in owner suspension and a fine of between €35,000 and €100,000. Own emission factors are used to estimate NH_3 emissions [89].

2.16. Latvia

The implementation of European Directive 2010/75/EU has been effected by the amendment of the Pollution Act of 15 March 2001, which set new conditions for the categories of permits for polluting activities and the implementation of these activities. Furthermore, the Directive was also incorporated into the Environmental Impact Assessment Act of 14 October 1998. The permit is issued for the entire period of operation of the installation. The EMEP/EEA Tier 2 methodology is used to estimate emissions [92–94].

2.17. Lithuania

The IPPC Directive has been implemented by the Declaration of the Minister of Environment No. 80. The amended IPPC Directive 2010/75/EU is written in the Lithuanian Law on Environmental Protection No. I-2223 of 30 January 1992. The issuance of an integrated permit shall take place following Regulation No. D1-528. Annex I to this

Regulation lists the limit parameters for installations submitted for an integrated permit (the installation requirements correspond to the European Directive) [95–98].

The Environmental Protection Agency issues the operating permit. Compliance with the conditions specified in the integrated permit is controlled by the Ministry of Environment of the Republic of Lithuania. The permit is issued for an indefinite period and may be revoked for the reasons stated in Regulation No. D1-528, chapter XII. The EMEP/EEA Tier 1 methodology is used to estimate emissions [97].

2.18. Luxembourg

Luxembourg incorporates Directive 2010/75/EU into its legal system through the Environment Act. Installations that must apply for an integrated permit are listed in Annex II of this law. The criteria have not been tightened [99,100].

2.19. Malta

Regulation S.L.549.77 transposes the European Industrial Emissions Directive 2010/75/EU into the legal system of Malta, and at the same time implements the framework for the regulation of industrial emissions S.L.549.76. Annex I, Regulation S.L.549.77, lists the installations that must apply for an integrated permit. The Environment and Resource Authority issues the permit. An owner who violates the provisions of Regulation S.L.549.77 may be penalized:

- For a first conviction, a fine of €23,000–233,000 or a maximum term of imprisonment of 2 years, or both;
- For the second and subsequent convictions, a fine of €46,000–466,000 or a maximum term of imprisonment of 2 years, or both [101–105].

2.20. Netherlands

The Netherlands implemented the Industrial Emissions Directive into its legislation by the Environmental Law-General Provisions of 6 November 2008. The Directive has been incorporated into the Act through two amending acts: Gazette 2012, 552 and Gazette 2013, 159. The Environmental Act defines the term IPPC installation, which uses a direct reference to the definitions of industrial emission installations in Annex I, Directive 2010/75/EU. Own emission factors are used to estimate emissions [106–109].

2.21. Poland

Poland integrates the Industrial Emissions Directive into its Environmental Protection Act. The Law from Article 236b refers to Annex I of Regulation 166/2006, which lists the facilities subject to the reporting obligation (category 7). This Annex is identical to Annex I of European Directive 2010/75/EU. The Ministry of Environment issues the permit [110–112].

The permit may be restricted or revoked if the installation owner violates the permit conditions, either regarding environmental protection or the endangerment of human health. In the event of a violation of the conditions of the permit, the facility risks a fine ranging from €11,000 to 110,000. The EMEP/EEA Tier 2 methodology is used to estimate emissions [112].

2.22. Portugal

Portugal transposed the IPPC Directive into its legal system by Legislative Decree No. 194/2000 of 21 August 2000, which was repealed by Legislative Decree No. 173/2008 of 28 August. Directive 2010/75/EU of the European Parliament and the Council was transposed into Portuguese legislation by Regulation No. 127/2013 of 30 August 2013. Installations are subject to an application for an integrated permit, therefore following the European Directive. In 2015, the Portuguese Government had issued Legislative Decree No. 75/2015 of 11 May 2015, approving the unified environmental licensing system. The EMEP/EEA Tier 2 methodology is used to estimate emissions [113–116].

2.23. Republic of Cyprus

The incorporation of the IPPC Directive into the Republic of Cyprus's legal order took place in the Water Pollution Control Act No. 106 (I)/2002. European Directive 2010/75/EU is integrated into Republic of Cyprus law by the Industrial Emissions Act No. 184 (I)/2013. This Law was amended in 2016 by Act No. 131 (I)/2016. Installations that must apply for an integrated permit are listed in Annex I, Act No. 184 (I)/2013, and fully follow the European Directive [117–119].

In the event of a breach of the terms of the integrated license, the licensee may be imprisoned for a maximum of three years or fined up to €500,000, or both. The EMEP/EEA Tier 2 methodology is used to estimate emissions [118,120].

2.24. Romania

The European Industrial Emissions Directive 2010/75/EU in the Romanian legal system has been implemented by Law No. 278/2013 on industrial emissions. Annex I of this law lists the facilities obliged to apply for an integrated permit. The equipment list is identical to the conditions set out in Directive 2010/75/EU [121].

The National Environmental Protection Agency issues the permit. The National Environmental Guard monitors compliance with permit conditions. Violation of the conditions of the integrated permit is punishable according to chapter XV, Article 96, Regulation No. 195/2005 on environmental protection. The EMEP/EEA Tier 2 methodology is used to estimate emissions [122,123].

2.25. Slovak Republic

The Slovak Republic has implemented the IPPC Directive into its legal system by Act No. 245/2003 of 19 June on integrated pollution prevention and control. Directive 2010/75/EU has been included in the laws of Slovakia by act No. 39/201379, and the Law was amended several times during its validity—the last time by act No. 193/2018 Coll., on 13 June. The parameters of the facilities that must apply for an integrated permit (Annex I, Law No. 39/2013 Coll.) have been taken from the European Directive, and they are fully compliant with it. The Ministry of Environment of Slovakia issues the permit; the Slovakia Inspectorate performs administrative supervision for Environmental Protection and imposes fines. If the conditions specified in the license are violated, the owner may be fined up to €1,000,000, following Article 37 of Act No. 39/2013. The EMEP/EEA Tier 2 methodology is used to estimate emissions [124,125].

2.26. Slovenia

The transposition of Directive 2010/75/EU of the European Parliament and the Government has been performed according to the Law on Environmental Protection. Installations required to apply for an integrated permit are defined in Annex I of the Regulation on the type of activities and installations that may cause large-scale pollution [126,127].

The Environmental Inspectorate performs control of environmental permits. Penalties related to violation of the conditions for issuing an integrated permit and the conditions specified therein are defined in chapter VII, Article 27, decrees on the type of activities and facilities that can cause pollution on a large scale. The EMEP/EEA Tier 2 methodology is used to estimate emissions [127,128].

2.27. Spain

The Ministry of Agriculture, Fisheries, and Food of Spain have established the ECO-GAN programme following European Directive 2010/75/EU, through which farmers can identify:

- Emissions of NH_3 and nitrogen oxides from the farm;
- Nitrogen emissions from sludge, manure, etc.

This programme enables farmers to appreciate their farms and introduces them to new reduction techniques related to pollutant emissions [129].

The Spanish Emission Records System is responsible for calculating the total emissions of all these pollutants for each category and activity of livestock following international EU regulations. The Directorate-General for Livestock Production is responsible for preparing methodological guidelines for determining emissions from livestock farming [130].

The implementation of Directive 2010/75/EU was effected by Law No. 16/2002 of 1 July on integrated pollution prevention and control, which was later amended by Royal Decree-Law No. 1 of 16 December 2016, approving the revised text of the Act on Integrated Pollution Prevention and Control. Livestock holdings covered by the integrated permit are listed in Annex I, category 9.3. The border capacities of intensive agriculture are within the lines of the European Directive [131,132].

The integrated permit is issued by the competent body of the autonomous administration. In the case of a change in breeding parameters with approval, there are two different situations:

- There is a slight change of breeding parameters, in which the owner notifies the competent authorities only with appropriate justification. This change is approved by the authority in an accelerated procedure;
- There is a significant change in the breeding parameters when assessing the operation and a new integrated permit is needed.

In the case of a severe breach of the integrated permit, the owner may be subject to sanctions ranging from €200,000 to €2,000,000; complete, partial, or temporary closure of the installation; or revocation of the permit.

In the event of a serious offense, there is a risk of sanctions ranging from €20,000 to €200,000, temporary or partial closure of the facilities for a maximum of two years, closure for a maximum of one year, or suspension of authorization of the permit for a maximum of one year. In the case of minor offenses, there is a risk of a fine of up to €20,000. The EMEP/EEA Tier 2 methodology is used to estimate emissions [132,133].

2.28. Sweden

The implementation of European Directive 2010/75/EU into the Swedish legal system was effected by Regulation SFS 2013:251, as amended by SFS 2016:1188. Installations for which a permit is needed are listed in Chapter 2, Section 1, and are within the lines of the European Directive [134,135].

The permit is issued by the Swedish Environmental Protection Agency based on SFS Regulation 1998:899, as amended by SFS Regulation 2013:262. The EMEP/EEA Tier 2 methodology is used to estimate emissions [136–138].

3. Summary and Discussion

3.1. Implementation IPPC Directive

All of the member states of the EU have implemented Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) into their national legislation. In particular, implementation has been carried out in the legislation on environmental and air protection, industrial emissions, integrated pollution prevention and control, and environmental impact assessment. Ireland has incorporated it in the Waste Management and Planned Development Act, Flanders in the Environmental Licensing Regulations. For most countries, there is a drive to centralize decision-making powers, such as in Austria, where state powers prevail over the federal state (region, province, etc.). Conversely, a decentralization approach has been taken in Belgium, where the primary responsibility lies with the autonomous regions (Flanders, Wallonia, and Brussels), and similarly in Great Britain, Spain, and Denmark (individual municipalities issue permits).

Annex 1 of Directive 2010/75/EU defines the activities covered by the Act. Category 6.6 includes agricultural activities—intensive poultry and pig farms with space for more than 40,000 poultry, 2000 fattening pigs weighing more than 30 kg, or 750 sows. All EU countries have adopted these values. Only Germany has tightened these thresholds; see

Table 1. For the construction of new installations or the extension of existing installations above the threshold, a simplified IPPC permit procedure must be carried out without public participation. If the size of the accommodation exceeds the IPPC set size, this is dealt with through the Emissions Act, and public participation must automatically be part of the approval process.

For violation of the legislation in effect or for operating without a permit, the operator is mainly subject to financial penalties ranging from €1000–60,000 (Greece) to €200,000–€2,000,000 (Spain), but also to revocation (France, Malta, Republic of Cyprus). In most countries, licenses are issued for an indefinite period, except for Hungary (10 years.) and Italy (5–8 years.).

3.2. Implementation of the NH_3 Emission Estimations Approach in EU Countries

According to Commission Implementing Decision (EU) 2017/302 of 15 February 2017, laying down BAT conclusions under Directive 2010/75/EU of the European Parliament and the Council for intensive poultry or pig farms, three approaches can be taken to monitor NH_3 emissions.

The first approach is to estimate annual NH_3 emissions using emission factors. Emission factors are designed according to national or international protocols. The total annual NH_3 emissions estimate is calculated from animal occupancy and multiplied by the emission factor for the corresponding animal category. Countries that use their national protocols to determine emission factors are listed below. Individual countries determine the emission factors based on experimental measurements, scientific studies, and outputs from research institutes. Table 2 shows the total emission factors, consisting of sub-emission factors representing housing, storage, and landspreading. EU countries have different approaches to setting emission factors. Germany has set high emission factors compared to the Netherlands, which has emission factor values defined at low levels. The Czech Republic is currently reviewing its emission factors to refine them. The member states that follow the methodology for determining emission factors are:

- Czech Republic (CR) [139];
- Denmark (DK) [140];
- Germany (GE) [141];
- Great Britain (GB) [142];
- Finland (FI) [58];
- Italy (IT) [143]
- Netherlands (NL) [144].

Table 2. NH_3 emission factors for selected livestock in kg NH_3·animal place^{-1}·year^{-1}.

Livestock	Manure Type	DK	GE	IT	NL	FI	GB	CR
Dairy cows	Slurry Manure	13.55	67.05	44.44	11.70	29.46	29.34	24.50
Other cattle	Slurry Manure	3.44	26.71	20.43	4.30	11.66	13.17	14.50 / 13.70
Fattening pigs	Slurry Manure	1.22	9.54	5.09	1.00	4.91	6.76	8.30/5.50 [1]
Sows	Slurry Manure Outdoors			10.52		10.47	7.95	11.90/19.70 [2]
Laying hens	Litter Droppings	0.21 -	0.62	0.22	0.13	0.25	0.25	0.27
Broilers	Litter	0.07	0.26	0.15	0.03	0.18	0.42	0.21
Turkeys	Litter	0.52	1.44	0.35	0.97	0.29	0.66	0.73
Ducks	Litter	0.01	0.31		0.20	0.20	0.24	
Geese	Litter		0.39					

[1] piglets; [2] gestating sows.

The second approach is to estimate annual NH$_3$ emissions using a mass balance based on excluding total nitrogen or TAN at different stages of manure handling. The NH$_3$ emissions are estimated by the amount of nitrogen excreted by each animal category, and by using the total nitrogen or TAN flux and the leaching coefficients for each phase of manure handling (housing, storage, and landspreading). The leaching coefficients are determined according to national or international protocols—the countries listed below use the international Tier methodology, Tier 1 and Tier 2.

The member states that set values using the Tier 1 methodology:

- Austria;
- Bulgaria;
- Greece;
- Lithuania;
- Malta.

The member states following the Tier 2 methodology:

- Belgium (Wallonia Region);
- Croatia;
- Ireland;
- Latvia;
- Poland;
- Portugal;
- Republic of Cyprus;
- Romania;
- Slovak Republic;
- Slovenia;
- Spain;
- Sweden.

Countries that use a combination of Tier 1 and Tier 2 methodologies with respect to livestock category:

- Estonia;
- Hungary.

The overview shows that most countries using mass balance estimation of annual NH$_3$ emissions use the international Tier by EMEP/EEA methodology and preferably use the Tier 2 methodology. The authors of the paper could not find any supporting evidence that would indicate the approach of Luxembourg.

France has developed a methodology which specifically states factor emissions from farms, storage, and manure application, and only then is the total NH$_3$ emissions recalculated [61]. In the Flemish Region of Belgium, an own methodology is also applied, which is called RAV (Regeling Ammoniak en veehouderij) [32].

Estimating annual NH$_3$ emissions by calculation using emission factors and estimation using mass balance can be reduced by the percentage of the functionality of the BAT used in the farms to reduce NH$_3$ emissions. These BATs and their percentage effectiveness in reducing NH$_3$ emissions can be found in Directive 2010/75/EU of the European Parliament and of the Council, the BAT conclusions of Directive 2010/75/EU, and national or international protocols approved in the country concerned.

Another approach for determining NH$_3$ emissions is to calculate them from NH$_3$ concentration and air ventilation rates. NH$_3$ is monitored for at least six days over one year. These days are determined by animal category. Due to this method's financial cost and time consumption, it is rarely used to measure annual emissions. This approach is mainly used to compare and verify the previous two approaches and also to verify the effectiveness of BAT.

To refine the measurements and address some key knowledge gaps in NH$_3$ emissions, the LowAmmo project was established in Ireland. The LowAmmo project involves measuring, modeling, and abating NH$_3$ emissions from livestock farms [86,145]. In the

Czech Republic, the Ministry of Agriculture monitors NH_3 emissions in selected intensive livestock farms in this way every year.

4. Conclusions

The study reviewed EU countries' approaches to estimating NH_3 emissions and implementing IPPC in their laws and decrees. Most countries accepted the European Commission's proposal and retained the recommended threshold for placing farms under IPPC (space for more than 40,000 poultry, 2000 fattening pigs weighing more than 30 kg, or 750 sows). Differences were found in approaches to estimating NH_3 emissions. The most widely used approach was to estimate emissions using a mass balance based on excluding total nitrogen or TAN at different stages of manure handling. In this approach, EU countries differentiate themselves by using methodologies Tier 1 and Tier 2. The estimation approach using emission factors is also popular. However, there is a difference in the determination of the relevant emission factors between EU countries. This is mainly due to differences in breeding technology, breeds or climatic conditions. From the information provided in this review, it can be argued that, despite their different approaches, EU country leaders are interested in using approaches and methodologies that reflect the realities in their countries, in particular, to estimate annual NH_3 emissions.

When issuing integrated permits for new or existing farms, it is essential to consider all environmental components. It is essential to avoid disputes with residents in the vicinity of farms. A particular issue is dealing with people's complaints about odours from intensive livestock farming and the application of manure (landspreading). Odour emissions are influenced not only by the distance of farms from inhabited areas but also by breeding technology, animal category, the use of BAT, climatic conditions, the time of year, the prevailing wind direction, or the terrain. By appropriate measures and approaches implemented in the integrated permit, these disputes can be avoided.

A major challenge in monitoring NH_3 emissions from intensive livestock farms is to refine the methodology for estimating annual NH_3 emissions. Some emission factors and approaches may already be outdated or inadequate due to animal breeding and feed conversion, new housing technologies, and BAT technologies used in the farms.

On the basis of the current revision (April 2022) of Directive 2010/75/EU of the European Parliament and the Council on industrial emissions (Directive IED), a reduction in the thresholds for pig and poultry numbers and an extension of the cattle category are being considered. The implementation of the Directive is planned for 2030. This modification and the introduction of the associated BAT are expected to reduce NH_3 emissions by 128 kt·year^{-1}. This will have significant benefits for the environment and human health.

References

1. Gerber, P.J.; Steinfeld, H.; Henderson, B. *Tempio Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013.
2. Gilchrist, M.J.; Greko, C.; Wallinga, D.B.; Beran, G.W.; Riley, D.G.; Thorne, P.S. The Potential Role of Concentrated Animal Feeding Operations in Infectious Disease Epidemics and Antibiotic Resistance. *Environ. Health Perspect.* **2007**, *115*, 313–316. [CrossRef] [PubMed]
3. Hoffmann, I. Livestock biodiversity and sustainability. *Livest. Sci.* **2011**, *139*, 69–79. [CrossRef]
4. Moreau, P.; Ruiz, L.; Vertès, F.; Baratte, C.; Delaby, L.; Faverdin, P.; Gascuel-Odoux, C.; Piquemal, B.; Ramat, E.; Salmon-Monviola, J.; et al. CASIMOD'N: An agro-hydrological distributed model of catchment-scale nitrogen dynamics integrating farming system decisions. *Agric. Syst.* **2013**, *118*, 41–51. [CrossRef]
5. Sommer, S.; Østergård, H.; Løfstrøm, P.; Andersen, H.; Jensen, L. Validation of model calculation of ammonia deposition in the neighbourhood of a poultry farm using measured NH_3 concentrations and N deposition. *Atmos. Environ.* **2009**, *43*, 915–920. [CrossRef]
6. EEA. Air Quality in Europe. Publications Office of the European Union. 2017. Available online: https://www.eea.europa.eu/publications/air-quality-in-europe-2017 (accessed on 5 November 2021).
7. Webb, J.; Menzi, H.; Pain, B.F.; Misselbrook, T.H.; Dämmgen, U.; Hendriks, H.; Döhler, H. Managing ammonia emissions from livestock production in Europe. *Environ Pollut.* **2005**, *135*, 399–406. [CrossRef] [PubMed]
8. Oenema, O.; Oudendag, D.; Velthof, G.L. Nutrient losses from manure management in the European Union. *Livest. Scie.* **2007**, *112*, 261–272. [CrossRef]
9. DC. Council Directive 91/676/EEC Concerning the Protection of Waters against Pollution Caused by Nitrates from Agricultural Sources. Official Journal of the European Communities. 1991. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676&from=EN (accessed on 25 October 2021).
10. Martinez, J.L. Environmental pollution by antibiotics and by antibiotic resistance determinants. *Environ. Pollut.* **2009**, *157*, 2893–2902. [CrossRef] [PubMed]
11. EEA. European Union Emission Inventory Report 1990–2015 under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP). Publications Office of the European Union. 2017. Available online: https://www.eea.europa.eu//publications/annual-eu-emissions-inventory-report (accessed on 5 November 2021).
12. UNECE. Protocol to Abate Acidification Eutrophication and Ground-Level Ozone to the Convention on Long Range Transboundary Air Pollution. United Nations Economic Commission for Europe. 2013. Available online: https://unece.org/environment-policy/air/protocol-abate-acidification-eutrophication-and-ground-level-ozone (accessed on 5 November 2021).
13. Giner, S.G.; Georgitzikis, K.; Scalet, B.M.; Montobbio, P.; Roudier, S.; Sancho, L.D. *Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*; Publications Office of the European Union: Luxembourg, 2017.
14. DC. Council Directive 96/61/EC Concerning Integrated Pollution Prevention and Control. Official Journal of the European Communities. 1996. Available online: https://leap.unep.org/countries/eu/national-legislation/council-directive-9661ec-concerning-integrated-pollution (accessed on 20 June 2021).
15. DC. Council Directive 2010/75/EC on Industrial Emissions (Integrated Pollution Prevention and Control). Official Journal of the European Communities. 2010. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:334:0017:0119:en:PDF (accessed on 20 October 2021).
16. EC. Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs, under Council Directive 96/61/EC. European Commission. 2003. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/419/dokumente/bvt_intensivtierhaltung_zf_1.pdf (accessed on 30 November 2021).
17. EC. Commission Implementing Decision (EU) 2017/302 of 15 February 2017 Establishing Best Available Techniques (BAT) Conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for the intensive Rearing of Poultry or Pigs. Official Journal of the European Union. 2017. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D0302&from=E (accessed on 5 November 2021).
18. Swelum, A.A.; El-Saadony, M.T.; El-Hack, M.E.A.; Ghanima, M.M.A.; Shukry, M.; Alhotan, R.A.; Hussein, E.O.; Suliman, G.M.; Ba-Awadh, H.; Ammari, A.A.; et al. Ammonia emissions in poultry houses and microbial nitrification as a promising reduction strategy. *Sci Total Environ.* **2021**, *781*, 146978. [CrossRef]
19. EMEP/EEA. EMEP/EEA Air Pollutant Emission Inventory Guidebook—2019, Technical Guidance to Prepare National Emission Inventories. European Environmental Agency. 2019. Available online: https://www.eea.europa.eu//publications/emep-eea-guidebook-2019 (accessed on 5 November 2021).
20. VERA. VERA Test Protocol for Livestock Housing and Management Systems. Verification of Environmental Technologies for Agricultural Production. 2018. Available online: https://www.vera-verification.eu/app/uploads/sites/9/2019/05/VERA_Testprotocol_Housing_v3_2018.pdf (accessed on 5 November 2021).
21. EMEP/EEA. EMEP/EEA GuideBook 2016—Tier 1, Tier 2: Agriculture—3.B Manure Management. European Environmental Agency. 2016. Available online: https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/4-agriculture/3-b-manure-management-2016/view (accessed on 5 November 2021).

22. Austria. List of IPPC Activities Used in the EDM. Federal Environmental Agency. 2020. Available online: https://secure.umweltbundesamt.at/edm_portal/cms.do?get=/dam/jcr:f01be7f3-9ff1-4067-a537-b59845c36f7e/EDM%20-%20Kategorien%20der%20IPPC%20T%25C3%25A4tigkeiten%20Version%201.0%20vom%2001.01.2014.pdf (accessed on 20 December 2021).

23. Austria. Austria's air emission projections 2021 for 2020, 2025 and 2030. 2021. Available online: https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0769.pdf (accessed on 5 December 2021).

24. Austria. Trade Regulations, Jusline. 1994. Available online: https://www.jusline.at/gesetz/gewo (accessed on 5 December 2021).

25. Austria. Questionnaire on the IPPC-Directive for the Annual Conference in Stockholm. EUFJE. 2009. Available online: https://www.eufje.org/images/docConf/sto2009/AT%20sto2009.pdf (accessed on 8 December 2021).

26. Austria. GewO § 366 Penal Provisions. Jusline. 1994. Available online: https://www.jusline.at/gesetz/gewo/paragraf/366 (accessed on 8 December 2021).

27. Ander, M.; Friedrich, A.; Haider, S.; Kriech, M.; Lampert, C.; Moosmann, L.; Pazdernik, K.; Pfaff, G.; Pinterits, M.; Poupa, S.; et al. Austria's National Inventory Report 2016. Umweltbundesamt GmbH. Available online: http://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0565.pdf (accessed on 3 December 2021).

28. Austria. Federal Law Consolidated: Entire Legislation for Waste Management Act. RIS. 2002. Available online: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20002086 (accessed on 8 December 2021).

29. Belgium. Integrated Pollution Prevention and Control-installations. Department Omgeving. 2013. Available online: https://omgeving.vlaanderen.be/gpbv-installaties (accessed on 1 December 2021).

30. Lavrysen, L.; The Implementation of the IPPC-Directive in Belgium. EU Forum of Judges for the Environment. 2009. Available online: https://www.eufje.org/images/docConf/sto2009/BE%20sto2009.pdf (accessed on 30 November 2021).

31. Belgium. Environmental Permitting Decree on the Environmental Permit. Flemish Government. 2016. Available online: https://navigator.emis.vito.be/pdfservlet?woId=297&woLang=nl&version=2016-03-31&compareVersion=2016-03-31&lang=nl (accessed on 1 December 2021).

32. IBGE-BIM. Informative Inventory Report. Government of Belgium. 2018. Available online: http://www.irceline.be/nl/luchtkwaliteit/emissies/IIR_BE.pdf (accessed on 3 December 2021).

33. VLAREM II. Decree of the Flemish Government Concerning General and Sectoral Provisions on Environmental Hygiene. Flemish Government. 1995. Available online: https://navigator.emis.vito.be/mijn-navigator?woId=10046 (accessed on 1 December 2021).

34. VLAREM III. Decision of the Flemish Government on Additional General and Sectoral Environmental Conditions for IPPC Installations. *Flemish Government.* 2014. Available online: https://navigator.emis.vito.be/mijn-navigator?woId=61471 (accessed on 1 December 2021).

35. Belgium. Decree on Environmental Permits. Belgium Monitoring. 1999. Available online: http://www.ejustice.just.fgov.be/cgi_loi/change_lg.pl?language=nl&la=N&cn=1999031139&table_name=wet (accessed on 1 December 2021).

36. VMM. Belgium's Greenhouse gas Inventory (1990-2014). ECONOTEC. 2016. Available online: https://www.klimaat.be/files/5414/6116/1810/BELGIUM_NIR_2016_120416.pdf (accessed on 3 December 2021).

37. Belgium. Ordinance on Environmental Permits. Belgium Monitoring. 1997. Available online: http://www.ejustice.just.fgov.be/cgi_loi/change_lg.pl?language=nl&la=N&cn=1997060533&table_name=wet (accessed on 1 December 2021).

38. Bulgaria. Environmental Protection Act. Bulgaria Government. 2002. Available online: https://www.moew.government.bg/static/media/ups/tiny/filebase/Industry/Legislation/Zakoni/English_versions/Environmental_Protection_Act.pdf (accessed on 1 December 2021).

39. Bulgaria. Bulgaria's Informative Inventory Report 2018. Bulgarian Government. Available online: http://cdr.eionet.europa.eu/bg/un/clrtap/iir/envwqkz5a/IIR_2018_BG.pdf (accessed on 3 December 2021).

40. Valkova, V.; Andonova-Rangelova, E.; Bulgaria Environment. Mondaq 2013. Available online: https://www.mondaq.com/waste-management/206920/environment-2013--bulgaria (accessed on 1 December 2021).

41. NASEM. National Automated System for Environment Monitoring, Emissions Control of Harmful Substances in Atmospheric Air. Executive Environment Agency. 2008. Available online: http://eea.government.bg/en/cds/iaos11.htm (accessed on 3 December 2021).

42. Croatia. Regulation on the Procedure for Establishing Integrated Environmental Protection Requirements. Government of the Republic of Croatia. 2008. Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2008_10_114_3301.html (accessed on 3 December 2021).

43. Croatia. Environmental Protection Act. Government of the Republic of Croatia. 2013. Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2013_06_80_1659.html (accessed on 3 December 2021).

44. Poljanac, M.; Marković, B.; Švedek, I.; Hublin, A.; Kos, R.; Herenčić, L.; Delija-Ružić, V.; Abrashi, A. Informative Inventory Report (1990–2016), EKONERG. 2018. Available online: http://cdr.eionet.europa.eu/hr/un/clrtap/iir/envwqjz5w/IIR_CROATIA_2018_v3.pdf (accessed on 3 December 2021).

45. Czech Republic. Law on Integrated Pollution Prevention and Control, on the Integrated Pollution Register and on Amendments to Certain Acts (Integrated Prevention Act). Collection of Laws. 2002. Available online: https://www.zakonyprolidi.cz/cs/2002-76/zneni-20220201 (accessed on 1 December 2021).

46. Denmark. Ordinance of the Law on Environmental Protection. Retsinformation. 2018. Available online: https://www.retsinformation.dk/eli/lta/2018/1121 (accessed on 1 December 2021).

47.   Denmark. EIA Directive Annex 1. Ministry of Environment of Denmark. 2011. Available online: https://eng.mst.dk/trade/industry/environmental-permits-for-industry/annex-1-industrial-activities/ (accessed on 3 December 2021).

48.   Djurhuus, H.; Hemmer, P.; Vilsbøll, A.S.K.; Bech-Bruun, J.B.; Environmental Law and Practice in Denmark: Overview. Thomas Reuter Practical Law. 2017. Available online: https://uk.practicallaw.thomsonreuters.com/0-522-0619?transitionType=Default&contextData=(sc.Default)&firstPage=true&comp=pluk&bhcp=1 (accessed on 3 December 2021).

49.   Denmark. BAT—Best Available Techniques. *Ministry of Environment of Denmark.* 2021. Available online: https://eng.mst.dk/trade/industry/environmental-permits-for-industry/environmental-permits-for-industrial-activities-listed/bat/ (accessed on 3 December 2021).

50.   Denmark. Ordinance on the Approval of Listed Companies. Retsinformation. 2017. Available online: https://www.retsinformation.dk/eli/lta/2017/1458 (accessed on 3 December 2021).

51.   Denmark. Ordinance of the Law on Livestock Farming and the Use of Manure. Retsinformation. 2018. Available online: https://www.retsinformation.dk/eli/lta/2018/1020 (accessed on 3 December 2021).

52.   Estonia. Outdoor Air Protection Act. Riigi Teataja. 2004. Available online: https://www.riigiteataja.ee/akt/116052013007 (accessed on 8 December 2021).

53.   Estonia. Industrial Emissions Act. Riigi Teataja. 2013. Available online: https://www.riigiteataja.ee/akt/116052013001 (accessed on 8 December 2021).

54.   Estonia. List of Sub-Activities and Threshold Capacities for Which a Complex Permit Is Required for the Operation of an Installation. Riigi Teataja. 2013. Available online: https://www.riigiteataja.ee/akt/125092018004 (accessed on 8 December 2021).

55.   Estonia. Informative Inventory Report Estonia 2017. EEIC. Available online: https://keskkonnaagentuur.ee/sites/default/files/estonia_iir_2017.pdf (accessed on 3 December 2021).

56.   Estonia. Ambient Air. Environment Agency Republic of Estonia. 2018. Available online: https://keskkonnaagentuur.ee/en/estonian-environmental-indicators/estonian-environmental-indicators/ambient-air (accessed on 3 December 2021).

57.   Finland. Environmental Protection Act. Finlex. 2014. Available online: https://www.finlex.fi/fi/laki/smur/2014/20140527 (accessed on 15 December 2021).

58.   Finland. Finland's Informative Inventory Report 2018—Air Pollutant Emissions 1980-2016. Finnish Environment Institute. 2018. Available online: http://cdr.eionet.europa.eu/fi/un/clrtap/iir/envwuuaga/FI_IIR_2018_Part_4_Agri_and_Waste__Final_3May2018.pdf (accessed on 3 December 2021).

59.   France. Decree No. 2013-375 Modifying the Nomenclature of Classified Installations. Legifrance. 2013. Available online: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000027385534&categorieLien=id (accessed on 3 December 2021).

60.   France. Environmental Code. Legifrance. 2021. Available online: https://www.legifrance.gouv.fr/affichCode.do;jsessionid=BACA63A0E38002AA8CC7726CEAD2E1F8.tplgfr28s_2?idSectionTA=LEGISCTA000006108640&cidTexte=LEGITEXT000006074220&dateTexte=20181025 (accessed on 3 December 2021).

61.   BRS. Methodological Procedure for Calculating Emissions. Ministry of Ecological, Transition and Solidarity. 2021. Available online: https://aida.ineris.fr/node/191 (accessed on 3 December 2021).

62.   France. Environmental Protection Act. Legifrance. 2013. Available online: https://www.legifrance.gouv.fr/affichCodeArticle.do;jsessionid=BACA63A0E38002AA8CC7726CEAD2E1F8.tplgfr28s_2?idArticle=LEGIARTI000025141923&cidTexte=LEGITEXT000006074220&dateTexte=20181025 (accessed on 3 December 2021).

63.   Germany. Law on the Order of the Water Balance. Federal Ministry of Justice. 2009. Available online: http://www.gesetze-im-internet.de/whg_2009/ (accessed on 3 December 2021).

64.   Germany. Act on Protection against Harmful Effects on the Environment Caused by Air Pollution, Noise, Vibrations and Similar Processes (Federal Immission Control Act). Federal Ministry of Justice. 2010. Available online: http://www.gesetze-im-internet.de/bimschg/BJNR007210974.html#BJNR007210974BJNG000103360 (accessed on 3 December 2021).

65.   Germany. Act to Promote the Circular Economy and Ensure Environmentally Sustainable Waste Management. Federal Ministry of Justice. 2012. Available online: http://www.gesetze-im-internet.de/krwg/ (accessed on 3 December 2021).

66.   Germany. Law on the Implementation of the Industrial Emissions Directive. Dejure. 2013. Available online: https://dejure.org/BGBl/2013/BGBl._I_S._734 (accessed on 3 December 2021).

67.   Germany. Fourth Ordinance on the Implementation of the Federal Immission Control Act. Federal Ministry of Justice. 2013. Available online: http://www.gesetze-im-internet.de/bimschv_4_2013/ (accessed on 3 December 2021).

68.   Latacz-Lohmann, U. Economic Analysis of Ammonia Regulation in Germany (Schleswig Holstein) in Relation to the Habitat Directive. University of Kiel, Germany. 2017. Available online: https://ifro.ku.dk/english/events/pastevents/2017/ammoniakregulering-af-husdyrproduktionen/GEr-economics-Final_report_21-11-17.pdf (accessed on 3 December 2021).

69.   Anker, H.T. Implementation of EU Directives with Regard to Livestock Farming in the UK, the Netherlands and Germany-a Summary of Questionnaire Responses. University of Copenhagen. 2010. Available online: https://www.ft.dk/samling/20101/lovforslag/L12/spm/88/svar/771732/943943.pdf (accessed on 3 December 2021).

70.   Great Britain. Pollution Prevention and Control Act. The National Archives. 1999. Available online: http://www.legislation.gov.uk/ukpga/1999/24/contents (accessed on 3 December 2021).

71.   Great Britain. The Pollution Prevention and Control (Scotland) Amendment Regulations. The National Archives. 2014. Available online: http://www.legislation.gov.uk/ssi/2014/267/contents/made (accessed on 3 December 2021).

72. Great Britain. The Pollution Prevention and Control (Industrial Emissions) Regulations (Northern Ireland). The National Archives. 2013. Available online: http://www.legislation.gov.uk/nisr/2013/160/contents/made (accessed on 3 December 2021).
73. Great Britain. Pollution Prevention and Control (Designation of Directives) (England and Wales) Order. The National Archives. 2019. Available online: https://www.legislation.gov.uk/uksi/2019/1417/contents (accessed on 3 December 2021).
74. Greece. Joint Ministerial Decision. Technologismiki. 2013. Available online: https://www.e-nomothesia.gr/kat-periballon/apobleta/kya-36060-1155-e103-2013.html (accessed on 3 December 2021).
75. Greece. Greece Informative Inventory Report 2018. Ministry of Environment and Energy. Available online: http://cdr.eionet.europa.eu/gr/un/clrtap/iir/envwxd9dq/2018_IIR_EL.pdf (accessed on 3 December 2021).
76. Greece. Rules to Facilitate and Modernise the Establishment and Operation of Livestock Farms, Provisions for the Implementation of Controls and the Imposition of Penalties and Other Urgent Regulations. Technologismiki. 2021. Available online: https://www.e-nomothesia.gr/kat-agrotike-anaptukse/ktenotrophia/nomos-4859-2021-phek-228a-27-11-2021.html (accessed on 3 December 2021).
77. Hungary. Act LIII of 1995 on General Rules for the Protection of the Environment. Wolters Cluver. 1995. Available online: https://net.jogtar.hu/jogszabaly?docid=99500053.tv (accessed on 3 December 2021).
78. Hungary. Government Decree 193/2001 (X. 19.) on Detailed Rules for the Single Environmental Authorisation Procedure. Wolters Cluver. 2001. Available online: https://net.jogtar.hu/jogszabaly?docid=A0100193.KOR&txtreferer=99500053.TV (accessed on 3 December 2021).
79. Hungary. Government Decree 314/2005 (XII. 25.) on the Environmental Impact Assessment and the Single Authorisation Procedure for the Use of the Environment. Wolters Cluver. 2005. Available online: https://net.jogtar.hu/jogszabaly?docid=A0500314.KOR (accessed on 3 December 2021).
80. Kis-Kovács, G.; Tarczay, K.; Kőbányai, K.; Ludányi, E.L.; Nagy, E.; Kőbányai, K.; Kőbányai, K.; Informative Inventory Report Hungary 2016. HMS. 2018. Available online: http://cdr.eionet.europa.eu/hu/un/clrtap/iir/envwql3ag/IIR_HU_2018march.pdf (accessed on 3 December 2021).
81. Ireland. Waste Management Act. Irish Statute Book. 1996. Available online: http://www.irishstatutebook.ie/eli/1996/act/10/enacted/en/ (accessed on 8 December 2021).
82. Ireland. Planning and Developmend Act. Irish Statute Book. 2000. Available online: https://www.irishstatutebook.ie/eli/2000/act/30/enacted/en/ (accessed on 8 December 2021).
83. Ireland. Environmental Protection Agency Act. Irish Statute Book. 1992. Available online: https://www.irishstatutebook.ie/eli/1992/act/7/section/88/enacted/en/html./ (accessed on 8 December 2021).
84. Ireland. Environmental Protection Agency-Industrial Emissions Regulations. Irish Statute Book. 2013. Available online: https://www.irishstatutebook.ie/eli/2013/si/137/made/en/ (accessed on 8 December 2021).
85. Duffy, P.; Hyde, B.; Ryan, A.M.; Alam, M.S. Ireland's Informative Inventory Report 2018. EPA. Available online: http://cdr.eionet.europa.eu/ie/un/clrtap/iir/envwtn_3q/Ireland_IIR_2018_Final.pdf (accessed on 3 December 2021).
86. Burchill, W.; Lanigan, G.; Kavanagh, I. LowAmmo: Measuring Ammonia in Agriculture. TResearch. 2017. Available online: https://www.teagasc.ie/media/website/publications/2017/6-LowAmmo-measuring-ammonia-in-agriculture.pdf (accessed on 3 December 2021).
87. Ireland. Environmental Protection Agency Act. Irish Statute Book. 2000. Available online: https://www.irishstatutebook.ie/eli/1992/act/7/enacted/en/html (accessed on 8 December 2021).
88. Italy. Legislative Decree Full Implementation of Directive 96/61/EC Concerning Integrated Pollution Prevention and Control. Bosetti Gatti & Partners. 2005. Available online: https://www.bosettiegatti.eu/info/norme/statali/2005_0059.htm (accessed on 3 December 2021).
89. Italy. Legislative Decree of Environmental Regulations. Legambiente. 2006. Available online: https://www.legambiente.it/sites/default/files/docs/d.lgs_._n._152_2006_t.u._ambientale-1.pdf (accessed on 3 December 2021).
90. Italy. Implementation of Directive 2010/75/EU on Industrial Emissions (Integrated Pollution Prevention and Control). Bosetti Gatti & Partners. 2014. Available online: http://www.bosettiegatti.eu/info/norme/statali/2014_0046.htm (accessed on 3 December 2021).
91. Italy. Environmental Italian Update of IPPC Permits. Lexology. 2016. Available online: https://www.lexology.com/library/detail.aspx?g=25249930-3418-4a0b-b17c-0b8f7860770d (accessed on 3 December 2021).
92. Latvia. Environmental Impact Assessment Act. Legislation of the Republic of Latvia. 2020. Available online: https://likumi.lv/ta/id/51522 (accessed on 3 December 2021).
93. Latvia. Pollution Act. Legislation of the Republic of Latvia. 2021. Available online: https://likumi.lv/ta/id/6075-par-piesarnojumu (accessed on 3 December 2021).
94. Skrebele, A.; Ratniece, V.; Rubene, L.; Ozoliņa, Z.; Cakars, I.; Siņics, L.; Klāvs, G.; Gračkova, L.; Bērziņa, L.; Frolova, O.; et al. Latvia's Informative Inventory Report 1990–2016. LEGMC. 2018. Available online: http://cdr.eionet.europa.eu/lv/un/clrtap/iir/envwqqvhw/IIR_2018_LV.pdf (accessed on 3 December 2021).
95. LEPA. Lithuanian Pollutants Emission Inventory for Period 1990–2016. The Lithuanian Environmental Protection Agency. 2018. Available online: http://cdr.eionet.europa.eu/lt/un/clrtap/iir/envwqqayw/NIIR_LT_2018_official_submission_final_v1.1.pdf (accessed on 3 December 2021).

96. Lithuania. The Approval of the Rules for the Issue, Renewal and Revocation of Integrated Pollution Prevention and Control Permits. The Republic of Lithuania. 2002. Available online: https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.181470?jfwid=-k3id7w0j6 (accessed on 3 December 2021).

97. Lithuania. The Approval of the Rules for the Issue, Renewal and Revocation of Integrated Pollution Prevention and Control Permits. The Republic of Lithuania. 2013. Available online: https://www.e-tar.lt/portal/lt/legalAct/TAR.8F44C64C509B (accessed on 3 December 2021).

98. Lithuania. Environmental Protection Act. The Republic of Lithuania. 2021. Available online: https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.2493/CTZxrqmwgN (accessed on 3 December 2021).

99. Luxembourg. Pollutant Release and Transfer Registers. Official Journal of the Grand Duchy of Luxembourg. 2005. Available online: http://data.legilux.public.lu/file/eli-etat-leg-memorial-2005-207-fr-pdf.pdf (accessed on 3 December 2021).

100. Luxembourg. Legislation: Memorial A-936. Central Legislation Department. 2018. Available online: http://legilux.public.lu/eli/etat/leg/code/environnement/20181014 (accessed on 3 December 2021).

101. Malta. Industrial Emissions (IPPC) Regulations—Subsidiary Legislation. Legislation Malta. 2013. Available online: https://legislation.mt/eli/sl/549.77 (accessed on 14 December 2021).

102. Malta. Industrial Emissions (Framework) Regulations—Subsidiary Legislation. Legislation Malta. 2013. Available online: https://legislation.mt/eli/sl/549.76/eng/pdf (accessed on 14 December 2021).

103. Malta. Industrial Emission (Integrated Pollution Prevention and Control Regulations. Legislation Malta. 2013. Available online: http://www.justiceservices.gov.mt/DownloadDocument.aspx?app=lom&itemid=11531&l=1 (accessed on 14 December 2021).

104. Malta. Applying for an Environmental Permit. Environment and Resources Authority. 2020. Available online: https://era.org.mt/era-topic-categories/applying-for-an-ep/ (accessed on 14 December 2021).

105. UNECE. Informative Inventory Report for Malta 2016. United Nations Economic Commission for Europe. 2016. Available online: http://cdr.eionet.europa.eu/mt/un/clrtap/iir/envwx_xka/IIR_for_2016_data_updatedv2.pdf (accessed on 3 December 2021).

106. Netherlands. Decision of 13 October 2012, Amending the Activities Decree Environmental Management, the Environmental Law Decree and a Few Other Decisions for the Transposition of Directive 2010/75/EU of the European Parliament and of the Council of 23 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). Official Journal of the Kingdom of the Netherlands. 2012. Available online: https://zoek.officielebekendmakingen.nl/stb-2012-552.html (accessed on 3 December 2021).

107. Netherlands. Guide to Determining BAT for Industrial IPPC Installations. Kenniscentrum. 2013. Available online: https://www.infomil.nl/onderwerpen/duurzaamheid-energie/ippc-installaties/handleiding-ippc/ (accessed on 3 December 2021).

108. Netherlands. Act of 11 April 2013 Amending the Environmental Law (General Provisions) Act, the Environmental Management Act and Some Other Acts for the Purpose of Implementing Directive No 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control. Official Journal of the Kingdom of the Netherlands. 2013. Available online: https://zoek.officielebekendmakingen.nl/stb-2013-159.html (accessed on 3 December 2021).

109. Netherlands. General Provisions Act. Official Journal of the Kingdom of the Netherlands. 2018. Available online: https://wetten.overheid.nl/BWBR0024779/2018-07-28 (accessed on 3 December 2021).

110. Dębski, B.; Olecka, A.; Bebkiewicz, K.; Chłopek, Z.; Kargulewicz, I.; Rutkowski, J.; Zasina, D.; Zimakowska-Laskowska, M.; Żaczek, M.; Waśniewska, S. Poland's Informative Inventory Report 2018. KOBiZE. Available online: http://cdr.eionet.europa.eu/pl/un/clrtap/iir/envwqolng/IIR_2018_POL.pdf (accessed on 3 December 2021).

111. Poland. Regulation (EC) No. 166/2006 of the European Parliament and of the Council of 18 January 2006 Concerning the Establishment of a European Pollutant Release and Transfer Register and Amending Council Directives 91/689/EEC and 96/61/EC. Official Journal of the European Union. 2006. Available online: https://eur-lex.europa.eu/legal-content/CS/TXT/?uri=CELEX:32006R0166&qid=1540750351307 (accessed on 3 December 2021).

112. Poland. Environmental Protection Law. Internet System of Legal Acts. 2021. Available online: http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20010620627/U/D20010627Lj.pdf (accessed on 3 December 2021).

113. Portugal. Decree Law No. 173/2008. Electronic Republic Diary. 2008. Available online: https://dre.pt/pesquisa/-/search/453550/details/maximized (accessed on 3 December 2021).

114. Portugal. Decree Law No. 127/2013. Electronic Republic Diary. 2013. Available online: https://dre.pt/pesquisa/-/search/499546/details/maximized (accessed on 3 December 2021).

115. Portugal. Decree Law No. 75/2015. Electronic Republic Diary. 2015. Available online: https://dre.pt/legislacao-consolidada/-/lc/115346808/201810290847/73540869/diploma/ (accessed on 3 December 2021).

116. Portugal. Portuguese National Inventory Report on Greenhouse Gases, 1990–2015. APA. 2017. Available online: https://www.apambiente.pt/_zdata/Inventario/2017/20170530/NIRglobal20170526.pdf (accessed on 3 December 2021).

117. Republic of Cyprus. Water Pollution Control Act. The Cypriot Source of Legal Information. 2002. Available online: http://www.cylaw.org/nomoi/enop/non-ind/2002_1_106/full.html (accessed on 3 December 2021).

118. Republic of Cyprus. Industrial Emissions (Integrated Pollution Prevention and Control) Act. The Cypriot Source of Legal Information. 2013. Available online: http://www.cylaw.org/nomoi/arith/2013_1_184.pdf (accessed on 3 December 2021).

119. Republic of Cyprus. Industrial Emissions (Integrated Pollution Prevention and Control) Act. The Cypriot Source of Legal Information. 2016. Available online: http://www.cylaw.org/nomoi/arith/2016_1_131.pdf (accessed on 3 December 2021).

120. Papadopoulos, C.H.; Savvides, C.; Yiannaki, A. Cyprus Informative Inventory Report 2016. MLWSI. 2018. Available online: http://cdr.eionet.europa.eu/cy/un/clrtap/iir/envwqkb6q/20180110-CyprusInformativeInventoryReport2016.pdf (accessed on 3 December 2021).

121. Romania. Law No. 278 on Industrial Emissions. Official Monitor. 2013. Available online: http://www.anpm.ro/documents/12220/2046999/Lege+nr+278-+2013+privind+Emisiile++Industriale.pdf/ (accessed on 14 December 2021).

122. Romania. An Overview on Environment Law in Romania. NNDKP. 2008. Available online: https://www.nndkp.ro/articles/environment-handbook/ (accessed on 14 December 2021).

123. Bălan, I.; Gassler, C.C.; Grosu, G.I.; Păpurică, L.-P.; Brojbă, L.C.; Stîngă, M.; Coica, T.M.; Fulgeanu, N.A. Romania's Informative Inventory Report 2018. NEPA. Available online: http://cdr.eionet.europa.eu/ro/un/clrtap/iir/envwqpiwq/RO_IIR_2018.pdf (accessed on 3 December 2021).

124. Slovak Republic. Integrated Pollution Prevention and Control and on Amendments and Additions to Certain Acts. Slov-Lex. 2018. Available online: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2018/193/20180701 (accessed on 3 December 2021).

125. Jonacek, Z.; Ďuricová, I.; Tonhauzer, K.; Horváth, J.; Zemko, M.; Jalšovská, M. Informative Inventory Report 2018. SHMÚ. Available online: http://cdr.eionet.europa.eu/sk/un/clrtap/iir/envwtcyiq/IIR_2018_v2.pdf (accessed on 3 December 2021).

126. Slovenia. Environmental Protection Act. Official Gazette. 2006. Available online: https://www.uradni-list.si/glasilo-uradni-list-rs/vsebina/2006-01-1682?sop=2006-01-1682 (accessed on 14 December 2021).

127. Slovenia. Regulation on the Type of Activities and Installations Likely to Cause Large-Scale Pollution of the Environment. Official Gazette. 2010. Available online: https://www.uradni-list.si/glasilo-uradni-list-rs/vsebina/2015-01-2392/uredba-o-vrsti-dejavnosti-in-naprav-ki-lahko-povzrocajo-onesnazevanje-okolja-vecjega-obsega (accessed on 15 December 2021).

128. Logar, M.; Verbič, J.; Majaron, T.M. Slovenia's Informative Inventory Report 2018. SEA. Available online: http://cdr.eionet.europa.eu/si/un/clrtap/iir/envwqjfag/Slovenia_IIR__2018.pdf (accessed on 3 December 2021).

129. Spain. Computer Application for Estimating Emissions and Resource Consumption in Livestock Farming Livestock. Ministry of Agriculture, Fisheries and Food. 2020. Available online: https://www.mapa.gob.es/en/ganaderia/temas/ganaderia-y-medio-ambiente/calculo-emisiones/default.aspx (accessed on 3 December 2021).

130. Spain. Nitrogen Balance and Gas Emission Inventory. Ministry of Agriculture, Fisheries and Food. 2019. Available online: https://www.mapa.gob.es/es/ganaderia/temas/ganaderia-y-medio-ambiente/balance-de-nitrogeno-e-inventario-de-emisiones-de-gases/ (accessed on 3 December 2021).

131. Spain. Integrated Pollution Prevention and Control. State Agency Official State Gazette. 2002. Available online: https://www.boe.es/buscar/doc.php?id=BOE-A-2002-12995 (accessed on 3 December 2021).

132. Spain. Approving the Revised Text of the Law on Integrated Pollution Prevention and Control. *State Agency Official State Gazette.* 2016. Available online: https://www.boe.es/buscar/doc.php?id=BOE-A-2016-12601 (accessed on 3 December 2021).

133. MAPAMA. Spain Informative Inventory Report 1990–2016. MAPAMA. 2018. Available online: http://cdr.eionet.europa.eu/es/un/clrtap/iir/envwplua/SPAIN_2018-CLRTAP-IIR_Submission-IIR.pdf (accessed on 3 December 2021).

134. Sweden. Environmental Impact Assessment Regulation. Sveriges Riksdag. 2013. Available online: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/miljoprovningsforordning-2013251_sfs-2013-251 (accessed on 15 December 2021).

135. Sweden. Swedish Statutory Instruments Decree Amending the Regulation on Incineration of Waste. Lagboken. 2016. Available online: https://www.lagboken.se/Lagboken/start/sfs/sfs/2016/1100-1199/d_2866021-sfs-2016_1189-forordning-om-andring-i-forordningen-2013_253-om-forbranning-av-avfall (accessed on 15 December 2021).

136. Sweden. Decree on Environmentally Hazardous Activities and Health Protection. Sveriges Riksdag. 1998. Available online: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-1998899-om-miljofarlig-verksamhet_sfs-1998-899 (accessed on 15 December 2021).

137. Sweden. Swedish Statutory Instruments Decree Amending the Regulation on Environmentally Hazardous Activities and Health Protection. Lagboken. 2013. Available online: https://www.lagboken.se/Lagboken/start/sfs/sfs/2013/200-299/d_1631442-sfs-2013_262-forordning-om-andring-i-forordningen-1998_899-om-miljofarlig-verksamhet-och-halsoskydd (accessed on 15 December 2021).

138. Sweden. Informative Inventory Report Sweden 2018. Rep. Swed. Environ. Prot. Agency. 2018. Available online: http://cdr.eionet.europa.eu/se/un/clrtap/iir/envwqeogg/ (accessed on 3 December 2021).

139. Czech Republic. Methodological Instruction on the Classification of Livestock Farms According to Act No. 201/2012 on Air Protection, on the Calculation of Pollutant Emissions from These Stationary Sources and on the List of Technologies Reducing Emissions from These Stationary Sources. Ministry of the Environment. 2019. Available online: https://www.mzp.cz/C1257458002F0DC7/cz/zemedelstvi/$FILE/OOO-MP_chovy-20190708.pdf (accessed on 3 December 2021).

140. Nielsen, O.K.; Plejdrup, M.S.; Winther, M.; Mikkelsen, M.H.; Nielsen, M.; Gyldenkærne, S.; Fauser, P.; Albrektsen, R.; Hjelgaard, K.H.; Bruun, H.G.; et al. Annual Danish Informative Inventory Report to Unece—Emission Inventories from the Base Year of the Protocols to Year 2016. AARHUS University. Available online: http://cdr.eionet.europa.eu/dk/un/clrtap/iir/envwqogaa/SR267.pdf (accessed on 3 December 2021).

141. Haenel, H.D.; Rösemann, C.; Dämmgen, U.; Döring, U.; Wulf, S.; Eurich-Menden, B.; Freibauer, A.; Döhler, H.; Schreiner, C.; Osterburgg, B. Calculations of Gaseous and Partivulate Emissions from German Agriculture 1990–2016. 2018. Available online: https://literatur.thuenen.de/digbib_extern/dn059722.pdf (accessed on 3 December 2021).

142. Wakeling, D. UK Informative Inventory Report (1990 to 2016). NAEI. 2018. Available online: https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1803161032_GB_IIR_2018_v1.2.pdf (accessed on 3 December 2021).

143. Taurino, E.; Bernetti, A.; De Lauretis, R.; Di Cristofaro, E.; Cordella, M.; Gagna, A.; Gonella, B.; Lena, F.; Pantaleoni, M.; Peschi, E.; et al. Italian Emission Inventory 1990–2016—Informative Inventory Report 2018. ISPRA. 2018. Available online: https://www.isprambiente.gov.it/files2018/pubblicazioni/rapporti/R_284_18_IIR2018.pdf (accessed on 3 December 2021).

144. Wever, D.; Coenen, P.W.H.G.; Dröge, R.; Geilenkirchen, G.P.; Hoen, M.; Jimmink, B.A.; Koch, W.W.R.; Leekstra, A.J.; te Molder, R.A.B.; Peek, C.J.; et al. Emissions of Transboundary Air Pollutants in the Netherlands 1990–2016. RIVM. 2018. Available online: http://cdr.eionet.europa.eu/nl/un/clrtap/iir/envwtc5fa/rap_2018-0013_met_omslag_beveiligd.pdf (accessed on 3 December 2021).

145. TEAGASC. Ammonia, Teagasc—Agriculture and Food Development Authority. Teagasc. 2017. Available online: https://www.teagasc.ie/environment/climate-change--air-quality/ammonia/ (accessed on 3 December 2021).

Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming

Pavel Kriz [1,2] [ID], Radim Kunes [1,*], Lubos Smutny [1], Pavel Cerny [1,2] [ID], Zbynek Havelka [1] [ID], Pavel Olsan [1], Maohua Xiao [3], Radim Stehlik [1], Antonin Dolan [1] and Petr Bartos [1,2]

[1] Department of Agricultural Machinery and Services, Faculty of Agriculture, University of South Bohemia, Studentska 1668, 370 05 Ceske Budejovice, Czech Republic; kriz@pf.jcu.cz (P.K.); smutny@zf.jcu.cz (L.S.); pcerny@pf.jcu.cz (P.C.); zhavelka@zf.jcu.cz (Z.H.); olsan@zf.jcu.cz (P.O.); stehlr00@zf.jcu.cz (R.S.); dolan@zf.jcu.cz (A.D.); bartos@zf.jcu.cz (P.B.)

[2] Department of Applied Physics and Technology, Faculty of Education, University of South Bohemia, Jeronymova 10, 371 15 Ceske Budejovice, Czech Republic

[3] College of Engineering, Nanjing Agricultural University, Nanjing 210031, China; xiaomaohua@njau.edu.cn

* Correspondence: kunesr00@zf.jcu.cz

Abstract: Determination of ammonia (NH_3) emissions for intensive livestock facilities (pork, poultry) is important from both a regulatory and a research point of view. Buildings housing livestock are a large source of ammonia emissions from the agriculture sector. However, measurements to determine emissions can be time-consuming and costly. Therefore, it is essential to find a suitable methodology for monitoring NH_3. The methodology for determining NH_3 emissions is legislatively unified in terms of sampling methodology, including sampling time (24 h), sampling points (input/output), number of sampling days, and their distribution during the year, and to determine only a general calculation of the annual average NH_3 emissions. For this reason, the researchers chose different approaches for the calculation of NH_3 emissions, and these approaches are not unified. Based on accurate monitoring and created models, the authors proposed a methodology for calculation of NH_3 emissions, which divides the 24 h measurement into time windows (30 min), from which the arithmetic mean and standard deviation are determined, and the total emissions for one year is determined. The chosen time windows for the partial calculation are important from the point of view of reflecting the microclimatic conditions inside the stable and the device limits for sampling the NH_3 concentration and airflow.

Keywords: Innova 1412; NH_3; welfare; microclimatic conditions; livestock; environment

1. Introduction

At present, NH_3 is a significant air pollutant, and its concentration does not decrease rapidly. The reduction in ammonia emissions has been slow over the last three decades, particularly compared to the reduction in emissions of other pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and non-methane volatile organic compounds [1]. In principle, NH_3, as a pollutant gas, accelerates the formation of fine particles in the atmosphere. Ammonia is crucial for the acidification and eutrophication of ecosystems and consequently contributes to climate change [2,3].

In addition to the environmental aspects, particulate NH_3 also has a negative impact on human health [4]. Due to the biogenic and anthropogenic origin of atmospheric ammonia, it is particularly harmful to human health, especially to the eyes and respiratory systems [5–7]. Exposure to ammonia is accompanied by clinical symptoms such as coughing, sneezing, salivation, excessive lachrymal secretions, loss of appetite, and lethargic behavior [8,9]. Ammonia also participates in reactions forming organic and inorganic aerosols that can adsorb a high concentration of toxic air pollutants, which affects human health by mutagenic and genotoxic activities [10–12].

The agro-industry is considered the primary contributor of NH_3 in most developed countries [1,13,14]. Due to demographic growth and changes in food preferences, global NH_3 emissions are expected to double by 2050 [2,15]. The major source of NH_3 in agriculture is livestock excreta emitting NH_3 immediately after deposition and during decomposition. Reactions of urease enzyme or microbial activity quickly release NH_3 to the atmosphere, consuming unconverted nitrogen originating from high-protein feeds used to fulfill nutritional requirements [16]. From the chemical point of view, nitrogen-based emissions are probably caused by ammonia (NH_3-N) losses from the interconversion of total ammoniacal nitrogen (NH_3-N + NH_4^+-N) and organic nitrogen, eventually by the aqueous equilibrium of (NH_3-N) and (NH_4^+-N) [17].

Ammonia has a perceptible odor even at very low concentrations, and its emissions are mainly observed in locations with high-density livestock farming, especially in pig farms [18]. Pig farming is globally responsible for about 15% of NH_3 emissions associated with livestock breeding [19]. The main source of NH_3 releases from buildings with daily housing emission factors of 34.3–146.4 g NH_3 per 500 kg live weight for fattening pigs [20]. The amount of nitrogen-based emissions also depends on the type of housing and technologies, waste management, environmental conditions (e.g., temperature, wind speed, enzymatic activity, pH, relative humidity), and efficiency of utilizing nitrogen by the animal [21,22].

The precise identification and determination of NH_3 emissions seems essential both for meeting legislative standards (identifying the effectiveness of mitigation strategies at the national and regional level, preparing national annual emission inventories for regulatory purposes) and developing technologies aimed at reducing these emissions [23].

As NH_3 emissions are complex and depend on many factors, the effort is made to determine the resulting emissions from farms as accurately as possible. Three approaches have been identified for this purpose. Two of them estimate the total emissions over each manure management phase (housing, manure storage, landspreading), and the third approach determines only emissions from housing.

The first one estimates the value on the basis of a mass balance based on the excretion and total nitrogen, or total ammoniacal nitrogen (TAN), present at each manure management phase. Ammonia emissions are estimated based on the amount of nitrogen excreted by each animal category and using the total nitrogen or TAN flow and the volatilization coefficients over each manure management phase (housing, manure storage, landspreading).

The second one is an estimation by application of emission factors. Ammonia emissions are estimated on the basis of emission factors derived from measurements designed and performed according to a national protocol in a farm with an identical type of technique (housing, manure storage, landspreading) and similar climatic conditions.

For this above approach, methodologies (models) have been developed and approved, which calculate these emissions on the basis of data from operating conditions. These methodologies are used in European Union countries, and they are time-saving but less accurate.

The third possibility estimates emissions by a calculation from measured values of ammonia concentration and ventilation rate only from housing. This method is more accurate in comparison with the two above-mentioned methods. Their outputs are based on methodologies for estimation of emissions by calculation, and they are used to determine the emissions produced accurately, to verify the use of Best Available Technologies (BAT), but it is more time- and money-consuming. In addition, it is methodically complete in terms of measurement methodology (data collection in the stable), but the algorithm for evaluating the emissions from the measured data is not explicitly defined [24,25].

The Directive 2010/75/EU of the European Parliament and of the Council, for the intensive rearing of poultry or pigs, defines the general principles of the estimation of ammonia emissions. Pig farming is characterized as a category of animals with a linear increase in emissions per breeding cycle; therefore, the days on which NH_3 emissions

are measured must be evenly distributed over the period of their growth. Ammonia emissions must be evaluated in at least six sampling days over a period of a breeding cycle. This means that three measurements are evenly distributed in the first half of the breeding cycle and three further measurements in the second half of the breeding cycle. The annual ammonia emissions are calculated from the mean of the one-day emissions obtained during six 24 h measurements multiplied by the number of days of stable occupancy by animal [26].

Sampling is carried on at the air inlet and outlet of the stable for 24 h. Ventilation performance is also measured (alternatively it can be generated from the ventilation control unit). The concentration of NH_3 in the air output from the stable is measured, adjusted to the concentration of the inlet air to the stable, and the daily NH_3 emissions are derived by measuring and multiplying the ventilation and NH_3 concentration. The annual average NH_3 emissions are determined from the daily average NH_3 emissions multiplied by the number of days of stable occupancy by animal [26].

Despite many devices, the measurement of NH_3 emissions has not usually been implemented in day-to-day monitoring due to the high specialization of each device, making it difficult to use them in typical farming situations. At any rate, the measurement of NH_3 in pig farms and development of an appropriate measurement methodology are necessary to increase agricultural efficiency and, consequently, the quality of life and the environment. Generally, NH_3 measurement methodology includes selecting a suitable monitoring system, sampling configuration of the used device, the additional equipment for measuring other physical quantities, the spatial and layout arrangement of used equipment in the pig house, and the method of statistical analysis of obtained data.

There is obviously a strong need for unification in order to compare the research data with each other effectively. Thus, the aim of this study is to provide an accurate and effective methodology for measuring and statistically evaluating NH_3 emissions in pig houses based on performed experiments and previous studies.

2. Materials and Methods

2.1. Scheme of Methodology

The overview schema of methodology for measurements and determination of the ammonia emissions from intensive livestock farming is below in the Figure 1. This methodology is described in detail in the following chapters.

2.2. Experimental Pig House

The study was carried out in a pig production house located in the Czech Republic in the district of Tabor at an altitude of 455 m (GPS coordinates 49°15′03″ N, 14°33′01″ E). The stable for breeding sows with piglets (mating and gestating sows) was divided into five pens, each with a concrete floor with deep straw litter (BAT 30.a6) and middle corridor for assessing the manure. There were service alleyways on both sides. An automatic feeding system for moist feed for phase feeding (BAT 3.b) was situated in every pen. In every breeding section, negative pressure ventilation was addressed by two wall ventilators by diametral 0.45 m, which automatically control the indoor microclimate. Outdoor air was sucked in by three 0.8×0.3 m wall openings. The data collecting was performed in one selected pen, which is illustrated in Figure 2. At the time of monitoring, there were 12 sows and 76 piglets in the pen.
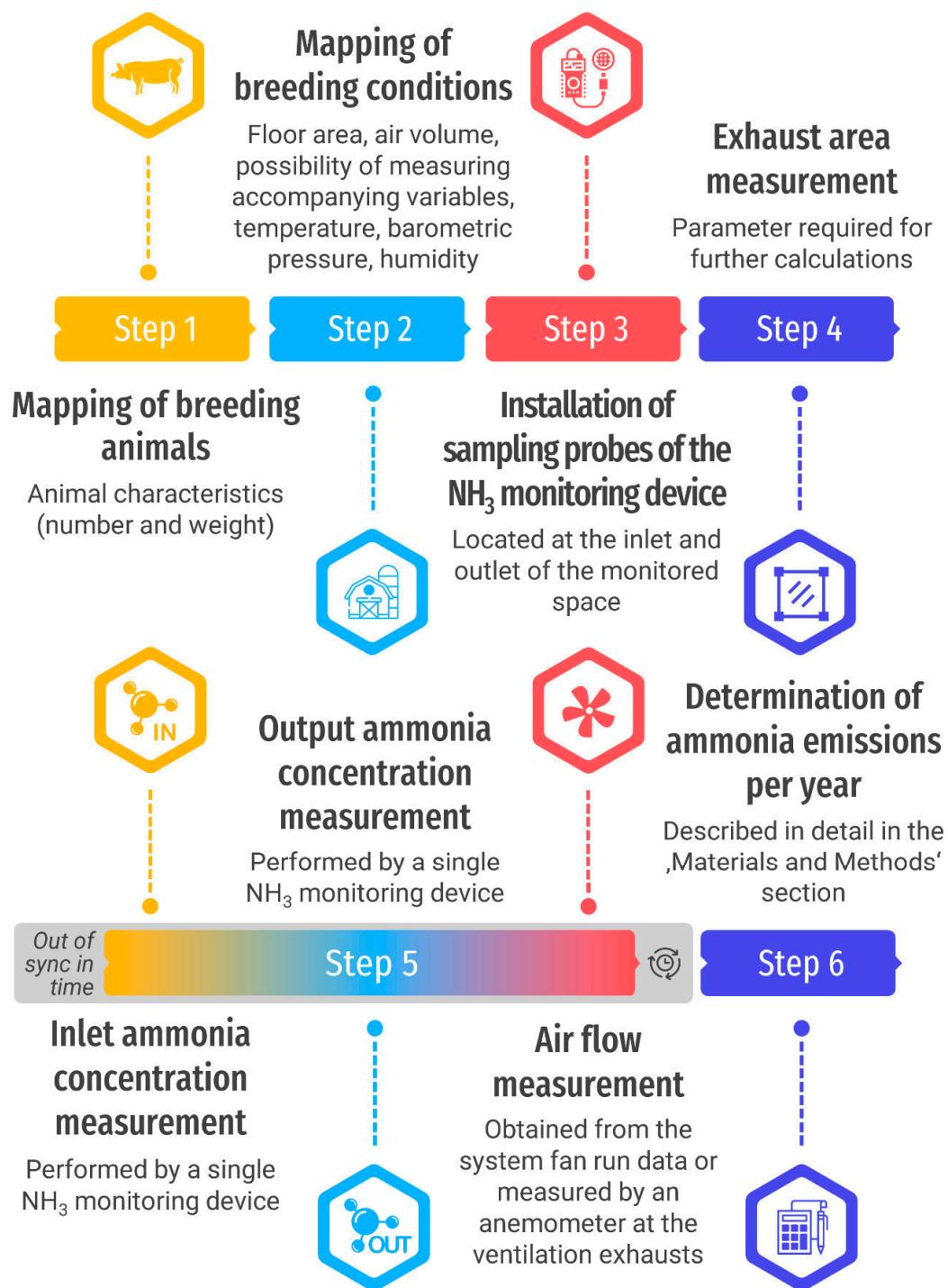
Figure 1. Scheme of measurements and determination of the ammonia emissions.
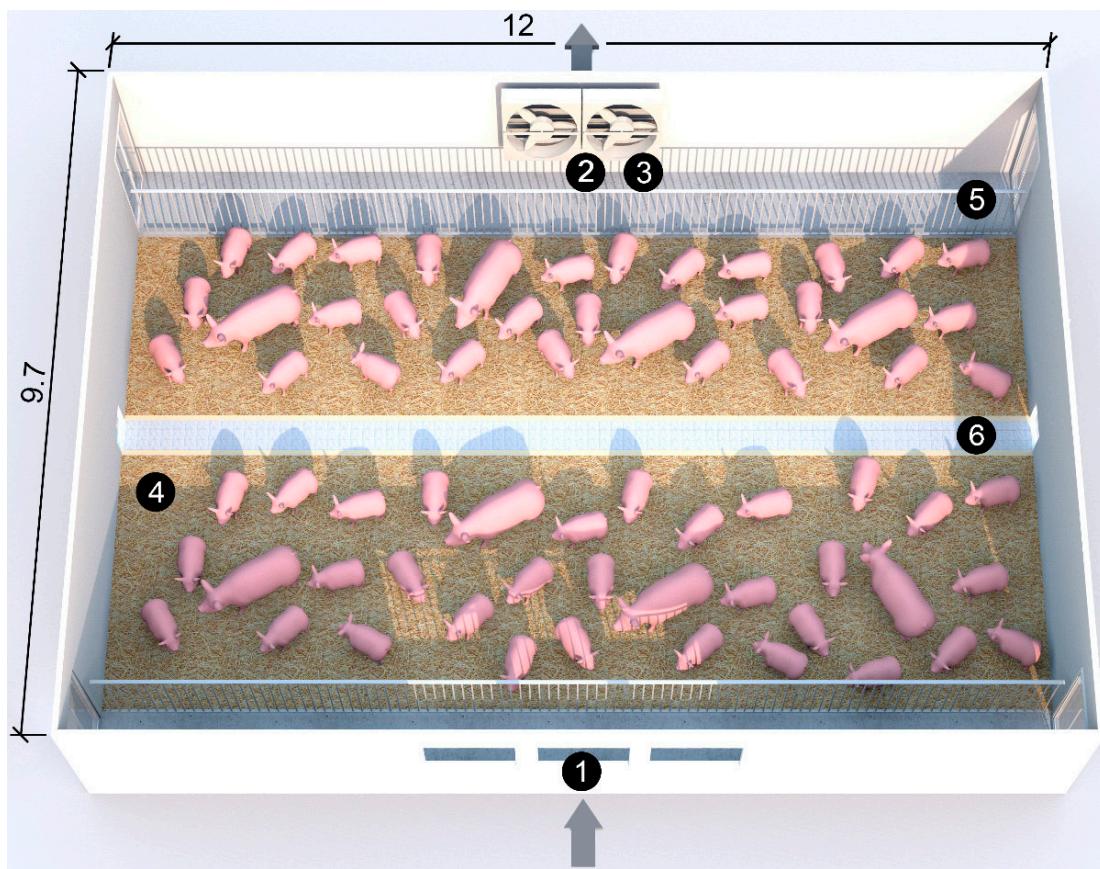
Figure 2. Illustration of the pen in the experimental pig house (1—input concentration sensor; 2—output concentration sensor; 3—anemometer for air velocity measurement; 4—deep straw litter; 5—service alleyway, 6—manure corridor).

2.3. Methodology for Measurements of the Ammonia Concentration in the Pig Farm

Ammonia concentration measurements were performed simultaneously at the air inlet and outlet from the stable continuously for 24 h. A photoacoustic multigas monitor INNOVA 1412 by LumaSense Technologies A/S, Ballerup, Denmark, equipped with a multi-channel sampling and dosing device Multipoint Samplet 1309 D or similar devices are recommended to be used for the NH_3 concentration measurement. From the measuring device, special Teflon hoses were stretched to the sampling points (air inlet and outlet). The device continuously uploading the measured values to its internal memory, while the sampling frequency was set to once every 6 min. At the same time, other physical quantities (indoor and outdoor temperature, relative humidity, atmospheric pressure) were monitored during the measurement using a multi-purpose device (COMMETER D4141, COMET SYSTEM spol. s r.o., Rožnov pod Radhoštěm, Czech Republic), and the airflow rate in the exhaust fans was measured by means of an anemometer (TESTO 445, TESTO AG, Lenzkirch, Germany).

2.4. Methodology for Calculation of NH_3 Emissions

The determination of NH_3 emissions in the stable is based on the data from measuring ammonia concentrations in the air entering and exiting the stable. Another parameter for finding out the emission is the determination of the airflow outwards. Last but not least, it is necessary to know the area of the vents exhaust and also the number of housed animals for the purposes of determining the total production of specific NH_3 emissions per year. The measurement of the input and output NH_3 concentration is usually performed by INNOVA 1412 with two sensors connected; therefore, it is not possible to obtain data from both sensors at the same time. In addition, the airflow through the stable ventilation

is usually determined independently of the concentration measurement time. It is either obtained from the stable system data on the operation of the fans or is directly measured by an anemometer at the ventilation exhausts. In both cases, there is no group of three corresponding data points available to calculate the NH$_3$ emission rate. For this reason, it is necessary to calculate emissions from several independently measured data points of all input variables during a suitably selected time interval, the so-called time window. Its length must be chosen carefully with regard to the accuracy of measurement but also to the problem of monitoring NH$_3$ production in the stable during the day.

The ammonia emission rate E (mg·s^{-1}) can be now figured out from this formula:

$$E = (C_{\text{OUT}} - C_{\text{IN}}) \cdot v \cdot S, \tag{1}$$

where C_{OUT} is NH$_3$ concentration in an outlet (mg·m^{-3}), C_{IN} is NH$_3$ concentration in the input (mg·m^{-3}), v is air velocity by venting the stable (m·s^{-1}), and S is the area of the exhaust of the stable vents (m^2).

The arithmetic mean and standard deviation are determined from all obtained values of effective emissions during one day (24 h). Subsequently, the total production-specific emissions per year E_{YEAR} (kg·animal^{-1}·year^{-1}) are determined and converted to a value per pig using this formula:

$$E_{\textbf{YEAR}} = E_{\text{AVG}} \cdot N^{-1}, \tag{2}$$

where E_{AVG} is arithmetic mean of the E (kg·year^{-1}), and N is the number of pigs housed in the stable.

2.5. Creation of Model Data for Method Testing

For the purpose of creating a methodology for evaluating NH$_3$ emissions from stables, model data of monitored variables were firstly created. Because the input values for the calculation (input and output NH$_3$ concentration and gas flow through the stable vents) are not interdependent quantities, the input data for the model were based on real measured data. From these data, a simple regulation simulating the stable situation was created (see Figure 3).
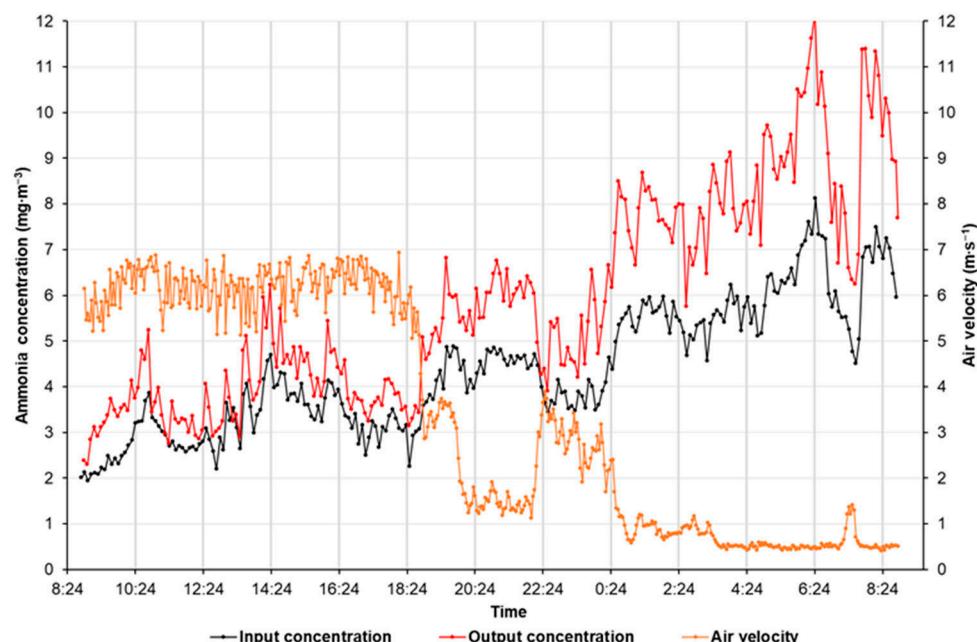

Figure 3. Measured data from experimental pig house.

Breakpoints were identified based on the visual evaluation of the course of individual quantities; their values were roughly determined with an accuracy of 0.5 mg·m^{-3} or

0.5 m$^3 \cdot$s^{-1}, respectively, including their time offset from the starting time (integral multiples of 0.5 h). The entire waveforms of the input quantities were then replaced by a polyline connecting the above-mentioned points. Furthermore, the normally distributed noise was added to the concentration values, with a mean value of 0 and a standard deviation of 0.5 for the input concentration and 0.9 for the output concentration, respectively. From the measured data it was evident the input concentration fluctuated less than the output concentration; therefore, a different standard deviation was chosen in the model. In the case of flow values, the fluctuation depends on the absolute value of the measured flow; at higher flow rates, it fluctuates more; at lower flow rates, the fluctuation is significantly lower. Therefore, the flow values on the polyline were multiplied by a coefficient having a Gaussian distribution with a mean value of 1 and a standard deviation of 0.05. The resulting model is shown in Figure 4.
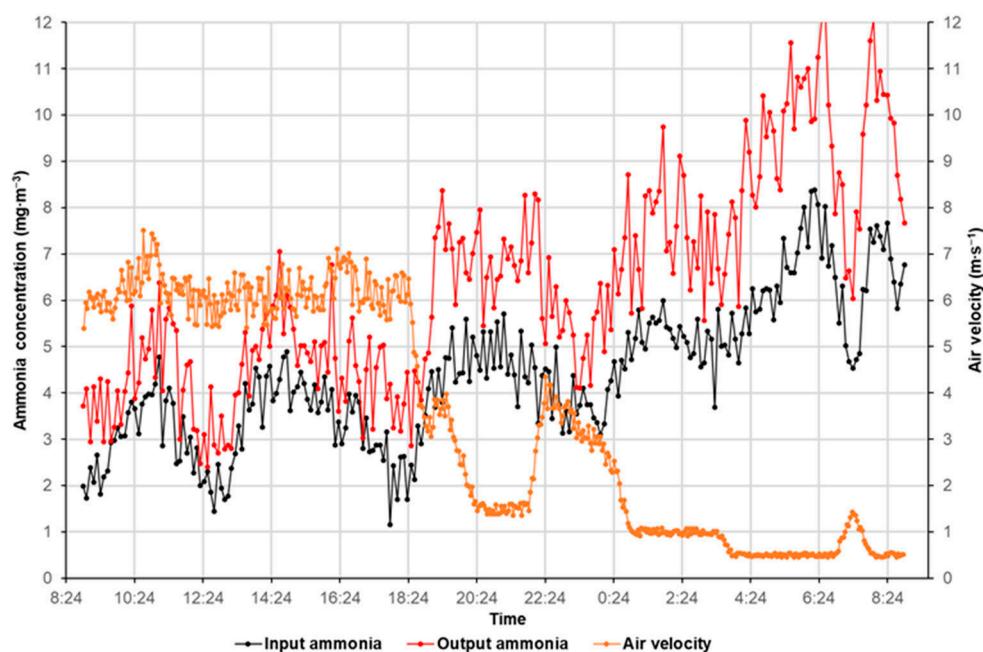
Figure 4. Creation of model values based on real data from the stable.

For the purpose of testing the evaluation methodology, the second set of model data was created based on the original model and where, in addition, the data were artificially modified at randomly selected time intervals. In the time interval from 3:14:17 to 4:14:17, the model data were sorted so the input concentration C_{IN} decreased continuously throughout this hour, while the output concentration C_{OUT} and the airflow v continuously increased. This situation simulates the maximum possible error load in the E evaluation due to the impossibility of measuring all input variables simultaneously. This will lead to the largest fluctuations in the calculation of the E. In the time interval from 11:55:13 to 12:55:13, both the input concentration C_{IN} and the output concentration C_{OUT} were arranged in ascending order, and the air flow fluctuated in the usual manner. This adjustment best corresponds to the real situation due to the interdependence of both concentrations of ammonia, i.e., that the trend of both concentrations was the same (in this case, growth). The last adjustment was made in the time interval from 18:44:40 to 20:44:40, when the air flow was set equal to zero. This simulates the failure of the anemometer or system flow sensors in the stable. The modified model data are in the graph in Figure 5; the vertical green lines indicate the intervals in which the model data were artificially modified.
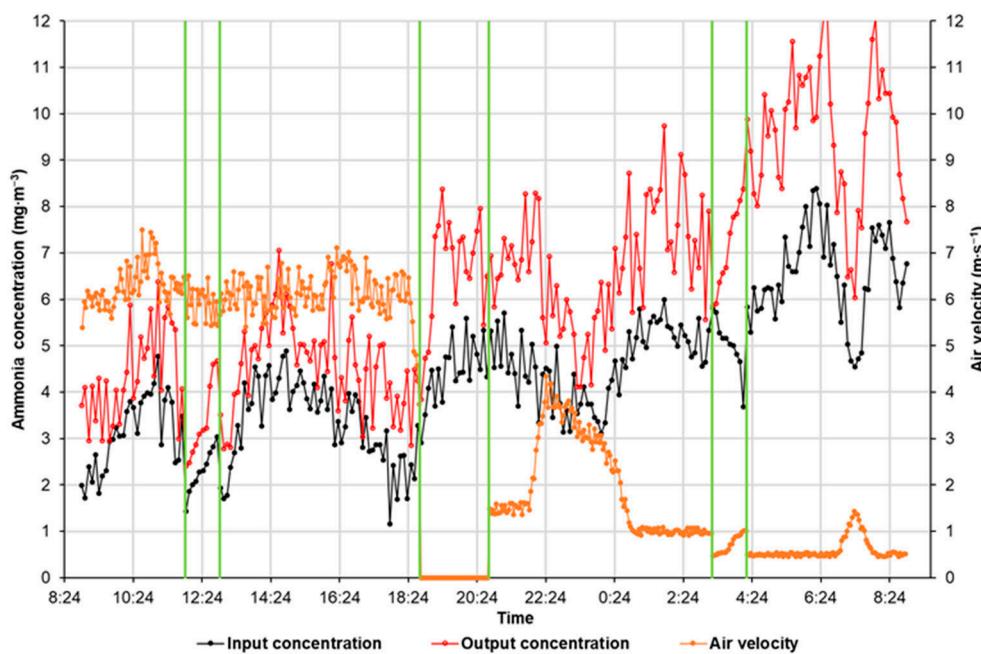
Figure 5. Creation of model values with randomly modified time intervals (three green gaps).

2.6. Testing the E Evaluation Method

The reference E_{ref} value was determined for testing of the developed methodology of the evaluation of ammonia emissions. It was determined analytically from Equation (1) on the basis of the known equations of the individual parts of the polylines from which the input variable waveforms were created (see Section 2.5).

We divided the methodology tests into two parts. The proposed E evaluation methodology was applied in every case. In the first part, we investigated the effect of the time window length on the average ammonia emissions over 24 h. The time window length was gradually chosen from a series of 15 min, 20 min, 30 min, 45 min, 60 min, 90 min, 2 h, 3 h, 4 h, 6 h, 8 h, and 12 h. The area of the vents exhaust and the number of housed animals corresponded to the real situation on which the model was based (see Section 2.2).

At first, the methodology was tested on a model polyline with no added noise to determine the effect of time window length on the total ammonia emissions. The obtained values were compared with the analytical E_{ref} reference using relative percentage deviation. Subsequently, the methodology was applied to both the unmodified model with added Gaussian noise and the artificially modified model to calculate ammonia emissions. The differences between the individual calculated values were tested using ANOVA analysis and Tukey's HSD test. Differences between calculated emissions of given time window lengths for both models were tested also by Student's *t*-test. The significance level of every statistical test was 0.05.

In the second part of the methodology testing, only a few windows were selected, and the influence of their length on the course of the specific emission curves during 24 h was monitored. As no statistically significant differences were found in the first phase of testing, no statistical method was not used in this part, but the calculated diurnal wave-forms were visually compared to each other.

3. Results

The reference ammonia emission E_{ref} was analytically determined to be 0.5767 mg·s^{-1} and 1.5157 kg·animal^{-1}·year^{-1}. The relative deviations of the calculated emissions of the model data without added noise were increased with increasing time window length. The lowest value of 0.17% was reached for the shortest 20 min time window. Similarly, for longer time windows up to 60 min it did not exceed 1.00%. On the contrary, the highest

value was calculated for the time window of 24 h length, where it reached up to 52.60%. However, despite the rather significant relative deviation, even ANOVA analysis together with Tukey's HSD test showed no statistically significant difference ($p > 0.999$), which may be due to the small sample size in the case of longer time windows.

The same *E* evaluation algorithm with time window selection was used for both unmodified and modified model data. The obtained *E* values for individual windows are shown in Figure 6 (unmodified model) and in Figure 7 (modified model). Both graphs show that with the increasing length of the time window, the average value of *E* increased, initially very slowly. For longer time windows the increase was more pronounced (for the time window of 12 h, *E* was more than 10% higher than for the time window of 15 min). The standard deviation also increased because 24 h of data was processed, which decreased the total number of time windows with its increasing length. Figure 6 shows that for time windows up to 2 h, the increase in *E* was very small, almost imperceptible (increase was less than 2.5% compared to the value for the 15 min time window), which implies that the effect of time windows of 2 h and below was practically negligible for the calculation of the average *E*.
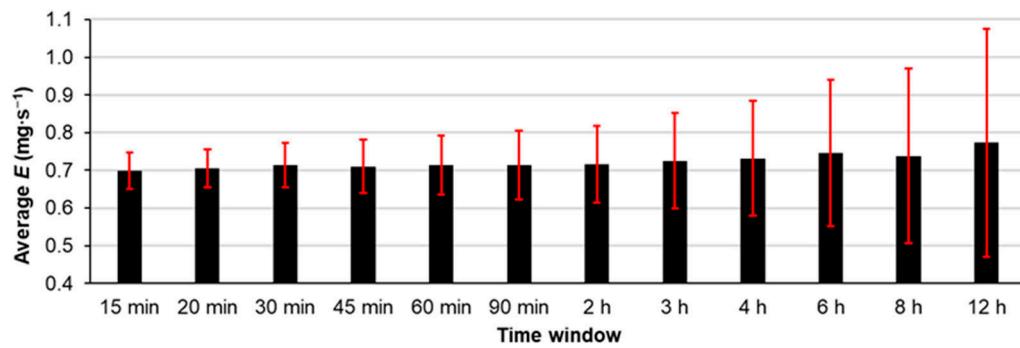
Figure 6. *E* dependence on the time window width for model data (vertical red lines are standard deviation bars).
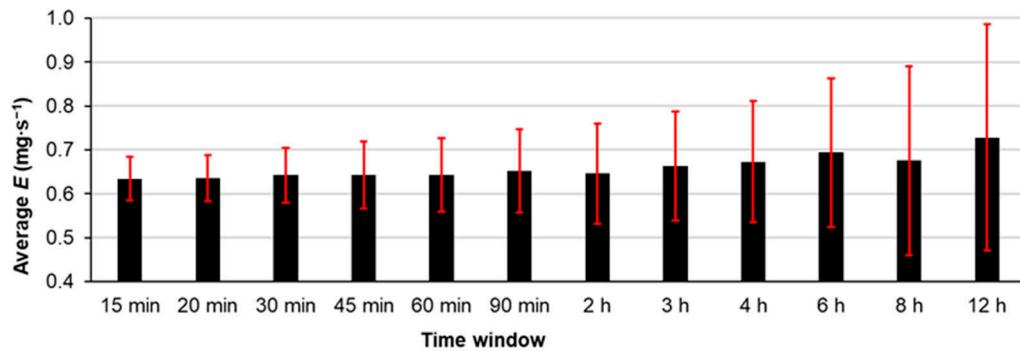
Figure 7. *E* dependence on the time window width for artificially modified model data (vertical red lines are standard deviation bars).

A similar situation can be observed in the case of an artificially modified model in Figure 7. Modifications to the model generally reduced the size of the average *E*, which corresponds to a zero contribution to the average *E* in the period simulating the failure of the anemometer. However, the modifications did not affect the trend of its dependence on the time window length. The increase in *E* for time windows up to 2 h did not exceed 3%, but at 12 h the time window was almost 15% higher than the calculations for the 15 min time window. Artificially created short-term singularities in the time courses of measured quantities thus had a very small effect on the average values of *E* when using the developed evaluation methodology with time windows up to 2 h. We can assume that the mentioned

singularities will not be present at all in real data, or they will be of shorter duration than was modeled, and thus will not affect the resulting specific annual NH_3 emissions.

In the second part of the methodology testing, only four-time windows were selected (30 min, 60 min, 2 h, and 3 h), and the influence of their length on the course of the specific emission curves during 24 h was monitored. The respective waveforms are shown in Figure 8 (unmodified model) and Figure 9 (modified model). It is clear from the waveforms for the individual time windows that the increasing length of the window significantly reduced the fluctuations of the calculated value of ammonia emissions; on the other hand, it significantly eliminated the actual fluctuations of the emissions during the day. For the time window of 3 h, it is possible to determine only the all-day trend of NH_3 emissions in the stable, and it is not possible to identify shorter-term singularities based on it.

When comparing the course of the polylines in Figures 8 and 9, the influence of artificial modifications of model data on the actual course of the curves was well visible. While the slightest adjustment corresponding to the real data trend (from 11:55:13 to 12:55:13) will not affect the actual waveforms too much and will only show a slight deviation in the shortest time window of 30 min, the same length adjustment from 3:14:17 to 4:14:17 already significantly changed the course of the curve for this time window and was also clearly visible when using the time window of 60 min. On the other hand, for longer time windows (2 and 3 h), these singularities had a negligible effect on the course of the curves. More significant influence on the curves was caused by the third adjustment simulating the failure of an anemometer in the time from 18:44:40 to 20:44:40, where all curves reacted significantly to this singularity. However, for the time window of 3 h, the response of the curve was distinctly smaller than that in the remaining three curves.
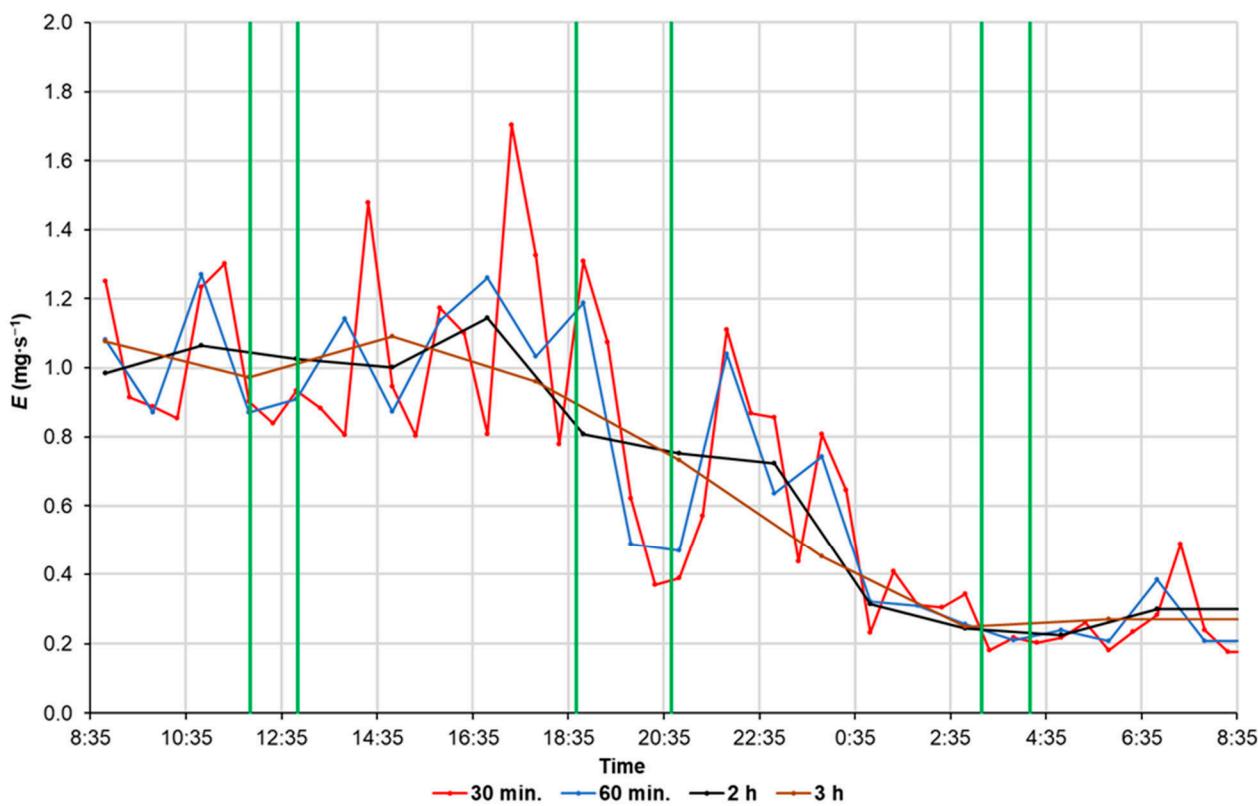
Figure 8. Dependence of the *E* value on time for different time window widths for model data (the vertical green lines indicate artificially modified intervals).
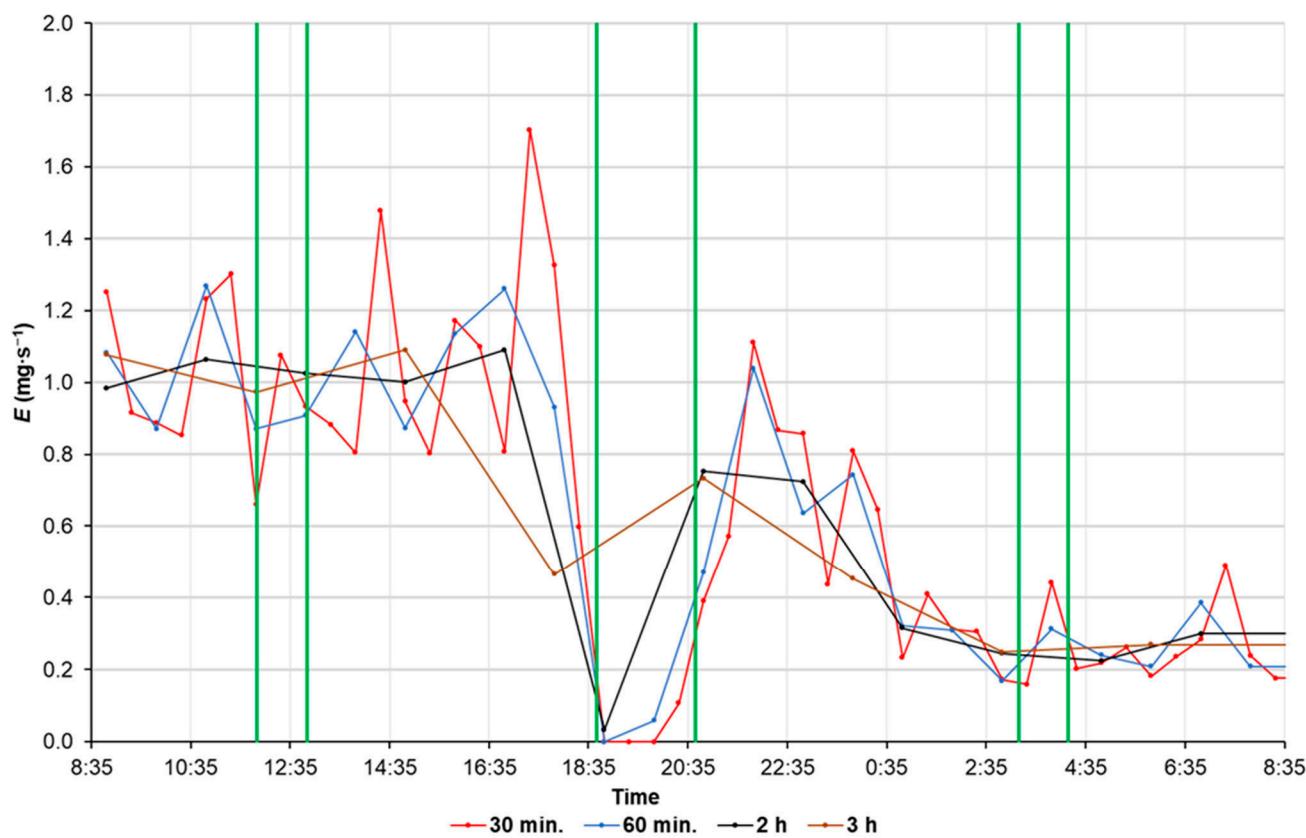
Figure 9. Dependence of the *E* value on time for different time window widths for artificially modified model data (the vertical green lines indicate artificially modified intervals).

4. Discussion

Similar measurements of ammonia emissions from pig houses were presented by other authors. A brief overview of selected parts of their methodologies is given in Table 1. Most of them used the Photoacoustic Multi-gas Monitor INNOVA 1412 and 1312, respectively, to measure ammonia concentration [27–34]. On the other hand, publications [35–38] reported other instruments used, such as the NO_x analyzer, to measure ammonia concentrations in livestock [35,38]. The variability in the total duration of measurements is very high, ranging from 8 h [36] to 345 days [38]. Sampling frequencies also vary among authors, ranging from one record per hour [36] to twelve measurements in one hour [37].

Nevertheless, compared to the articles published previously, this is the most detailed processing of measured data to determine the resulting NH_3 emissions. The calculation of total ammonia emissions was often based on the same equations as ours. Still, the authors did not address the effect of the length of the averaging interval on the resulting emissions. Almost all of them calculated the total mean and standard deviation of ammonia emissions based on daily means of ammonia concentrations, or they provided the minimum and maximum values. However, as our results showed, the *E* is influenced by the selected time window length. It turned out that it is necessary to set the time window as short as possible. Although no statistically significant difference was shown in our tests ($p > 0.999$, ANOVA, Tukey's HSD, Student's *t*-test), the total annual ammonia emissions estimation was based on diurnal averages of internal and outside concentrations, and airflow can lead to deviations of more than 50%. However, this discrepancy does not reduce the quality of the results of earlier published measurements because they presented the comparisons of the effect of changes in pig farming on emissions, and it was not intended to determine the total ammonia emission from buildings with maximum accuracy.

Table 1. Recent studies on the measurement of NH_3 emissions in pig farms and their methodology.

NH_3 Monitoring System	Experiment Duration	Sampling Frequency (Records per Hour)	Statistical Analysis	Reference
Innova 1312	37 days	6	Total mean, standard deviation	[31]
Air sampling pump Gilian Instrument 7lG9	8 h	1	Total mean, min. and max. values	[36]
Innova 1412	N/A [1]	N/A [1]	Total mean, min. and max. value	[27]
Innova 1312	20 h	1.18	Mean of individual measurement, standard deviation	[29,30]
Innova 1412	24 h	N/A [1]	Total mean, standard deviation	[28]
N/A [1]	345 days	5	Determination of factors to make predictions	[38]
NO_x analyzer with a thermal converter	24 h	8.6	Total mean, hourly means, day and night means, min. and max. values	[35]
Innova 1412	155 days	6	Daily means	[32]
Innova 1412	24 h	2	Daily means	[33]
Innova 1412	146–154 days	5	Daily means	[34]
iTX Multi-gas monitor	43–165 days	12	Daily means	[37]

[1] not available.

Generally, there are two ways to determine more accurate values for total emissions. The first uses less precise measurements but is performed over a very long period, e.g., [34,37,38]. However, not only is this much more time consuming, but it is also money consuming. The second way is based on the most accurate measurements over short time intervals. This approach requires measurements to be made at a high sampling frequency within one day, ideally. Such measures need to be repeated at different times of the year and during the breeding cycle. As shown in [38], it is possible to estimate annual ammonia production relatively accurately from precise measurements taken on only a few well-selected days during the breeding cycle. This direction fully follows the relevant legislation [26]. It will undoubtedly be preferred also regarding the high financial costs connected with the purchase and operation of suitable ammonia concentration measuring equipment for ordinary farmers.

The sampling frequency cannot be increased disproportionately because it is also limited by the measuring equipment. When one device is used to detect ammonia concentration at several sampling locations simultaneously, it is necessary to ensure sufficient cleaning time for replacing the air in the measuring chamber of the monitor and/or to reach equilibrium after switching to other air sampling locations before a new measurement starts. A sampling rate of 10 per hour seems to be sufficient for such measures. It means that a concentration value is recorded every 6 min. The proposed algorithm showed imperceptible differences for time windows from 15 min up to 3 h, but the deviation increases noticeably for a longer time window. Nevertheless, as the length of the time window decreases, fewer values are averaged, and the resulting mean is more sensitive to possible significantly deflected or even erroneous measurements. In the case of a 15 min time window, a maximum of three values is involved, which is a relatively small number; in the case of a 30 min window, five values will be averaged, and one significantly deflected value affects the mean less.

Hence, based on the performed tests of the methodology on model data and artificially modified model data, the ideal solution appears to be a time window of 30 min. There are enough averaged measurements, and such a time window is short enough to capture all short-term changes in the stable manifested by increased or reduced ammonia emissions during the day. When using longer time windows, it would not be possible to monitor deviations from the ordinary course of emission curves adequately, and it would be practically impossible to respond to problems arising in the stable for various reasons, either due to problems associated with animal welfare or only technologically associated with measurement methodology.

5. Conclusions

This study identifies suitable methods for determining NH_3 emissions from intensive livestock farming from the point of view of the calculation of measured data. The motivation for this article was that the methodology established by the legislation is only general, and different approaches are emerging across researchers. This can lead to different interpretive results. The precise identification and determination of NH_3 emissions seem essential for meeting legislative standards, developing technologies aimed at reducing these emissions. As NH_3 emissions are complex and depend on many factors, the effort is made to determine the resulting emissions from farms as accurately as possible.

Based on the performed tests of the methodology on model data and artificially modified model data, the most ideal solution appears to use a time window of 30 min to calculate measured data. When using it, there are enough averaged measurements (minimum of five values for concentrations and ten values for flow), which eliminates the effect of one potentially incorrectly performed measurement. On the other hand, such a time window is short enough to capture all short-term changes in the stable manifested by increased or reduced ammonia emissions during the day. When using longer time windows, it would not be possible to adequately monitor deviations from the normal course of emission curves. Use of longer time windows of 45 min, 90 min, and 2 h still seems satisfactory.

The findings from this study can be used to refine the methodology for calculation by measuring the NH_3 concentration and the ventilation rate. These procedures can be applied in the above cases due to the unification of methods for evaluation and better comparability of measured values between farms and authors.

References

1. Guthrie, S.; Giles, S.; Dunkerley, F.; Tabaqchali, H.; Harshfield, A.; Ioppolo, B.; Manville, C. *The Impact of Ammonia Emissions from Agriculture on Biodiversity*; The Royal Society Reports; Rand Corporation: Cambridge, UK, 2018. Available online: https://www.rand.org/content/dam/rand/pubs/research_reports/RR2600/RR2695/RAND_RR2695.pdf (accessed on 26 June 2021).
2. Krupa, S. Effects of atmospheric ammonia (NH3) on terrestrial vegetation: A review. *Environ. Pollut.* **2003**, *124*, 179–221. [CrossRef]
3. Renard, J.J.; Calidonna, S.E.; Henley, M.V. Fate of ammonia in the atmosphere—A review for applicability to hazardous releases. *J. Hazard. Mater.* **2004**, *108*, 29–60. [CrossRef] [PubMed]
4. Brunekreef, B.; Holgate, S.T. Air pollution and health. *Lancet* **2002**, *360*, 1233–1242. [CrossRef]
5. Visek, W. Some Aspects of Ammonia Toxicity in Animal Cells. *J. Dairy Sci.* **1968**, *51*, 286–295. [CrossRef]
6. Griffiths, R.; Megson, L. The effect of uncertainties in human toxic response on hazard range estimation for ammonia and chlorine. *Atmos. Environ.* **1984**, *18*, 1195–1206. [CrossRef]
7. Naseem, S.; King, A.J. Ammonia production in poultry houses can affect health of humans, birds, and the environment—Techniques for its reduction during poultry production. *Environ. Sci. Pollut. Res.* **2018**, *25*, 15269–15293. [CrossRef]
8. Donham, K.J. The Concentration of Swine Production: Effects on Swine Health, Productivity, Human Health, and the Environment. *Vet.-Clin. N. Am. Food Anim. Pract.* **2000**, *16*, 559–597. [CrossRef]

9.   Kim, K.Y.; Ko, H.J.; Kim, H.T.; Kim, C.N.; Byeon, S.H. Association between pig activity and environmental factors in pig confinement buildings. *Aust. J. Exp. Agric.* **2008**, *48*, 680–686. [CrossRef]

10. ElAssouli, S.M.; Alqahtani, M.H.; Milaat, W. Genotoxicity of Air Borne Particulates Assessed by Comet and the Salmonella Mutagenicity Test in Jeddah, Saudi Arabia. *Int. J. Environ. Res. Public Health* **2007**, *4*, 216–223. [CrossRef]

11. Claxton, L.D.; Woodall, G.M., Jr. A review of the mutagenicity and rodent carcinogenicity of ambient air. *Mutat. Res. Rev. Mutat. Res.* **2007**, *636*, 36–94. [CrossRef]

12. van Zelm, R.; Huijbregts, M.; Hollander, H.A.D.; van Jaarsveld, H.A.; Sauter, F.J.; Struijs, J.; van Wijnen, H.J.; van de Meent, D. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmos. Environ.* **2008**, *42*, 441–453. [CrossRef]

13. EEA. European Environment Agency. Ammonia (NH3) Emissions. European Environment Agency Retrieved 02/01/2019. 2019. Available online: http://www.eea.europa.eu/data-and-maps/indicators/eea-32-ammonia-nh3-emissions-1/assessment-4 (accessed on 10 July 2021).

14. EUROSTAT. *Agriculture, Forestry and Fishery Statistics*; European Union: Brussels, Belgium, 2016.

15. Clarisse, L.; Clerbaux, C.; Dentener, F.J.; Hurtmans, D.; Coheur, P.-F. Global ammonia distribution derived from infrared satellite observations. *Nat. Geosci.* **2009**, *2*, 479–483. [CrossRef]

16. Waldrip, H.; Cole, N.A.; Todd, R.W. Review: Nitrogen sustainability and beef cattle feedyards: II Ammonia emissions. *Prof. Anim. Sci.* **2015**, *31*, 395–411. [CrossRef]

17. Groenestein, C.; Van Faassen, H. Volatilization of Ammonia, Nitrous Oxide and Nitric Oxide in Deep-litter Systems for Fattening Pigs. *J. Agric. Eng. Res.* **1996**, *65*, 269–274. [CrossRef]

18. Insausti, M.; Timmis, R.; Kinnersley, R.; Rufino, M. Advances in sensing ammonia from agricultural sources. *Sci. Total Environ.* **2020**, *706*, 135124. [CrossRef]

19. Olivier, J.; Bouwman, L.; Van der Hoek, K.; Berdowski, J. Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990. *Environ. Pollut.* **1998**, *102*, 135–148. [CrossRef]

20. Misselbrook, T.; van der Weerden, T.; Pain, B.; Jarvis, S.; Chambers, B.; Smith, K.; Phillips, V.; Demmers, T. Ammonia emission factors for UK agriculture. *Atmos. Environ.* **2000**, *34*, 871–880. [CrossRef]

21. Canh, T.T.; Aarnink, A.J.A.; Mroz, Z.; Jongbloed, A.W.; Schrama, J.W.; Verstegen, M.W.A. Influence of electrolyte balance and acidifying calcium salts in the diet of growing-finishing pigs on urinary pH, slurry pH and ammonia volatilisation from slurry. *Livest. Prod. Sci.* **1998**, *56*, 1–13. [CrossRef]

22. Arogo, J.; Westerman, P.W.; Heber, A.J.; Robarge, W.P.; Classen, J.J. *Ammonia Emissions from Animal Feeding Operations*; Report: White Papers; National Center for Manure & Animal Waste Management: Raleigh, NC, USA, 2001.

23. Faulkner, W.; Shaw, B. Review of ammonia emission factors for United States animal agriculture. *Atmos. Environ.* **2008**, *42*, 6567–6574. [CrossRef]

24. Santonja, G.G.; Georgitzikis, K.; Scalet, B.M.; Montobbio, P.; Roudier, S.; Sancho, L.D. *Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs*; EUR 28674 EN; Publications Office of the European Union: Luxembourg, 2017. [CrossRef]

25. U.S. EPA. *EPA's Report on the Environment (ROE)*; U.S. Environmental Protection Agency: Washington, DC, USA, 2008.

26. Council Directive 2010/75/EU of 15 February 2017 Establishing Best Available Techniques (BAT) Conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for the Intensive Rearing of Poultry or Pigs. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2017.043.01.0231.01.ENG (accessed on 27 October 2021).

27. Xie, Q.; Ni, J.-Q.; Su, Z. A prediction model of ammonia emission from a fattening pig room based on the indoor concentration using adaptive neuro fuzzy inference system. *J. Hazard. Mater.* **2017**, *325*, 301–309. [CrossRef] [PubMed]

28. Zong, C.; Feng, Y.; Zhang, G.; Hansen, M.J. Effects of different air inlets on indoor air quality and ammonia emission from two experimental fattening pig rooms with partial pit ventilation system—Summer condition. *Biosyst. Eng.* **2014**, *122*, 163–173. [CrossRef]

29. Ye, Z.; Zhu, S.; Kai, P.; Li, B.; Blanes-Vidal, V.; Pan, J.; Wang, C.; Zhang, G. Key factors driving ammonia emissions from a pig house slurry pit. *Biosyst. Eng.* **2011**, *108*, 195–203. [CrossRef]

30. Saha, C.; Zhang, G.; Kai, P.; Bjerg, B. Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. *Biosyst. Eng.* **2010**, *105*, 279–287. [CrossRef]

31. Blanes-Vidal, V.; Hansen, M.; Pedersen, S.; Rom, H. Emissions of ammonia, methane and nitrous oxide from pig houses and slurry: Effects of rooting material, animal activity and ventilation flow. *Agric. Ecosyst. Environ.* **2008**, *124*, 237–244. [CrossRef]

32. Liu, S.; Ni, J.-Q.; Radcliffe, J.S.; Vonderohe, C.E. Mitigation of ammonia emissions from pig production using reduced dietary crude protein with amino acid supplementation. *Bioresour. Technol.* **2017**, *233*, 200–208. [CrossRef] [PubMed]

33. Jeppsson, K.-H.; Olsson, A.-C.; Nasirahmadi, A. Cooling growing/finishing pigs with showers in the slatted area: Effect on animal occupation area, pen fouling and ammonia emission. *Livest. Sci.* **2021**, *243*, 104377. [CrossRef]

34. Ni, J.-Q.; Shi, C.; Liu, S.; Richert, B.T.; Vonderohe, C.E.; Radcliffe, J.S. Effects of antibiotic-free pig rearing on ammonia emissions from five pairs of swine rooms in a wean-to-finish experiment. *Environ. Int.* **2019**, *131*, 104931. [CrossRef]

35. Phillips, V.; Holden, M.; Sneath, R.; Short, J.; White, R.; Hartung, J.; Seedorf, J.; Schröder, M.; Linkert, K.; Pedersen, S.; et al. The Development of Robust Methods for Measuring Concentrations and Emission Rates of Gaseous and Particulate Air Pollutants in Livestock Buildings. *J. Agric. Eng. Res.* **1998**, *70*, 11–24. [CrossRef]

36. Kim, K.Y.; Ko, H.J.; Kim, H.T.; Kim, Y.S.; Roh, Y.M.; Lee, C.M.; Kim, C.N. Quantification of ammonia and hydrogen sulfide emitted from pig buildings in Korea. *J. Environ. Manag.* **2008**, *88*, 195–202. [CrossRef]
37. Hayes, E.; Curran, T.; Dodd, V. Odour and ammonia emissions from intensive pig units in Ireland. *Bioresour. Technol.* **2006**, *97*, 940–948. [CrossRef]
38. Vranken, E.; Claes, S.; Hendriks, J.; Darius, P.; Berckmans, D. Intermittent Measurements to determine Ammonia Emissions from Livestock Buildings. *Biosyst. Eng.* **2004**, *88*, 351–358. [CrossRef]

Article

Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic

Radim Kunes [1,*], Zbynek Havelka [1], Pavel Olsan [1], Antonin Dolan [1], Radim Stehlik [1], Bojana Petrovic [1], Lubos Smutny [1], Petr Bartos [1,2], Maohua Xiao [3], Pavel Kriz [1,2] and Pavel Cerny [1,2]

[1] Department of Technology and Cybernetics, Faculty of Agriculture and Technology, University of South Bohemia, Studentska 1668, 37005 Ceske Budejovice, Czech Republic
[2] Department of Applied Physics and Technology, Faculty of Education, University of South Bohemia, Jeronymova 10, 37115 Ceske Budejovice, Czech Republic
[3] College of Engineering, Nanjing Agricultural University, Nanjing 210031, China
[*] Correspondence: kunesr@fzt.jcu.cz; Tel.: +420-606263674

Abstract: This study compares three approaches in the monitoring of ammonia (NH_3) emissions from intensive breeding of fattening pigs in relation to compliance with the standards arising from the requirements of Integrated Pollution Prevention and Control (IPPC) used in the Czech Republic. The first approach was based on the determination of NH_3 emissions calculation by measurement using reduced sampling days focused on the final fattening phase. The second approach was based on the determination of NH_3 emissions calculation by measurement respecting the Best Reference Document for Intensive Rearing of Poultry or Pig (BREF IRPP) and relevant best available techniques (BAT) conclusions under Directive 2010/75/EU. The third approach was based on estimation by using emission factors respecting BREF IRPP and Methodological Instruction of the Air Protection Department of the Czech Republic. The results show that the determined emission factors in the Czech Republic may not always reflect the actual production of NH_3 emissions even when reduced by the applied BAT. Determination of NH_3 emissions calculation by measurement respecting BREF IRPP represents the predominant phases of fattening (refinement) and microclimatic conditions; however, it is time and money-consuming.

Keywords: air pollution; IPPC; pig farm; BREF; BAT

1. Introduction

The largest source of NH_3 emissions is agriculture, including animal husbandry and NH_3-based fertilizer applications [1]. Nowadays, animal husbandry is a significant source of CH_4, NO_x, CO_2, and NH_3 in agriculture [2]. NH_3 release into the atmosphere is caused by the reactions of urease enzyme or microbial activity while consuming unconverted nitrogen originating from high-protein feeds used to fulfill nutritional requirements [3]. Nitrogen-based emissions are probably caused by NH_3 (NH_3-N) losses from the interconversion of total ammoniacal nitrogen (NH_3-N + NH_4^+-N) and organic nitrogen, eventually in the case of the aqueous equilibrium of (NH_3-N) and (NH_4^+-N) [4]. NH_3 emissions have a negative influence on the environment. After deposing the ecosystems, excess nitrogen, including NH_3, could cause nutrient imbalances and eutrophication. NH_3 also plays a primary role in the deterioration of atmospheric visibility as nitrogen is deposited in the atmosphere [5]. NH_3, as a prevalent harmful gas in the atmosphere with an amount of approximately 55 Tg-N, reacts chemically with other gases such as SO_2 and neutralizes the hydrogen ion. It remains in the atmosphere for a short time, a few hours to a day, and it

mostly returns to the ground, but in an altered form [6]. Humans and land animals are at low risk of contracting illnesses due to ammonium consumption [7].

However, an increase in NH_3 concentration contributes to particulate matter ($PM_{2.5}$) formation in the atmosphere. The contribution of NH_3 to atmospheric aerosols affects human health, which can increase the likelihood of hospitalization [8]. As a result of exposure to fine $PM_{2.5}$, air pollution is one of the leading causes of damage to human health in Europe with an estimate of about 380,000 premature deaths per year in the European Union (EU) [9]. Furthermore, NH_3 emissions are expected to increase [10], which gives cause for concern. In the EU, the focus lies on pig and poultry housing facilities, which contribute to NH_3 emissions [11]. According to [12], pig farming is globally responsible for about 15% of emissions associated with livestock breeding. Worldwide pig consumption had been expected to increase by 75% between 2000 and 2020 [13].

Furthermore, [14] stated that pig production is responsible for nearly 25% of livestock NH_3 emissions. If all assessments of the environmental impacts of the areas of NH_3 emission are handled in a new area-based regulation, it would be possible to issue an environmental permit where the production is kept in the existing pig buildings even with increased pig production [15]. Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions (integrated pollution prevention and control), which sets out rules for reducing emissions to air, water, and land and preventing waste, is intended to help reduce the production of NH_3 and other harmful substances from intensive livestock farming. It also applies to intensive poultry farms with a capacity of more than 40,000, fattening pig farms with a capacity of more than 2000, or sow farms with a capacity of more than 750. These farms must have an integrated operating permit [16]. In order to achieve environmental standards, they use the best available techniques (BAT), which are listed in the Best Reference Document for Intensive Rearing of Poultry or Pig (BREF IRPP) [17]. The implementation of these policies has resulted in an estimated 40–85% reduction in emissions over the last 15 years, depending on the pollutant [18]. Ref. [19] provides in his study an overview of BAT that reduce emissions from livestock production. They divide them according to the areas of application into: emission reduction by modifying the animals' diet (reduction of nitrogen and phosphorus excretion), methods of emission reduction in connection with livestock housing (floor modification, ventilation, air cleaning, removal, and storage of excreta), principles of proper manure storage (covering of storage areas, modification of composition, appropriate placement), and spreading of manure on the soil (technology of spreading, time of application from spreading).

Monitoring of NH_3 emissions in the EU is currently incomplete but should continue, especially for pig breeding. All the essential factors for building structures and management policies are linked to animal well-being, indoor air quality, and environmental pollution [20]. The magnitude of emissions and factors influencing emissions from pig farming can only be studied if proper measurement techniques are available [21]. Techniques for monitoring the production of NH_3 emissions according to BAT 25.C [22] include:

- *Estimation using mass balance by excreted and total nitrogen (or ammoniacal).* Estimation by excreted nitrogen or total ammoniacal nitrogen and volatilization coefficients for each stage of manure handling (housing, storage, landspreading). The general equations for the calculation are:

$$E_{housing} = N_{excreted} \cdot VC_{housing}, \tag{1}$$

$$E_{storage} = N_{storage} \cdot VC_{storage}, \tag{2}$$

$$E_{spreading} = N_{spreading} \cdot VC_{spreading}, \tag{3}$$

where E is the annual NH_3 emission, N is the total annual excreted nitrogen or ammoniacal nitrogen, and VC is the volatilization coefficient, which is specified in international or national protocols for each EU country [22].

- *Calculation by measuring the internal NH₃ concentration and ventilation performance*. Monitoring should be carried out on at least 6 days divided over one year. Fattening pigs is defined as a farm with a linear increase in emissions per breeding cycle; therefore, the measurement days are evenly distributed over the growing period (50% of the measurements in the first half of the breeding cycle and 50% of the measurements in the second half of the breeding cycle). The daily average is calculated as the mean over all sampling days. One measurement shall be taken over a 24 h period and shall be taken at the air inlet and outlet of the housing (breeding pen). The daily average of NH₃ emissions is multiplied by the number of days the housing is occupied to obtain the annual emissions [22,23].
- *Estimation using emission factors*. NH₃ emissions are estimated using emission factors determined according to national or international protocols. These are determined on the basis of housing, manure storage, and landspreading [22].

Therefore, this study aimed to compare three approaches for the determination of NH₃ emissions from intensive fattening pig farming.

The first approach basically determined NH₃ emissions by calculation from measurements of the internal NH₃ concentration in the breeding house with reduced sampling days focused on the final fattening phase.

The second approach basically determined NH₃ emissions by calculation from measurements of the internal NH₃ concentration in the breeding house, strictly BREF IRPP [17] and relevant BAT conclusions under Directive 2010/75/EU [22].

The third approach was determined according to the estimation by emission factors that are valid in the Czech Republic [24] and respect BREF IRPP [17].

2. Materials and Methods

2.1. Methodology for Determining NH₃ Emissions by Calculation from Measurements of the Internal NH₃ Concentration

Two approaches were used to monitor NH₃ emissions by intensive fattening pig farms. The first approach was breeding monitoring, chosen arbitrarily during the fattening cycle and focused mainly on the final stages. This is mainly because the final phase is expected to produce more NH₃ emissions, and thus has a more representative impact on the environment and the possibility of comparison with emission limits.

The second approach was based on the monitoring of NH₃ emissions according to BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22]. The basis of the methodology is to take measurements during six days of the period of interest (year). Fattening pigs are classified as breeding with a linear increase in NH₃ emissions. The sampling days will be evenly distributed over the growing season. Half of the measurements shall be taken in the first half of the breeding cycle and the remainder in the second half. The sampling days in the second half of the breeding cycle shall be evenly distributed throughout the year (same number of measurements per season). The daily average was calculated as the mean overall sampling days.

2.2. Methodology Measurement of the NH₃ Concentration and Calculation of NH₃ Emissions

For assessing NH₃ emissions, it is essential to follow the methodology set out in BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22]. Therefore, it is essential to determine the NH₃ concentrations at the inlet and outlet of the stable and to measure the airflow out of the stable at the same time for a period of 24 h.

For the measurement of NH₃ was used the photoacoustic multi-gas monitor INNOVA 1512 by Advanced Energy Industries, Inc, United States of America. The instrument works based on the principle of the infrared photoacoustic method. It is supplemented by a switch of measuring points Innova Multipoint Sampler 1409 D with the possibility of taking air samples from up to twelve places. The device continuously uploads the measured values to its internal memory, and the sampling frequency was set to 6 min. The flow meter was used to analyze the airflow from the stable by TESTO 445, TESTO AG, Lenzkirch, Germany.

Climatic and microclimatic conditions were also monitored during the measurements (temperature, relative humidity, and atmospheric pressure) by COMMETER D4141 and COMMETER S3120 COMET SYSTEM spol. s r.o., Rožnov pod Radhoštěm, Czech Republic.

For the calculation of NH_3 emissions, a methodology [25] was selected based on the BREF IRPP. It also details how the measured data were evaluated during the 24 h measuring cycle.

The NH_3 emission rate E (mg·s^{-1}) can be now figured out from this formula:

$$E = (C_{OUT} - C_{IN}) \cdot v \cdot S, \qquad (4)$$

where C_{OUT} is NH_3 concentration in an outlet (mg·m^{-3}), C_{IN} is NH_3 concentration in the input (mg·m^{-3}), v is the air velocity caused by the stable ventilation (m·s^{-1}), and S is the area of the exhaust of the ventilation (m^2).

The arithmetic mean and standard deviation are determined from all obtained values of effective emissions during one day (24 h). Subsequently, the total production-specific emissions per year E_{YEAR} (kg NH_3·animal^{-1}·year^{-1}) are determined and converted to a value per pig using this formula:

$$E_{YEAR} = E_{AVG} \cdot N^{-1}, \qquad (5)$$

where E_{AVG} is the arithmetic mean of the E (kg NH_3·year^{-1}), and N is the number of pigs housed in the stable.

2.3. Experimental Pig Houses

Monitoring of NH_3 emissions was carried out in intensive fattening pig farms located in the South Bohemia region in the Czech Republic. Different BATs were used in the breeding, see Table 1. Two approaches were used for this monitoring:

(1) The first approach aimed to monitor breeding farms by using measurements in the final fattening phase to represent the farm in terms of NH_3 emissions. These breeding farms are listed below.

The farm in Jindřichův Hradec district (420 m above sea level) was equipped with a fully slated floor with a deep pit (BAT 30.a0) in a combination with feed additives Axtra Phy (Danisco Animal Nutrition, Marlborough, Great Britain), BioAktiv (BioAktiv GmbH. Zeitz, Germany), Fresta F Plus (Delacon Biotechnik GmbH, Engerwitzdorf, Austria), and Algitek AD (Tekro s.r.o., Prague, the Czech Republic). Air exchange is provided by forced negative pressure ventilation. There are seven ceiling fans with a diameter of 0.4 m in the breeding pen.

In the Tábor district, there were two farms (first farm Tábor No.1, second farm Tábor No.2). Tábor farm No. 1 (424 m above sea level) had a slated floor with a deep pit (BAT 30.a0) in combination with feed additives Synergen (Alltech, Inc., Nicholasville, KY, USA) and Fortibach F Plus (Addicoo Group s.r.o., Sumperk, the Czech Republic). Air exchange is provided by forced positive pressure ventilation. There are five ceiling shafts in the breeding pen with a diameter of 0.5 m × 0.5 m. Fresh air is supplied by four side fans with a diameter of 0.4 m.

The Tábor farm No. 2 (439 m above sea level) used a deep litter on a solid concrete floor (BAT 30.a8) in combination with feed additives 6-Phytase 1500 FTU (Danisco Animal Nutrition, Great Britain) and Quantum Blue (Roal Oy, Rajamäki, Finland). Air exchange is provided by forced positive pressure ventilation. There are four ceiling shafts in the breeding pen with a diameter of 0.5 m × 0.5 m. Fresh air is supplied by four side fans with a diameter of 0.35 m.

Příbram district (470 m above sea level) had a farm with a fully slated floor with a deep pit (BAT 30.a0) in combination with feed additives Natuphos (BASF a.g, Düsseldorf, Germany) and Quantum Blue (Roal Oy, Rajamäki, Finland). Air exchange is provided by forced negative pressure ventilation. In the breeding pen, there are four under-slatted fans with a diameter of 0.6 m. Fresh air is supplied by ten wall flaps with a dimension of 0.9 m × 0.3 m.

(2)   The second approach aimed to monitor farms that have been monitored according to BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22] methodology, which specifies an even distribution of six sampling days over the growing season (same number of measurements per season). Half of the measurements have been performed in the first half of the breeding cycle and the rest in the second half.

Monitoring was carried out on the farm located in the České Budějovice district (438 m above sea level). The farm was equipped with a fully slated floor with a deep pit (BAT 30.a0) in a combination with feed additives 6-Phytase 1 500 FTU (Danisco Animal Nutrition, Marlborough, Great Britain) and Forbtibach F Plus (Addicoo Group s.r.o., Sumperk, the Czech Republic). Air exchange is provided by forced negative pressure ventilation. In the breeding pen, there are eight ceiling fans with a diameter of 0.7 m. Fresh air is supplied by side flaps on both sides of the hall (18 pieces) with a dimension of 0.3 m × 0.6 m.

Table 1. BAT applications in selected breeds.

Districts	Designation of BAT for Housing	Effectiveness in Reducing NH_3 Emissions by Using BAT for Housing (%)	Feed Additives	Effectiveness in Reducing NH_3 Emissions by Using Feed Additives (%)
Jindřichův Hradec	BAT 30.a0	25	Axtra Phy BioAktiv Fresta F Plus Algitek AD	23 27 27 45
Tábor (Farm No. 1)	BAT 30.a0	25	Synergen Fortibach F Plus	39 48
Tábor (Farm No. 2)	BAT 30.a8	0	6-Phytase 1500 FTU Quantum Blue	23 22
Příbram	BAT 30.a0	25	Natuphos Quantum Blue	29 22
České Budějovice	BAT 30.a0	25	6-Phytase 1500 FTU Fortibach F Plus	23 48

2.4. Methodology for Estimation of NH_3 Emissions by Using Emission Factors

The third approach was determined according to the estimation by emission factors that are valid in the Czech Republic [24] and respect BREF IRPP [17]. Emission factor is determined based on scientific knowledge and varies according to the category of animals, the number of animals, and the occupancy during the year. These factors (Table 2) were established in the Czech Republic in the past on the basis of experimental measurements made to represent local breeding conditions.

Table 2. Emission factors specified in the Czech Republic in (kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$) [24].

Animal Category	Housing	Manure Storage	Landspreading
Piglets	2.0	2.0	2.5
Sows	4.3	2.8	4.8
Gestating sows	7.6	4.1	8.0
Fattening pigs	3.2	2.0	3.1

In the Czech Republic, from the breeding process of fattening pig's, the total emission factor is determined at 8.3 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$. Of those, 3.2 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$ represents NH_3 emissions from housing, 2.0 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$ from manure storage, and 3.1 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$ from landspreading. For the purpose of this study, an emission factor is considered that represents the NH_3 emissions from the housing (3.2 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$) [24]. According to [24], the emission factor from each area (housing, manure storage, landspreading) may be reduced by the BAT used. The farmer can use a combination of reducing BAT based on the housing system and BAT based on

feeding measures in the stables. Since the exact effect level of both reducing BAT cannot be determined, only the one with the higher reducing effect is counted in the calculation.

3. Results

3.1. Climatic and Microclimatic Conditions

As mentioned in the previous chapter, the climatic and microclimatic conditions (temperature, relative humidity, atmospheric pressure, air velocity) that prevailed during each measurement were also monitored in each studied area. Table 3 shows the values for the farms that were selected in terms of similar age and weight groups during arbitrary monitoring. Table 4 shows the values for the farm in České Budějovice district, where two complete breeding cycles were monitored in each of the two sections that could be monitored during the year.

Table 3. Climatic and microclimatic conditions during the first approach monitoring.

Districts	Number of Pigs (pc)	Weight (kg)	Outdoor Temperature (°C)	Indoor Temperature (°C)	Outdoor Humidity (%)	Indoor Humidity (%)	Atmospheric Pressure (hPa)	Airflow Rate $(m^3 \cdot s^{-1})$
Jindřichův Hradec	450	100.0	−0.7	9.3	90.4	70.8	972.2	6.80
	703	90.0	5.3	12.3	53.3	57.9	964.1	7.26
Tábor (Farm No. 1)	196	102.0	16.5	19.1	39.1	70.0	968.5	2.36
	198	102.0	−0.9	20.8	35.1	65.2	968.5	3.55
Tábor (Farm No. 2)	256	90.0	18.3	21.1	48.1	55.7	969.7	19.07
Příbram	156	91.0	15.2	23.2	31.1	58.9	963.4	1.90

Table 4. Climatic and microclimatic conditions during the second approach monitoring.

Breeding Section	Breeding Cycle	Number of Pigs (pc)	Weight (kg)	Outdoor Temperature (°C)	Indoor Temperature (°C)	Outdoor Humidity (%)	Indoor Humidity (%)	Atmospheric Pressure (hPa)	Airflow Rate $(m^3 \cdot s^{-1})$
1	1	676	25.0	0.4	17.1	68.6	70.8	967.9	1.13
		627	51.0	0.5	20.6	94.0	67.5	942.7	1.72
		579	75.1	10.2	17.7	47.1	57.8	967.5	1.75
		560	99.3	17.1	21.6	31.3	42.1	967.2	19.85
		558	103.2	22.5	24.2	51.2	66.7	965.5	21.42
	2	680	18.0	17.1	18.7	73.1	75.7	964.1	6.01
		653	33.2	26.6	24.8	54.3	63.0	965.7	19.86
		611	70.7	21.4	21.4	49.6	57.0	972.5	19.31
		606	88.7	14.0	20.0	57.3	58.4	968.4	9.31
		559	120.0	12.1	19.6	84.5	64.1	961.8	7.92
2	1	676	25.0	0.4	19.2	68.6	75.7	966.8	1.03
		599	49.6	0.5	21.1	94.0	64.2	943.2	1.70
		576	73.3	10.2	17.2	47.1	52.2	968.8	1.70
		536	97.3	17.1	21.0	31.3	44.9	967.5	19.80
		533	102.9	22.5	25.0	51.2	60.4	965.7	21.39
	2	680	21.0	17.1	17.1	73.1	77.6	965.8	6.20
		659	35.2	26.6	25.4	54.3	66.1	965.8	19.80
		630	64.7	21.4	21.7	49.6	58.5	972.5	15.33
		606	94.7	14.0	19.9	57.3	57.3	968.5	9.81
		545	112.0	12.1	17.3	84.5	69.9	961.8	7.95

3.2. Results of NH$_3$ Emissions Values

The resulting calculated NH$_3$ emissions values for both monitoring groups are presented in Tables 5 and 6. They have listed different breeding and feed technologies, including the feed additives used and their percentage of effectiveness in reducing NH$_3$ emissions.

Table 5. Results of the calculated NH$_3$ emission from the first approach monitoring.

Districts	Weight (kg)	Date of Measurement	NH$_3$ Emissions (kg NH$_3$·animal^{-1}·year^{-1})
Jindřichův Hradec	100	10–11 February	1.92 ± 0.01
	90	9–10 May	1.00 ± 0.04
Tábor (Farm No. 1)	102	14–15 February	1.75 ± 0.04
	102	4–5 September	3.51 ± 0.03
Tábor (Farm No. 2)	90	3–4 July	2.03 ± 0.08
Příbram	91	13–14 September	1.45 ± 0.03

Table 6. Results of the calculation of NH$_3$ emission from the second approach monitoring.

Section	Breeding Cycle	No. of Measurement	Weight of Pigs (kg)	Date of Measurements	Calculated NH$_3$ Emission According to BREF IRPP	Measured NH$_3$ Emission
					(kg NH$_3$·animal^{-1}·year^{-1})	
1	1	A1	25.0	8–9 February		0.18 ± 0.02
		A2	51.0	6–7 March		0.13 ± 0.01
		A3	75.1	5–6 April		0.18 ± 0.03
		A4	99.3	7–8 May		0.77 ± 0.04
		A5	103.2	31 May–1 June	0.91 ± 0.02	0.67 ± 0.02
	2	A6	18.0	11–12 June		0.71 ± 0.03
		A7	33.2	8–9 August		1.67 ± 0.03
		A8	70.7	11–12 September		1.71 ± 0.03
		A9	88.7	16–17 October		2.22 ± 0.02
		A10	120.0	6–7 November		1.06 ± 0.02
2	1	A11	25.0	8–9 February		0.21 ± 0.02
		A12	49.6	6–7 March		0.22 ± 0.02
		A13	73.3	5–6 April		0.23 ± 0.03
		A14	97.3	7–8 May		1.35 ± 0.04
		A15	102.9	31 May–1 June	1.03 ± 0.03	1.49 ± 0.02
	2	A16	21.0	11–12 June		0.65 ± 0.03
		A17	35.2	8–9 August		3.10 ± 0.04
		A18	64.7	11–12 September		1.93 ± 0.03
		A19	94.7	16–17 October		2.12 ± 0.03
		A20	112.0	6–7 November		1.49 ± 0.02

The measurements of NH$_3$ emissions during the breeding cycle in the České Budějovice district from fattening pigs have been investigated too. The investigation was performed for two breeding cycles in one section and two breeding cycles in the second section. For each breeding cycle, the measurements of five repetitions were performed. The first fattening cycle occurred between February and June; the second one was between June and November. A total of 20 measurements were taken here, monitoring fattening pigs in two breeding sections. The authors managed to monitor two complete fattening cycles in each breeding section. For experimental reasons, the number of measurements was overestimated compared with the above-mentioned methodology. Otherwise, three measurements for each breeding cycle would have been sufficient.

To calculate the NH$_3$ emissions in accordance with the BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22] methodology, regarding Section 1, the first three measurements from the first breeding cycle (No. A1, A2, A3) and the last three measurements from the second breeding cycle (No. A8, A9, A10) were used. A similar procedure was followed for Section 2.

4. Discussion

To determine NH$_3$ emissions from intensive livestock breeding, methodologies have been developed to estimate these emissions based on the data from the operating conditions. In general, NH$_3$ emissions can be determined by calculation from measurements of the

internal NH_3 concentration in the breeding house, emission factors, or using a mass balance based on the total nitrogen.

In the Czech Republic, emission factors are mainly used to determine NH_3 emissions. This approach is popular because of its financial and time-saving benefits. The emission factors are set out in the national protocol [24]. For our analysis, we will only use an emission factor that considers the air emissions from the stables (3.2 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$). Technologies used to reduce NH_3 emissions are also considered; therefore, this value will be reduced by the BAT used. The farmer can use a combination of BAT reducing emissions from the housing system. Since the exact effect level of more reducing BATs cannot be determined, only the one with the higher reducing effect is counted in the calculation.

Table 7 shows that the emission factors are set for farming conditions that do not use any BAT. Therefore, it is advantageous for the farmers to reduce the calculated emissions by the efficiency of the most efficient BAT. It can also be seen that even if some NH_3 emission values exceed the stated value of emission factor of 3.2 kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$ during monitoring, this value is overestimated in terms of the evolution of emissions over the entire breeding period. Exceedances occur mainly at the end of the fattening period in the summer months. From a theoretical point of view, it is clear that combining BAT for housing and feeding results in more significant emission reductions than farmers can account for in the final calculations, where they can only apply a percentage reduction for the more efficient BAT. Estimating realistic emission reductions using BAT for feed is challenging, as farmers combine different feed additives with varying effectiveness in reducing NH_3 emissions.

Table 7. Determination of NH_3 emissions (kg $NH_3 \cdot animal^{-1} \cdot year^{-1}$) calculation by measuring in comparison with estimation by emission factors.

Districts	NH₃ Emissions Calculation by Measuring —First Approach	NH₃ Emissions Calculation by Measuring —Second Approach	Emission Factor for Housing —Third Approach	Estimated Reduced Emissions —Feed Additives
Jindřichův Hradec	1.92 ± 0.01 1.00 ± 0.04	- -	3.2 3.2	1.76–2.46
Tábor (Farm No. 1)	1.75 ± 0.04 3.51 ± 0.03	- -	3.2 3.2	1.66–1.95
Tábor (Farm No. 2)	2.03 ± 0.08	-	3.2	2.46–2.50
Příbram	1.45 ± 0.03	-	3.2	2.27–2.50
České Budějovice (Section 1)	-	0.91 ± 0.02	3.2	1.66–2.46
České Budějovice (Section 2)	-	1.03 ± 0.03	3.2	

It depends on each EU member's approach whether it will be used to determine NH_3 emissions based on emission factors derived according to a national or an international protocol [23,26]. In general, it would be advisable to update the established emission factors at the national level in order to refine the overall estimate of emissions, even if this is time-consuming and costly [27].

Table 7 and, respectively, Figures 1 and 2, also show that it is more objective to use BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22] methodology to determine NH_3 emissions (six sampling days over the growing season). One measurement, for example, taken at the start of the fattening period in colder conditions, may be quite different from a measurement taken in summer weather. These differences may become more pronounced with the length of the fattening period. Interestingly, even breeding sections in one breeding building with similar microclimatic conditions and identical breeding and fattening technology show differences in NH_3 emissions. From Figures 1 and 2, the breeding houses are labeled A4/A14, A5/A15, A7/A17, and A10/A20. On detailed

examination, it was found that the internal conditions were at the limit of moderate thermal stress when measurements A4/A14, A5/A15, and A7/A17 were made. This may have caused each group of pigs to react differently to this phenomenon, and, therefore, such different values may have been measured.
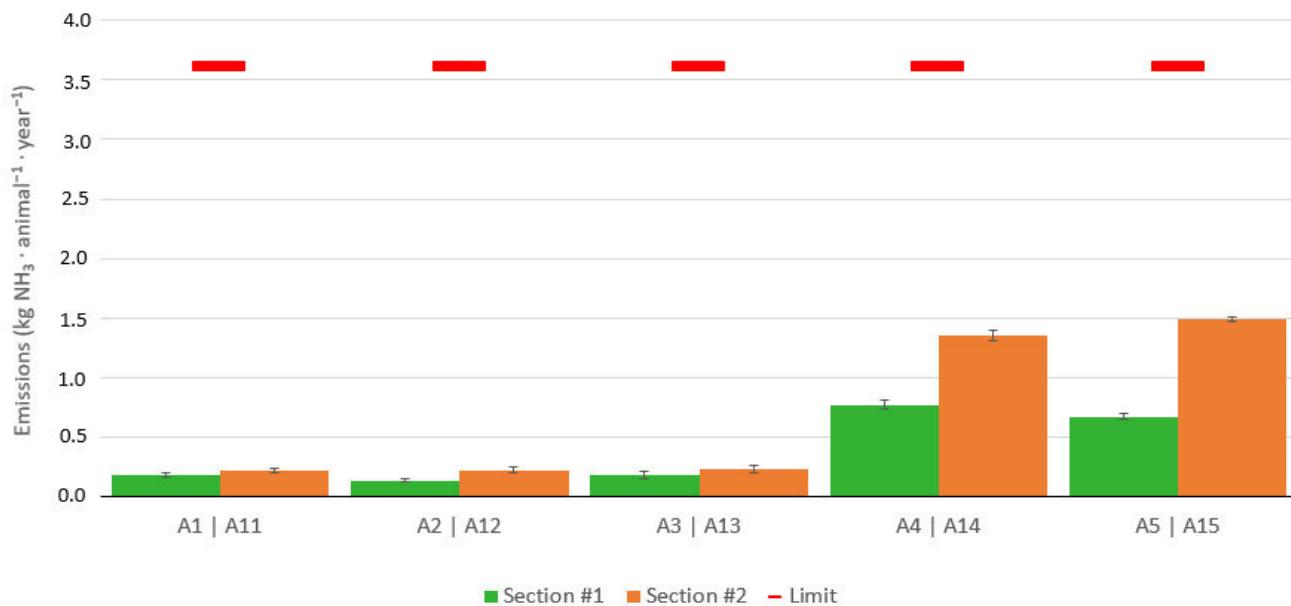
Figure 1. NH_3 emissions between February and June in 1st breeding cycle.
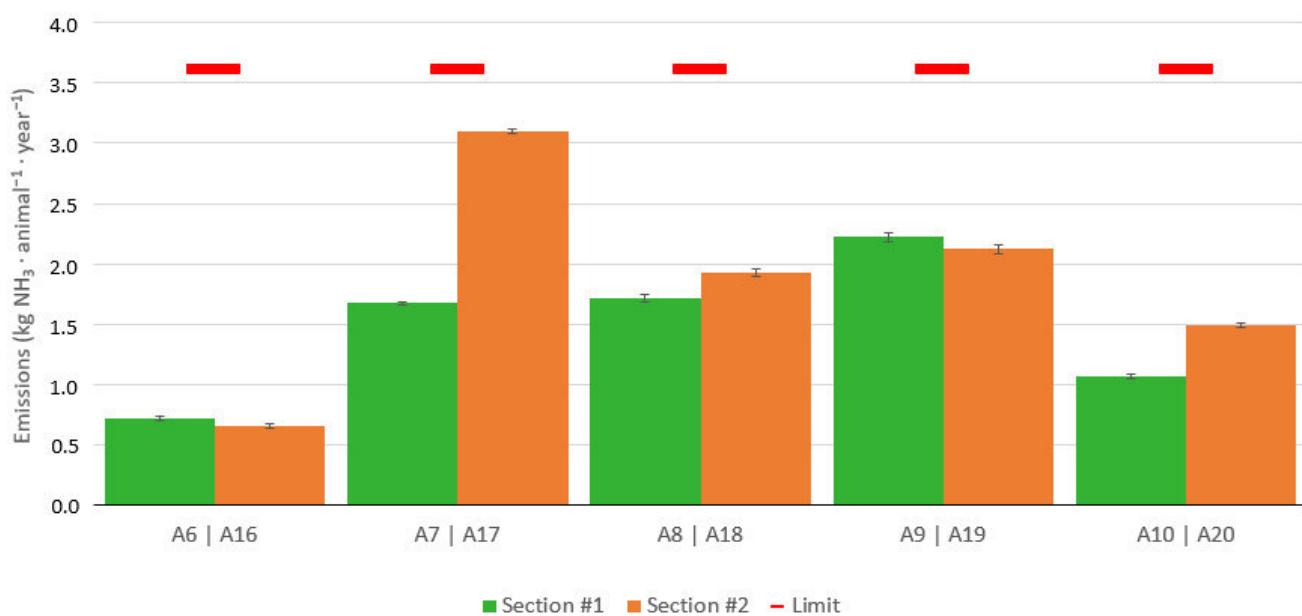
Figure 2. NH_3 emissions between June and November in 2nd breeding cycle.

According to [28], NH_3 emissions from confined livestock buildings used for fattening pigs production are expected to increase by about 15% to 20% due to the increasing temperature. Our study has also shown that climatic and microclimatic conditions can affect NH_3 emissions, particularly the values from monitoring whole fattening cycles shown in Figures 1 and 2. Since the monitoring of the breeding cycle was carried out in the February to June period and the second breeding cycle in the June to November period, these values can be considered conclusive and attribute a non-negligible influence on the production of NH_3 emissions to the time of the year.

The above aspects support the approach of the BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22] methodology, according to which half of the measurements should be taken during the first and the other half during the second phase of the breeding cycle and still be planned throughout the year. There have been many studies on this issue that have aimed to optimize the monitoring process, see [23,29–31], and are based on the following assumptions.

The method of *intermittent measurements* from establishing a model for determination of NH_3 emissions from fattening pigs. This model entered data from twelve measurements taken from the entire fattening period. Maximum model error of 10% was determined between simulated and measured NH_3 emissions [30].

5. Conclusions

Nowadays, the determination of NH_3 emissions from livestock farms is a topical issue due to the reduction efforts. Large-scale farmers in the Czech Republic are obliged to estimate these emissions annually and report them to the competent authority. In particular, the following are used to determine their estimation by using emission factors, because it is a very simple and inexpensive method, but as our study confirms, also inaccurate.

Another option that was tested in our study is to use calculation by measuring the NH_3 concentration. This option is costly and time-consuming but the most accurate. However, as we argue in our study, it should be implemented following BREF IRPP [17] and BAT conclusions under Directive 2010/75/EU [22]. When planning the measurements, it is essential to reflect on the different fattening phases and the seasons. Experiments have confirmed this theory, because taking measurements only in a specific part of the fattening cycle or only in a particular season can significantly distort the result.

The results of the study that indicate emission factors for determining NH_3 emissions from the housing may be overestimated. The Czech Republic is currently reviewing these emission factors to refine these calculations. As breeding feeding practices relating to the conversion of nutrients by animals continue to be modernized, it may be that these emission factors do not correspond to reality. Experience shows that each country should have its emission factors due to the different breeding technologies used, climatic conditions, and pig breeds and hybrids. Together with efforts to update them, this should ensure that NH_3 emissions are estimated as accurately as possible. It is also challenging to consider a more significant number of BAT when estimating NH_3 emissions, where only BAT with the highest efficiency in reducing NH_3 emissions was considered in the calculations. However, it is assumed that other BAT also contributes to their elimination somehow. Unfortunately, there are so many variables influencing the production of NH_3 emissions that it is difficult to investigate this issue more experimentally.

An approach that could improve the accuracy of statistical data on emissions production from intensive livestock farms covered by the IPPC is the refinement of emission factors by individual countries, which is widespread for determining these monitored emissions.

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References

1. Behera, S.N.; Sharma, M.; Aneja, V.P.; Balasubramanian, R. Ammonia in the atmosphere: A review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environ. Sci. Pollut. Res.* **2013**, *20*, 8092–8131. [CrossRef] [PubMed]
2. Ogunlaja, O.O. Measurement of Air Pollutant Emissions from A Confined Poultry Facility. Master's Thesis, Utah State University, Logan, UT, USA, 2009.
3. Waldrip, H.M.; Cole, N.A.; Todd, R.W. Review: Nitrogen sustainability and beef cattle feedyards: II. Ammonia emissions. *Prof. Anim. Sci.* **2015**, *31*, 395–411. [CrossRef]
4. Groenestein, C.M.; Van Faassen, H.G. Volatilization of Ammonia, Nitrous Oxide and Nitric Oxide in Deep-litter Systems for Fattening Pigs. *J. Agric. Eng. Res.* **1996**, *65*, 274–296. [CrossRef]
5. Wang, S.; Nan, J.; Shi, C.; Fu, Q.; Gao, S.; Wang, D.; Cui, H.; Saiz-Lopez, A.; Zhou, B. Atmospheric ammonia and its impacts on regional air quality over the megacity of Shanghai. *China Sci. Rep.* **2015**, *5*, 1–13. [CrossRef] [PubMed]
6. Jurić, I.; Drenjančević, M.; Jukić, V.; Turalija, A.; Babić, V.; Vujić, D. Ammonia emissions in cattle and pig production in Slavonia. In Proceedings of the 44th Croatian and 4th International Symposium of Agronomists, Strossmayer University, Faculty of Agriculture in Osijek, Opatija, Croatia, 16–20 February 2009.
7. Rahul, S.; Kyunghoon, K.; Gyutae, P.; Seokwon, K.; Taehyun, P.; Jihee, B.; Siyoung, C.H.; Jeong, S.; Dong-Gil, Y.; Jung-Hun, W.; et al. Seasonal and Spatial Variations of Atmospheric Ammonia in the Urban and Suburban Environments of Seoul, Korea. *Atmosphere* **2021**, *12*, 1607. [CrossRef]
8. Wu, Y.; Gu, B.; Erisman, J.W.; Rei, A.; Fang, Y.; Lu, X.; Zhang, X. PM2.5 pollution is substantially affected by ammonia emissions in China. *Environ. Pollut.* **2016**, *218*, 86–94. [CrossRef] [PubMed]
9. Thunis, P.; Clappier, A.; Beekmann, M.; Putaud, J.P.; Cuvelier, C.; Madrazo, J.; de Meij, A. Non-linear response of $PM_{2.5}$ to changes in NO_X and NH_3 emissions in the Po basin (Italy): Consequences for air quality plans. *Atmos. Chem. Phys.* **2021**, *21*, 9309–9327. [CrossRef]
10. Pinder, R.W.; Gilliland, A.B.; Dennis, R.L. Environmental impact of atmospheric NH_3 emissions under present and future conditions in the eastern United States. *Geophys. Res. Lett.* **2008**, *35*, L12808. [CrossRef]
11. Van der Heyden, C.; Demeyer, P.; Volcke, E.I.P. Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: State-of-the-art and perspectives. *Biosyst. Eng.* **2015**, *134*, 74–93. [CrossRef]
12. Olivier, J.G.J.; Bouwman, A.F.; Van der Hoek, K.W.; Berdowski, J.J.M. Global air emission inventories for anthropogenic sources of NO_X, NH_3 and N_2O in 1990. *Environ. Pollut.* **1998**, *102*, 135–148. [CrossRef]
13. Fiala, N. Meeting the demand: An estimation of potential future greenhouse gas emissions from meat production. *Ecol. Econ.* **2008**, *67*, 412–419. [CrossRef]
14. United Nations Economic Commission for Europe, European Environment Agency. *European Emission Inventory Report 1990–2010 under the UNECE Convention on Long–Range Transboundary Air Pollution*; European Environment Agency: Copenhagen, Denmark, 2012.
15. Danish Environmental Protection Agency. *Review Of Ammonia Emissions from a Pig House Slurry Pit and Outside Storage: Effects of Emitting Surface and Slurry Depth*; Danish Environmental Protection Agency: Copenhagen, Denmark, 2014.
16. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0075&from=cs (accessed on 1 October 2022).
17. Germán, G.S.; Konstantinos, G.; Bianca, M.S.; Paolo, M.; Serge, R.; Luis, D.S. *Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs. Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and Control*; European Commission: Luxembourg, 2017.
18. Questions and Answers on Revised EU Rules on Industrial Emissions. Available online: https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_2239 (accessed on 1 October 2022).
19. Loyon, L.; Burton, C.H.; Misselbrook, T.; Webb, J.; Philippe, F.X.; Aguilar, M.; Doreau, M.; Hassouna, M.; Veldkamp, T.; Dourmad, J.Y.; et al. Best available technology for European livestock farms: Availability, effectiveness and uptake. *J. Environ. Manag.* **2016**, *166*, 1–11. [CrossRef] [PubMed]
20. Oenema, O.; Oudendag, D.; Velthof, G.L. Nutrient losses from manure management in the European Union. *Livest. Sci.* **2007**, *112*, 261–272. [CrossRef]
21. Bartoš, P.; Dolan, A.; Smutný, L.; Šístková, M.; Celjak, I.; Šoch, M.; Havelka, Z. Effects of phytogenic feed additives on growth performance and on ammonia and greenhouse gases emissions in growing-finishing pigs. *Anim. Feed Sci. Technol.* **2016**, *212*, 143–148. [CrossRef]
22. BAT. Conclusions under Directive 2010/75/EU of the European Parliament and of the Council, for the Intensive Rearing of Poultry or Pigs. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D0302&from=EN (accessed on 1 October 2022).
23. VERA. TEST PROTOCOL for Livestock Housing and Management Systems. Verification of Environmental Technologies for Agricultural Production. Available online: https://www.veraverification.eu/app/uploads/sites/9/2019/05/VERA_Testprotocol_Housing_v3_2018.pdf (accessed on 1 October 2022).

24. Methodological Instruction of the Air Protection Department on the Classification of Livestock Farms According to Act No. 201/2012 Coll., on Air Protection, for the Calculation of Pollutant Emissions from These Stationary Sources and on the List of Technologies Reducing NH$_3$ Emissions from These Stationary Sources. Available online: https://eagri.cz/public/web/file/564268/Publikace_Emise_amoniaku_a_zapachu.pdf (accessed on 25 January 2022).

25. Kriz, P.; Kunes, R.; Smutny, L.; Cerny, P.; Havelka, Z.; Olsan, P.; Xiao, M.; Stehlik, R.; Dolan, A.; Bartos, P. Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming. *Agriculture* **2021**, *11*, 1073. [CrossRef]

26. European Environmental Agency. EMEP/EEA Air Pollutant Emission Inventory Guidebook–2019, Technical Guidance to Prepare National Emission Inventories. Available online: https://www.eea.europa.eu//publications/emep-eea-guidebook-2019 (accessed on 10 January 2022).

27. Ulens, T.; Daelman, M.R.; Mosquera, J.; Millet, S.; van Loosdrecht, M.C.; Volcke, E.I.; Van Langenhove, H.; Demeyer, P. Evaluation of sampling strategies for estimating ammonia emission factors for pig fattening facilities. *Biosyst. Eng.* **2015**, *140*, 79–90. [CrossRef]

28. Simpson, D.; Andersson, C.; Christensen, J.H.; Engardt, M.; Geels, C.; Nyiri, A.; Posch, M.; Soares, J.; Sofiev, M.; Wind, P.; et al. Impacts of climate and emission changes on nitrogen deposition in Europe: A multi-model study. *Atmos. Chem. Phys.* **2014**, *14*, 6995–7017. [CrossRef]

29. Blanes-Vidal, V.; Hansen, M.N.; Pedersen, S.; Rom, H.B. Emissions of ammonia, methane and nitrous oxide from pig houses and slurry: Effects of rooting material, animal activity and ventilation flow. *Agric. Ecosyst. Environ.* **2008**, *124*, 237–244. [CrossRef]

30. Dekock, J.; Vranken, E.; Gallmann, E.; Hartung, E.; Berckmans, D. Optimisation and validation of the intermittent measurement method to determine ammonia emissions from livestock buildings. *Environ. Pollut.* **2009**, *104*, 396–403. [CrossRef]

31. Mosquera, J.; Ogink, N.W.M. Reducing the sampling periods required in protocols for establishing ammonia emissions from pig fattening buildings using measurements and modelling. *Biosyst. Eng.* **2011**, *110*, 90–96. [CrossRef]

Article

Technology of Microclimate Regulation in Organic and Energy-Sustainable Livestock Production

Zbynek Havelka [1], Radim Kunes [1], Yevhen Kononets [1,*], Jessica Elizabeth Stokes [2], Lubos Smutny [1], Pavel Olsan [1], Jan Kresan [1], Radim Stehlik [1], Petr Bartos [1], Maohua Xiao [3], Pavel Kriz [1], Pavol Findura [1] and David Roztocil [1]

[1] Faculty of Agriculture and Technology, University of South Bohemia in České Budějovice, Studentska 1668, 370 05 České Budějovice, Czech Republic

[2] School of Agriculture, Food and the Environment, Royal Agricultural University, Cirencester GL7 6JS, UK

[3] College of Engineering, Nanjing Agricultural University, Nanjing 210031, China

* Correspondence: yevhen.kononets@ukr.net or kononets@fzt.jcu.cz

Abstract: The control of climatic conditions where cattle are kept is one of the challenges in the livestock sector regarding the digital automation of the process. (1) Background: The main purpose of this study is to define the optimal foundations for automatic climatic systems in organic and energy-sustainable livestock production. In particular, the following components are suggested: (a) the determination of current deviations and interdependency between factors; (b) an algorithm for defining the possible sources of regulation; (c) the ranking approach of the optimal sequence of possible sources; and (d) ensuring transparency and coordination of the model with organic and energy certificates. (2) Methods: This investigation accumulates information on the characteristics of the main microclimatic parameters and simulates their possible combinations in a livestock building in Poland within 24 h of a spring day. A few indices are considered that signal the impact on the thermal comfort of cattle based on the example of recommended measures for the Angus steer genotype. (3) Results: The proposed transparent algorithm is designed for selecting and ranking potential sources of microclimate control according to three criteria. (4) Conclusions: This paper potentially contributes to determining the most optimal digital algorithm for managing microclimate conditions to ensure acceptable comfort for animals, meeting the requirements of organic certification with minimum costs of production, and switching to sustainable types of energy with consideration of technologies' efficiency. The algorithm is scalable and adjustable to the individual conditions of any livestock premise with a digitally controlled environment.

Keywords: algorithm for automatic microclimate; choosing sources of microclimate regulation; controlled environment for livestock; organic livestock production; energy-sustainable agricultural production

1. Introduction

The importance of establishing a favorable microclimate on farms has been described by many authors in the scientific literature. For example, it has been calculated that 20% calf mortality reduces profitability by 60% [1–3], and establishing a stable microclimate is an important factor in reducing calf mortality [4]. Furthermore, breeding of livestock in climatically comfortable conditions is essential for maintaining good health of the animals [5].

Microclimatic parameters inside livestock buildings are divided into three basic categories: the physical (i.e., temperature, including radiation heat (°C); relative humidity of the air (%); illumination (Lx); air-exchange rate ($m^3 \cdot h^{-1}$); and air velocity ($m \cdot s^{-1}$)), the chemical (i.e., contents of gases in air, such as O_2 (%); CO_2, NH_3, H_2S, and CO (ppm); and organic dust ($mg \times m^{-3}$)), and the biological (i.e., pathogens and parasites). Microclimate

control in a livestock building should be considered as a complex holistic mechanism consisting of microclimatic parameters considering species, life stage, genetic potential, and nutritional period in order to create favorable health conditions for the breeding and fertility of the housed animals. Significantly, on average, when animals are kept in livestock housing, it is too hot 27% of the time and too cold 17% of the time [6].

Among the accumulated knowledge in the literature, there are quite a number of approaches to analyze strategies for modeling the management of the microclimate in livestock buildings. For example, humidity balance and heat-exchange models are used to simulate and analyze the microclimate conditions in animal and poultry housing in current research [7], and recent studies [8,9] have used sensible heat balance justification models. However, [7] states that in the most frequently ventilated periods, predictions of indoor temperature are extremely difficult. Moreover, inaccurate predictions of relative humidity are observed in stables when the indoor air mixes with the external air during the natural ventilation process. Another recent study [10] claims that due to the lack of quantitative studies it is difficult for livestock managers to select system configurations with multiple measures of microclimate control; thus, regulations are mostly based on random and probabilistic decisions.

In general, there are two recognized basic methods of modeling the regulation of microclimate in agricultural premises [11]. The first method is called black-box simulation, which is based on the analysis of cause-and-effect relationships between input and output data. This method is built on intelligent algorithms such as neural network systems [12], support-vector models [13], and others. However, black-box modeling has a number of disadvantages, such as weak universality in practice and poor justification of the physical parameters in processes. The second method is called mechanism modeling, to which the proposed approach belongs, which ranks sources by taking into account physical laws and relationships. Numerous studies have utilized this modeling method [14–18] considering major energy balance and mass-exchange approaches. For example, a recent study [19] investigated the relationships between three basic parameters: indoor temperature, humidity, and CO_2 concentration. It is difficult to find a model idea in the literature that combines the "black box" and "mechanism" methods in one approach [20]. These approaches are generally focused on physical processes and do not usually consider the severity of the economic efficiency of energy sources, the criticality of the time spent, and sustainability priorities in one algorithm. The latter includes the need to intensify the agricultural sector in the use of renewable energy sources, which is in especially high demand due to the changing political events on the European continent.

There exist various control strategies for enclosed animal buildings in the literature, such as fuzzy decoupled control strategies—mainly for temperature and humidity [7,14]—and logical reasoning for multiple and coupled environmental factors, as in the current investigation.

Herein, the authors emphasize the importance of determining the cost-effectiveness and sustainability of each available measure that represents a source of influence on a microclimatic parameter. Moreover, the scarcest information in the literature is the analysis of time consumption in combination with the efficacy and sustainability of available measures affecting microclimate. The objective of this research is to define the most optimal algorithm for choosing and sequencing the measures or sources that affect the regulation of the microclimatic parameters for possible future implementation in automatic climatic systems for use in livestock buildings. In particular, the suggestions include the following: (1) the determination of the current recommendations based on basic microclimatic parameters and their interdependency in the general set of factors and indicators of thermal comfort; (2) an algorithm for determining and approving the possible sources of regulation of the deviated microclimatic values; and (3) an algorithm for making automatic decisions on the optimal sequence of possible applied sources for regulating those values that have gone beyond the recommended thresholds.

1.1. Existing Recommendations for Basic Microclimatic Parameters

The following recommendations for basic microclimate parameters refer to the maintenance of the Angus steer genotype, based on the findings of previous studies in the literature.

1.1.1. Temperature (T_A)

The temperature regime in a room is one of the fundamental factors of the microclimate. An increase in temperature above 25 °C leads to a significant decrease in the milk production of cattle [21–24]. When the ambient temperature reaches 30 °C, a cow produces an average of 4 L less milk per day [25], and at 40 °C the milk yield dramatically drops by 50% [26] as a result of heat stress. Furthermore, heat stress causes a general deterioration of animals' health and welfare [27,28]. The most comfortable temperature, especially for lactating cows, lies between +4 °C and +16 °C, depending on the air humidity [29]. In Finland, the lowest critical temperatures for dairy cows are considered to be from −15 °C to −25 °C, depending on the humidity and airflow speed [30]. According to Tarr [31], for every 1 °C drop below the lowest critical temperature, an approximate 2% increase in energy supplementation is required under a state of cold stress.

1.1.2. Relative Humidity (RH)

The recommended RH level for cattle is between 60% and 80% [26]. The optimal level of RH for calves, lactating cows, and pigs is between 50% and 70% [30,32–34]. Higher RH hinders heat dissipation from animals by evaporation from the skin, especially when high relative humidity is accompanied by high temperatures that threaten overheating; on the other hand, in winter, this causes overcooling and increases the animals' energy requirements while simultaneously prolonging the survival of pathogens attacking the gastrointestinal and respiratory systems [35–37].

1.1.3. Air Velocity (v)

There are four main methods of heat removal: radiation, convection, evaporation, and heat conduction [38–40]. Two of them—evaporative and convective cooling—directly depend on the airflow speed. The airflow speed inside buildings should be kept within the range 0.2–0.5 m×s^{-1} [41–43]. In particular, the indoor airflow rate should not exceed 0.2 m×s^{-1} in winter and 0.5 m×s^{-1} in summer if the heat-exchange coefficient remains in the range from 350 to 400 W·animal^{-1}×h^{-1} [43]. In contrast with the outdoor terms, according to Wathes et al. [44], summer winds of as high as 7 m×s^{-1} are not detrimental to cows' comfort, and the cooling effect starts to be sensitive from 1–2.5 m×s^{-1}.

1.1.4. Air Exchange (Ventilation)

The rate of fresh air renewal is also an important parameter. Low renewability of fresh air leads not only to a decrease in oxygen concentration and an increase in the concentrations of harmful gases, but also to pollution through the development of pathogenic bacteria, viruses, and fungi, leading to animal disease. According to Teye et al. [45], the microclimate can be kept within recommended values during microclimatic experiments if the proper air-exchange rate is provided, even in cases where the temperature or humidity level goes beyond the optimum. Broom [46] stated that in winter the ventilation should provide four full inside air (V) exchanges per hour (h) with fresh air, i.e., $(4 \cdot V^3) \times h^{-1}$ in a livestock building and in a range of 40–60 full exchanges of fresh air in summer time—thus, a maximum of $(60 V^3) \times h^{-1}$. According to other standards for poultry production, the air-exchange rate in cold periods should be 0.75 m^3×h^{-1} per kg of live weight, and in warm seasons it should be 5.0 m^3·h^{-1} per kg of live weight [47]. Ventilation rates can be estimated by the CO_2 balance method.

1.1.5. Greenhouse Gases (GHG) and Dust Contents

Based on the requirements of the Ministry of Social Affairs and Health (2005) in Finland [48], the acceptable concentration of harmful gases in animal buildings should

not exceed the following thresholds: carbon dioxide (CO_2) $\leq$3000 ppm) or $\leq$2 L (l)$\cdot$m^{-3} assessed as good-quality air inside a livestock building (while the normal atmospheric concentration is 0.35 L$\times$m^{-3}; acceptable air quality of 2–3 L$\times$m^{-3}; $\geq$3 L$\times$m^{-3} is bad-quality air [49–52]); ammonia (NH_3) $\leq$10 ppm; hydrogen sulfide (H_2S) $\leq$0.5 ppm; carbon monoxide (CO) $\leq$5 ppm.

The dust content inside livestock buildings should be as low as possible. The accumulation of dust should not exceed 120 mg$\times$m^{-3} for 24 h or more than 50 mg$\times$m^{-3} on average throughout the year [53].

1.1.6. Illumination (Lx)

Gavan and Motorga [54] studied the positive effects of lighting on cattle and showed an increase in milk yields by 2.2%. Dairy cows that have good lighting conditions for 16–18 h per day have 5–16% higher productivity and optimal feed consumption when all other things are equal [55]. They distinguish two sources of light: natural and artificial. The intensity level of direct sunlight is 100,000 Lx, but in cloudy conditions it is about 5000 Lx [56]. The recommended illumination level for a milking parlor is 540 Lx [57]. To meet their basic physiological needs, animals require at least 100–160 Lx. According to Dimov et al. [58], the highest level of light intensity was registered at 2360 Lx in the spring season at midday milking in cow barns, while 78 Lx was the minimum level in the winter at evening milking.

1.2. Interdependence of Microclimatic Parameters

For the subsequent analysis of microclimatic parameters, they should be viewed as an interrelated set of data, since a change in one parameter invariably entails a change in other parameters. These relationships are confirmed by positive or negative dependency, or are insufficiently proven.

1.2.1. Temperature-Relative Humidity

Based on the following equation [59]:

$$RH \approx 100 - 5 \times (T - T_{dp}) \tag{1}$$

where T is the dry-bulb temperature and T_{dp} is the dew point temperature. If the RH is higher than 50%, an increase in the temperature by 1 °C leads to a decrease of approximately 5% in the relative humidity level.

1.2.2. Temperature-O_2 Concentration

This relationship is described by the following ideal gas law [60]:

$$P \times V = n \times R \times T \tag{2}$$

where P is the pressure (Pa), V is the volume (m^3), n is the gas quantity (mol), T is the temperature (K), R is the ideal gas constant (8.314 J mol$^{-1}\times$K^{-1}), and the amount of oxygen (O_2) in the atmosphere—assuming a dry (i.e., no water vapor) atmosphere—is 0.2095 kPa O_2 per kPa air, or 20.95%. It follows that a 1 °C temperature increase from 20 °C results in a 0.0714% decrease in O_2 (0.341% $\times$ 0.2095 = 0.0714%).

1.2.3. Air Changes per Hour (Ventilation)—Air Velocity

The air changes per hour in buildings are typically calculated as follows [61]:

$$ACH = (3600 \times S \times v) \times V^{-1} \tag{3}$$

where S is the area of the ventilation openings in the building (m^2), v is the average indoor air velocity (m$\cdot$s^{-1}), and V is the volume of the premises (m^3). Hence, it follows that there is a positive relationship between the air-exchange rate and the average airflow speed in

a building. The more air exchanged per hour, the higher the indoor airflow velocity, and vice versa.

1.2.4. Airflow Rate (Ventilation)—Indoor Temperature

This relationship is explained by the heat transfer theory in kW and expressed as shown in the following equation [62]:

$$Q = p \times c \times A \times (T_{out} - T_{in}) \tag{4}$$

where p is the density of the air (kg·m^{-3}) (1225 kg·m^{-3} (ISA) at sea level and 15 °C), c is the specific heat of the air (kJ·kg^{-1}×K^{-1}) (at normal atmospheric pressure of 1.013 bar, c is equal to 1.006), A is the airflow rate through the ventilation system (m^3×s^{-1}), T$_{out}$ is the outdoor air temperature (°C), and T$_{in}$ is the indoor air temperature (°C). Thus, the quantity of heat accumulation or loss inside the livestock building mostly depends on the positive relationship of the outside air temperature and the airflow rate (m^3·s^{-1}).

1.2.5. Airflow Rate (Ventilation)—Indoor Relative Humidity

Based on the following equation [51]:

$$L = A \times p \times (RH_{out} - RH_{in}) \tag{5}$$

where L is the latent heat balance on humidity through the ventilation system, A is the airflow volume rate through the ventilation system (m^3×s^{-1}), p is the density of air (kg×m^{-3}), RH$_{out}$ is the outdoor relative humidity of air by mass in kilograms of water vapor per kilogram of dry air (kg×kg^{-1}), and RH$_{in}$ is the indoor relative humidity (kg×kg^{-1}). Hence, the indoor humidity level tends to equalize with the outdoor level. The higher the ventilation flow and air density, the faster this trend.

1.2.6. Airflow Rate (Ventilation)—Indoor CO$_2$ Concentration

This formula expresses the CO$_2$ mass balance (C) as follows [6]:

$$C = V \times (CO_{2out} - CO_{2in}) \tag{6}$$

where V is the volume flow (m^3×s^{-1}), CO$_{2out}$ is the outdoor CO$_2$ concentration (L×m^3), and CO$_{2in}$ is the indoor CO$_2$ concentration (L×m^3). Likewise, the concentration of carbon dioxide in the livestock building can be controlled by the flow rate of the fresh outdoor air through the ventilation system.

1.3. Basic Indices for the Evaluation of Microclimate Conditions

1.3.1. Temperature-Humidity Index (THI)

The existing thresholds of temperature and humidity levels are closely interrelated and cannot be seen as separate indicators when analyzing the thermal comfort of animals. For example, at an ambient temperature of 26.7 °C and relative humidity of 25%, animals do not experience heat stress and remain thermally comfortable. However, at the same temperature but at 100% humidity, animals experience severe stress [63]. For another example, at an ambient temperature of 28.9 °C and relative humidity of 60%, animals are at risk of mild heat stress; however, at the same humidity and increased dry-bulb temperature of 43.9 °C, animals are already at risk of death. Therefore, the temperature–humidity index (THI; [64]) is used to reflect the level of thermal comfort based on ambient temperature and relative humidity. The THI can be determined according to the following formula:

$$THI = (0.8 \times T_a) + [(RH/100) \times (T_A - 14.4)] + 46.4 \tag{7}$$

where *THI* is the temperature–humidity index, T_a is the ambient air temperature, and RH is the relative humidity of the environment. Hence, the evaluation of the temperature–humidity index is as follows [64]: ≤74 = no stress; 74–79 = mild stress; 79–84 = strong

stress; $\geq$84 = very strong stress [65]. *THI* is the most accurate assessment of thermal comfort [66,67] and can be used as a universal mean for the evaluation and prediction of the milk productivity of dairy cows [24]. However, *THI* does not include the impacts of overcooling, solar radiation, and airflow speed [68,69]. For example, for practical purposes, the average solar intensity is calculated as 0.9 kW$\times$m^{-2} on the Earth's surface under an angle from the sun's rays close to 90° [70], which cannot be ignored in a heat balance analysis. The overall basis for the success of the proposed formula is the relative accessibility of its data for calculation, which can be obtained from ordinary meteorological stations, such as ambient temperature and relative humidity. The data on the amounts of heat emitted by animals, wind speed, and the amount and duration of precipitation are usually not publicly available.

1.3.2. The Black Globe Temperature (BGT)

If animals are kept indoors under direct sunlight it creates additional solar radiation intensity (W$\times$m^{-2}), and this impact can be more accurately assessed using the black globe temperature (*BGT*) [71]. The model of *BGT* calculation as a linear equation is as follows:

$$BGT = 0.01498 \cdot SR + 1.184 \cdot T_a - 0.0789 \cdot RH - 2.739 \qquad (8)$$

where *SR* is the solar radiation (W$\times$m^{-2}), T_a is the dry-bulb ambient temperature (°C), and *RH* is the relative humidity (%). The *BGT* is usually measured using a dark globe thermometer; however, the intensity of solar radiation is practically measured at almost all weather stations around the world. The data from these stations are thoroughly collected and can be used for evaluating heat loads in microclimatic environments considering the properties and features of analyzed livestock premises along with the shade characteristics and the degree of sunlight filtration.

1.3.3. Heat Load Index (HLI) and Accumulated Heat Load (AHL)

An alternative index for analyzing thermal comfort of animals is the heat load index, which also considers solar radiation and airflow velocity [72,73]. The HLI has two formulae for determination, depending on whether the black globe temperature (BGT) is above or below 25 °C [74], as follows:

$$\text{If } BGT \geq 25\,°C, \text{ then } HLI = 8.62 + (0.38 \times RH) + (1.55 \times BGT) - (0.5 \times v) + e^{2.4\text{-v}} \qquad (9)$$

$$\text{If } BGT < 25\,°C, \text{ then } HLI = 1.3 \times BGT + 0.28 \times RH - v + 10.66 \qquad (10)$$

where *RH* is the relative humidity (%) (decimal form), *BGT* is the black globe temperature (°C), v is the airflow velocity (m$\times$s^{-1}) and e is an exponential—the base of the natural logarithm—which is approximately equal to 2.71828 [75]. If the HLI exceeds the threshold of 86, the animals will gain heat; if the *HLI* falls below 77, then the animals lose heat. However, these thresholds are quite genotype-specific and are also affected by management factors such as access to shade, drinking water temperature, or the general health of the animal [76]. In a case where the mean *HLI* is within the range of 77–86, it is accepted that the animals are in a heat load balance (*HLB*) and the *HLB* equals 0. If the number exceeds the upper threshold of 86, the HLB rises to +1. *HLB* can be used to assess the cumulative effect of heat load over a longer time—e.g., 24 h—through the accumulative heat load units (*AHLU*). The *AHLU* is based on the body's ability to accumulate heat, and vice versa, having a long cooling impact, which the body requires for thermal compensation. Long-term stay outside the optimal threshold values leads to changes in the biological state of animals, including parameters such as body temperature, respiration rate, panting score, and heart rate. The *AHLU* is measured as follows:

$$[AHLU]\text{day} = \sum[HLB]\text{n, where n—the meaning of each hour} \qquad (11)$$

1.4. Transparency with Socially Significant Data

1.4.1. Organic Certification

Industry guidelines and organic certification requirements clearly indicate the critical need for protection from extreme weather conditions, mitigation of the effects of thermal stress, and ensuring a comfortable environment for animals. However, these regulations are not consistent in providing specific microclimatic parameters and recommended indicators [77,78]. For example, the basic document on organic production—Regulation (EU) 2018/848, p. 44 [79]—promotes the implementation of the best environmental and climate action practices ensuring that the behavioral needs of the animals are met, along with a high level of animal welfare in general, describing the best practices in management in more detail (e.g., pain mitigation, access to outdoor space and drinking water, manure management, and shade provision) [80]. However, the bio-certification system has been actively developing, and the obtained digital data from the production sites can be effectively processed to determine the possible risks of non-compliance with a certain level of climatic comfort for animals. According to a recent study [81], microclimate data from sites of agricultural production can be sent to socially accessible platforms, where risks can be carefully evaluated and processed by a certification body (CB). The present study takes this operational function into account in the proposed algorithm.

1.4.2. Sustainable Energy

Our review indicates the total dependency on and domination of fossil fuels in livestock production in Europe [82]. Today, a sound strategy for climate control in agricultural buildings is hard to imagine without taking into account the type of energy source, along with its impact on the environment, renewability, greenhouse gas emissions, waste disposal, and affordability. The choice of energy source—for instance, burning hydrocarbons for heating rooms in winter—should not be guided only by availability and economic feasibility in the short-term, but should be analyzed from all major perspectives, including the long-term resilience and sustainability of the energy source. For example, agriculture is responsible for 10.3% of the EU's greenhouse gas emissions, and up to 81% of those come from the livestock sector [83,84]. Looking towards 2050, the European Commission's strategic long-term objective [85,86] illustrates the contributions that energy efficiency—including in agriculture—can make towards achieving climate neutrality. In September 2020, the European Commission proposed significantly reducing net greenhouse gas emissions by at least 55% by 2030 compared with 1990. Thus, the shares of electricity, heating, and cooling in livestock premises provided by renewables will help meet the overall EU target, and must be considered in unifying algorithms of microclimate regulation. For example, there are proposals to create energy sources from manure for biogas production [87] and from post-fermentation products for granulated organic fertilizer with anaerobic digesters [88].

In particular, based on life-cycle assessment and analytical hierarchy models [89] for determining the best type of renewable energy for rural areas, it was established that solar energy scored the highest priority weight of 0.299, followed by mini-hydro energy, biomass, and wind energy sources, with scores of 0.271, 0.230, and 0.200, respectively. Another investigation [90] demonstrated the ranking of energy alternatives using a fuzzy weighted aggregated sum product assessment and integrated best–worst method approach, where solar energy was defined as the most prioritized source (0.81), followed by wind energy (0.79), biomass energy (0.66), and hydro power (0.64) which ranked 2nd, 3rd, and 4th, respectively. This approach produces a ranking of energy sources (solar PV, hydro, wind, biomass, geothermal) depending on the priority of different scenarios under the main factors, which are financial, technical, environmental, social, or equal [91]. Thus, the optimal algorithm of microclimate regulation should be based on the actual needs of society and the energy potential of the region, so that its main features can be digitally transparent for certification organizations and territorial committees dealing with energy development in the region, such as the Rural Electricity Resource Council in the USA

(http://rerc.org/aboutus.html; accessed on 20 September 2022). This sustainability feature is also considered in the presented algorithm.

2. Materials and Methods

2.1. Interconnections between Parameters

It is possible to depict basic interconnections between microclimatic parameters and, most importantly, to determine the main sources of regulation of each microclimatic parameter (Figure 1). Each parameter has proper measures of impact. For example, the temperature can be regulated with special equipment (T_1) (e.g., heaters, air coolers, radiators, etc.), ventilation (T_2), illumination (T_3) (from emitted heat), and solar radiation (SR) (i.e., direct sunlight or shade).
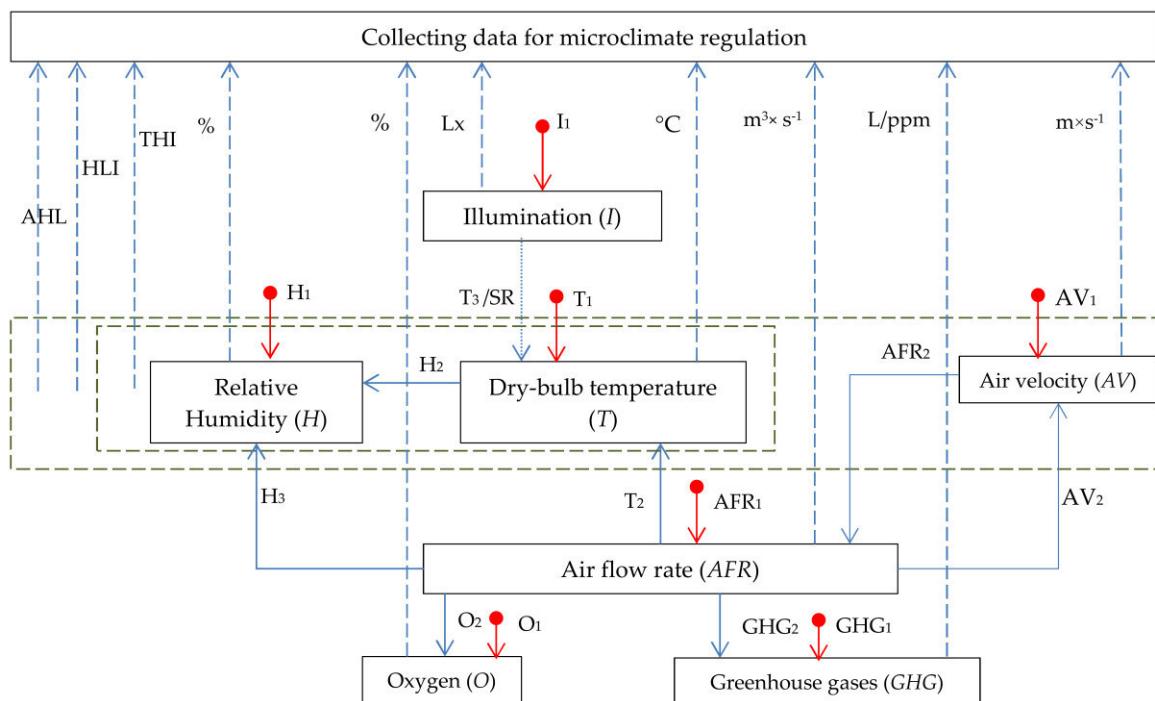
Legend: Xn – n-source for a change of X microclimatic parameter, 🔴 - Mechanical impact on a parameter; – – Data from sensors/ meters/ indices; – – Considered factors of indices

Figure 1. Interrelation between microclimatic parameters and indices.

In particular, T_1 generates heating or cooling via precise mechanical methods such as turbine bypass, biomass boilers, oil boilers, combined heat, power plants, and other coolers and heaters. In turn, H_1 is the source of mechanical regulation where the relative humidity can be tuned mechanically—for example, with driers or humidifiers.

Data collected for microclimate regulation are intended to be accessed by public and organic certification bodies and integrated with Internet-of-things-based real-time monitoring systems based on cloud platforms [92] or edge-distributed computer systems [93].

2.2. Marginal Costs for Sources

Marginal costs (MCs) reflect the cost (for instance, in EUR) for the last necessary unit of microclimatic parameter change, and are expressed as follows:

$$MC = (\Delta(\text{Total costs}))/(\Delta(Q)) \tag{12}$$

where Q is a unit of measurement for a definite microclimatic parameter. In order to have the opportunity to compare all influencing sources in terms of the different conditions of the

buildings and the environment, it makes sense to compare them by operating performances of a common value $\Delta(Q)$ of the factor and its changes with the changing environment.

2.2.1. Temperature

There are 4 common sources of temperature change: T_1 (mechanical impact, e.g., heaters, convectors), T_2 (ventilation), T_3 (illumination), and SR (regulation of solar radiation). The intensity and performance of these sources can be described by the quantity of emitted heating power (kW) per hour ($\Delta kW \times h^{-1}$). This is the common value for the determination of the cost for a unit change under existing ambient conditions. There is also a definite marginal cost for providing each kW per hour for each of the influencing sources under the existing terms. The level of the marginal costs (MCs) is highly dependent on the applied technology and can be provided by the technology provider or, alternatively, figured out via the appropriate calculations. It follows that the lower the MC per kW of heat energy under the given microclimatic conditions, the more preferable source is for the application. This is prioritized over other sources that of temperature change.

2.2.2. Humidity

For humidity changes, there are 3 widely applied basic measures: H_1 (mechanical impact, e.g., dryers, humidifiers, etc.), H_2 (indoor temperature/BGT), and H_3 (ventilation). Similarly to the factors influencing the temperature, the humidity is characterized by a quantity of absorbed or emitted moisture in liters per hour ($L \times h^{-1}$), giving the opportunity to rank the sources based on their economic advantage. The general approach is that the lower the cost of a change in each unit ($L \times h^{-1}$), the higher the priority the source is given when the final decision is made.

2.2.3. Airflow Rate

The ventilation is the only microclimatic parameter that can be regulated directly with only a technical solution. It has no direct influencing microclimatic parameters, and its economic efficiency is regulated within the applied technical solutions in a premise. Possible technical solutions are measured by the cost for a change of $1 \text{ m}^3 \times s^{-1}$.

2.2.4. Airflow Velocity

The speed of airflow can be measured in $m \times s^{-1}$. It can be adjusted with AV_1 (mechanical impact, e.g., air ventilators) and AV_2 (ventilation). The common measure to compare all determinants for airflow velocity is assessing their costs per $\Delta m \cdot s^{-1}$.

2.2.5. Illumination

The level of illumination can be regulated via two methods: natural solar radiation, and artificial lighting. The comparative unit for both methods is expressed in absolute values of $\Delta Lx \times h^{-1}$.

2.2.6. Oxygen and Greenhouse Gases

The content of useful oxygen is expressed as a percentage of the air volume; therefore, any sources of an increase in concentration are also expressed in $\Delta\% \times min^{-1}$. However, the content of harmful gases is expressed in parts per million (ppm) (or milligrams per liter ($mg \times L^{-1}$) in the metric system) since they have a harmful effect on animals in much lower concentrations and therefore any sources of reduction in concentration are expressed in $\Delta ppm \times min^{-1}$.

2.2.7. Assuming Zero Marginal Cost

In the event that a change in a source depends on a one-time impact, it is assumed that the marginal cost of changing such a source is zero, since they are short-term and one-time in action, and the costs per unit of the variable parameter are extremely low and difficult to calculate accurately. For example, obscured sunlight could be such a source,

which can reduce the level of solar radiation or open technical holes for more intensive natural ventilation (NV).

2.3. The Basic Approaches for the Digital Algorithm

Table 1 shows how definite influencing sources (Xn) affect the other microclimatic parameters and how the different influencing sources for one parameter are compared and ranked for the algorithm.

Table 1. Two basic sequential approaches for digital algorithms for automatic climate regulation.

Determinant	Source of Change (Xn)	Unit of Comparison (Xn)	1 Change in Dependent Parameters Y (Unit)	2 Marginal Cost per Unit Change (*MC*), *EUR*
Temperature, °C	T_1	$\text{kWt} \times \text{h}^{-1}$	Humidity (%)	$f_{MC}\left(T_{1(\text{kWt·h}^{-1})}\right)$
	T_2		Humidity (%); airflow velocity (m·s^{-1}), oxygen (%), greenhouse gases (ppm)	$f_{MC}\left(T_{2(\text{kWt·h}^{-1})}\right)$
	T_3		Humidity (%)	$f_{MC}\left(T_{3(\text{kWt·h}^{-1})}\right)$
	SR		Humidity (%)	$SR_{(\text{kWt·h}^{-1})} \to 0$
Humidity, %	H_1	$\text{L} \times \text{h}^{-1}$	*n/d*	$f_{MC}\left(H_{1(\text{L·h}^{-1})}\right)$
	H_2		*n/d*	$f_{MC}\left(H_{2(\text{L·h}^{-1})}\right)$
	H_3/NV		Temperature (°C), airflow velocity (m·s^{-1}), oxygen (%), greenhouse gases (ppm);	$f_{MC}\left(H_{3(\text{L·h}^{-1})}\right)/NV_{(\text{L·h}^{-1})} \to 0$
Airflow rate, m$^3 \times$s^{-1}	AFR_1	$\text{m}^3 \times \text{s}^{-1}$	Temperature (°C), humidity (%), airflow velocity (m·s^{-1}), oxygen (%), greenhouse gases (ppm)	$f_{MC}\left(AFR_{1(\text{m}^3\cdot\text{s}^{-1})}\right)/NV_{(\text{m}^3\cdot\text{s}^{-1})} \to 0$
	AFR_2		Temperature (°C), humidity (%), oxygen (%), greenhouse gases (ppm)	$f_{MC}\left(AFR_{2(\text{m}^3\cdot\text{s}^{-1})}\right)$
Airflow velocity, m$\times$s^{-1}	AV_1	$\text{m} \times \text{s}^{-1}$	Airflow rate (m^3·s^{-1}), temperature (°C), humidity (%), oxygen (%), greenhouse gases (ppm)	$f_{MC}\left(AV_{1(\text{m·s}^{-1})}\right)$
	AV_2		Temperature (°C), humidity (%), oxygen (%), greenhouse gases (ppm);	$f_{MC}\left(AV_{2(\text{m·s}^{-1})}\right)$
Illumination, Lx	I_1	$\text{Lx} \times \text{min}^{-1}$	Temperature (°C), humidity (%)	$f_{MC}\left(I_{1(\text{Lux·min}^{-1})}\right)$
	SR			$SR_{(\text{Lux·min}^{-1})} \to 0$
Oxygen, %	O_1	%	*n/d*	$f_{MC}\left(O_{1(1\%)}\right)$
	O_2		Temperature (°C), humidity (%), airflow velocity (m·s^{-1}), greenhouse gases (ppm)	$f_{MC}\left(O_{2(1\%)}\right)/NV_{(1\%)} \to 0$
Greenhouse gases	GHG1	ppm	*n/d*	$f_{MC}\left(GHG_{1(\text{ppm})}\right)$
	GHG2		Temperature (°C), humidity (%), airflow velocity (m·s^{-1}), oxygen (%)	$f_{MC}\left(GHG_{2(\text{ppm})}\right)/NV_{(1\text{ ppm})} \to 0$

Wherever resources are used with a subsequent impact on temperature or humidity, there is an effect on the THI, HLI, and AHL indices. Where there is only a change in temperature and/or humidity, there is only an effect on the THI index. If one of the microclimatic parameters is outside of the accepted values, it should be regulated. The source of the regulation is chosen by the developed algorithm, which is capable of making the optimal decisions considering two factors:

- The first is the expected changes in dependent values. These values include both microclimatic parameters and indices. They should also be predicted in terms of acceptable values;
- The second condition is the marginal cost for a unit change of a required parameter caused by a definite source (X_n), measured in monetary value—$fmc\,(X_{n.unit}^{-1})$;

Hence, the algorithm can be represented in three interrelated principles:

1. Approval: At first, the algorithm accepts or denies the application of each particular source that is able to change the required microclimatic parameter(s). The model predicts potential changes in the dependent meanings of other parameters or indices (based on the formulae in Table 1) and, in fact, allows or forbids them using a specific source to correct the required parameter. For example, if it is necessary to reach T (°C) = $T_{current} + 1$, it is theoretically possible to use relevant measures $\{T_1; T_2; T_3; SR\}$ or their combinations. However, it is acceptable to use each source of impact only if the expected dependent indicators will be within the acceptable range of values. In addition, the simultaneous use of some measures of influence may be highly undesirable or ineffective, even when they are all recommended by set equations. The direction of influence (increase ↑ or decrease ↓) on the climatic parameter is also taken into account. The compatibility depends on the applied solutions and technologies, but in most cases the patterns are the same. For example, there are some combinations of applied measures that contradict one another despite all being recommended by natural formulae. For example, the sources O_1 and O_2 or AFR_1 and GHG_2 in one-way changes such as "increase-increase" or "decrease-decrease", or the sources SR and I_1 or H_1 and H_2 in reverse directions such as "increase-decrease" and "decrease-increase".

2. Marginality: The main sorting of sources influencing the required microclimatic parameters considers the difference in the marginal costs of potential sources for changing the last unit of a given parameter and can be expressed as if $fmc\,(X_{n(last\ unit}^{-1}{}_)})$ = MCmin when the source $X_{n(last\ unit}^{-1}{}_)}$ is the first source for processing among the already-approved sources. Furthermore, each approved source usually has one or more technologies or solutions. For example, there are several potential sources $[T_1, T_2, T_3, SR]$ to change the indoor temperature in a livestock building—in particular, the source T_1 (mechanical impact) has several alternative technologies of application, such as turbine bypass, biomass boilers, oil boilers, or combined heat and power plants. These sources can operate in different combinations in order to meet dynamic heat or cooling requirements under different weather conditions, as the energy costs are different between technologies. All marginal costs for technologies should be compared with relevant costs of alternative technologies in all other approved measures. In addition, the technologies can be applied either individually or in combination with others to achieve a symbiotic effect with regard to time and monetary costs. This implies that all possible MCs and their combinations should be calculated and ranked by MCmin.

3. Transparency: A microclimate control model is bilateral and has an information connection with public organizations such as organic certification bodies. This is a fundamental difference from other similar algorithms. Algorithm data synchronization is performed in two independent stages: (1) Collection of data from sensors (e.g., T, H, AV, AFR, I, SR, O_2, GHG) and calculation of indicators of animal climate comfort (i.e., THI, HLI, and AHL), which are regularly and automatically sent to a secure platform to which a relevant bio-certification body has access. Based on

these data, it is possible to determine the risk of climatic discomfort of animals with high accuracy which, in turn, enables better control of animal welfare for organic production. (2) Reporting to a bio-certification company or local committee of the regulation and development of sustainable energy in the region regarding the extent and proportions of the use of sustainable types of energy in animal production. All involved energy costs are recorded as a single equivalent in kWh, along with the type of energy used. This enables the competent authorities to determine the degree of penetration of sustainable types of energy in a particular production system.

2.4. Conditions of Testing the Developed Algorithm and Assumptions

The indicators of a spring day (27 April 2013) in the average European climatic zone were based on data derived from the recent study of Glusky et al. in 2019 [8] in a milk cattle building in the town of Komarow (Poland). Some data were complemented and elaborated by the authors to simulate brighter possible extreme conditions of the environment to test the proposed algorithm. Temperature and humidity during a spring day fluctuated significantly, meaning that the model experienced a variety of microclimatic influences with deviations in different zones of climatic comfort. The table in Appendix A demonstrates the basic microclimatic parameters and indices over the course of 24 h inside a livestock building. The indices (i.e., THI, HLI, AHL, and HLB) are automatically calculated based on the commonly accepted equations described in Section 1.3. The recommended values of the recorded parameters are mentioned in Section 1.1. During the testing day, three critical moments were identified (Appendix A), where one or more microclimatic parameters and/or indices deviated from the recommended means for a particular animal (Angus steer). Those were:

- (03:00) A critical deviation of the HLI was detected, and the recommended values of humidity and airflow velocity were exceeded;
- (13:00) The THI index was exceeded. The BGT was within the critical values, but the dry-bulb temperature and HLI were also outside the recommended values;
- (21:00) The indicators of the HLI and the concentration of harmful gases turned out to be unsatisfactory.

This algorithm is theoretical and requires fundamental experimental work. The operation of the model involves some caveats and assumptions that should always be taken into account. These assumptions include the following:

- The algorithm is presented for the example of keeping certain animals and can be used for any other kind of livestock or poultry by substituting the corresponding values of norms and recommendations, as shown in Section 1.1 of our example.
- The internal airflow patterns are distributed evenly throughout the premises.
- It is assumed that systems for cleaning animal waste products are working properly and manure management does not allow the 50 mm layer to be exceeded.
- The use of microclimatic parameters is recommended together with the use of hematological (bio) indicators of animals to accurately monitor their health and welfare.
- In case of any source being approved twice—for example, $T2\downarrow$—it is written to strengthen the first recommendation as $T2\downarrow\downarrow$, $T2\downarrow\downarrow\downarrow$, $T2\downarrow\downarrow\downarrow\downarrow$, and so on.
- The heat conduction from the floor $W\times(m\times K)^{-1}$ is not considered as the integral part of the whole temperature impact.
- The marginal cost curve ($f$mc) for a source always depends on the level of applied technology.
- The time required for a unit change strongly depends on the given livestock conditions, their characteristics, and the applied technologies of the energy sources.

3. Results

3.1. 03:00 Case

At the 3 a.m. time case, an extremely low level of the HLI with excessive levels of humidity and airflow speed were observed (Table 2). Based on the HLI (Equation (10)), due

to BGT < 25 °C increasing the HLI indicator to an acceptable level, there are opportunities to increase the determinants of the direct dependent factors of BGT and relative humidity or to reduce the factors negatively impacting the airflow velocity.

Table 2. Microclimatic conditions and indices at 03:00 (24 h).

Recommended Values	Parameter/Index	Data
4–16	Dry-bulb temperature, °C	7
4–16	Black globe temperature, °C	13
-	Ambient temperature, °C	2
50–80	Humidity, %	82
-	Outdoor humidity, %	67
≤74	THI	46
0.2–0.5	Airflow velocity, m/s	1.5
77–86	HLI	49
-	HLB	−28
0	AHLU	−64
10–150 (×1000)	Airflow rate, m^3/h ×1000	25
≥20.95	Oxygen, O$_2$%	21
≤3	CO$_2$ (NH$_3$, H$_2$S, CO), ppm. ×1000	1.21
1–10	Illumination, Lx ×100	1.2

In our particular case, it was not possible to increase the relative humidity as it had already exceeded the maximum level, implying the need to gradually reduce the current level. Despite the many possible practices of increasing humidity in the cattle production during spring, we had to consider definite accepted values with a combination of heat stress indices to reflect the most probable state of animal health. The factor of negative interrelation with HLI is the airflow velocity (*v*), which is currently higher than the recommended value and, therefore, needs to be decreased by AV$_1$ or AV$_2$ to prevent further cooling of the animals (Table 3). The main factor affecting the index is the BGT determinant, since it has the highest coefficient and weight in the formula. A change by one unit of temperature would have a more significant effect on the index than an increase in humidity or a decrease in the airflow speed, taking into account that the relative humidity is already not recommended to be increased. Based on Figure 1, the determinants of BGT are T$_1$, T$_2$, T$_3$, and SR. Thus, the process of automatic decision-making is presented in Tables 3 and 4.

Table 3. Determining factors for change.

Problem:	HLI↓		
Required for correction	BGT↑	*RH*↑	*v*↓
Current compliance with recommendations	Norm	+2%′	+1 m×s^{-1}
Confirmed actions	BGT↑	x	*v* ↓

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value.

Table 4 presents the required corrections for the biased mean HLI and the current compliance of HLI determinants with the recommendations. Based on the conditions, the following actions are necessary: increasing the BGT and decreasing the airflow velocity. The relative humidity is not acceptable for higher values because it has already exceeded the recognized norm; on the contrary, further reduction in this factor is recommended. The next step (Table 4) is to determine the sequence of applying the sources. In turn, this step can be further divided into the following actions: (1) breaking down each changing factor by possible sources of impact; (2) checking the changes in the dependent parameters; (3) approving the sources among the possible ones; (4) comparing the MC and the time performance of the approved sources within each factor; and (5) ranking each source by priority.

Table 4. Making a sequence on applying sources for microclimate correction.

Factors	BGT↑							v↓	
Possible measures:	$T_1\uparrow$	$T_2\uparrow$	$T_3\uparrow$	SR↑	$H_1\downarrow$	$H_2\downarrow$	$H_3\downarrow$	$AV_1\downarrow$	$AV_2\downarrow$
Change in dependent parameters	RH↓	RH↑, AV↓, O_2↓, GHG↑	RH↓	SR↑	n/d	$=T_1\uparrow$	T↓, RH↓ AV↑, O_2↑, GHG↓	n/a	$=T_2\uparrow$
Approved sources	$T_1\uparrow\uparrow$	$T_2\uparrow\uparrow$	$T_3\uparrow$	SR↑	$H_1\downarrow$	x	x	$AV_1\downarrow$	X
Marginal costs, EUR/unit	MC (T_1)	-MC (T_2)/0	MC (T_3)	0	MC (H_1)	*n/d*		-MC (AV_1)	*n/d*
Sequence on applied sources	5	1	3	4	6			2	

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value.

3.2. 13.00 Time Case

At the 13.00 time point case we observed an extreme BG temperature together with exceeded THI (Table 5), as well as increased values of the temperature and the mean HLI. The most critical value was the THI index, which approached dangerous levels.

Table 5. Microclimatic conditions and indices at 13:00.

Recommended Values	Parameter/Index	Data
4–16	Dry-bulb temperature, °C	30
4–16	Black globe temperature, °C	41
-	Outdoor temperature, °C	19
50–80	Humidity, %	75
-	Outdoor humidity, %	55
≤74	THI	82
0.2–0.5	Airflow velocity, m/s	0.5
77–86	HLI	107
-	HLB	21
0	AHLU	−178
10–150 (×1000)	Airflow rate, m^3/h ×1000	84
≥20.95	Oxygen, O_2%	19.8
≤3	CO_2 (NH_3, H_2S, CO), ppm. ×1000	2.35
1–10	Illumination, Lx ×100	18.4

Based on the THI (Equation (1)), a decrease in the determinants of direct dependence T_A and RH (Table 6) was needed for reducing the index. In turn, for reducing the level of the black globe temperature, it was also necessary to decrease both the dry-bulb temperature and the solar radiation but increase the relative humidity in accordance with the BGT (Formula (2)); however, recommendations for both factors relating to relative humidity contradicted one another. Therefore, these changes in RH were not considered, while the reductions in the solar radiation and the temperature were accepted (Table 6). The HLI was also higher than required. Based on the HLI (Formula (3)) with BGT ≥ 25 °C, it was necessary to lower the BGT and the humidity levels along with a simultaneous increase in the airflow speed. Decreasing the BGT coincides with the first issue of the increased BGT. Thus, it is considered in the framework of the first issue.

Table 6. Determining factors for change.

Problem:	BGT↑			THI↑		T_a↑		HLI↑	
For correction	SR↓	Ta↓	RH↑	Ta↓	RH↓	Ta↓	BGT↓	RH↓	v↑
Current compliance with recommendations	+16 °C (BGT)	+14 °C	Norm	+14 °C	Norm	+14 °C	=SR↓, Ta↓, RH↑	Norm	Norm
Pre-confirmation	SR↓	Ta↓	x	Ta↓	x	Ta↓	x	x	v↑
Confirmed acts	SR↓				Ta↓				v↑

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value.

Table 7 reflects the process for determining the priority of applied sources in definite microclimatic conditions recorded at 13.00. On the final sequence choice, they are ranked according to the criteria of approval, marginality, compatibility and time per unit change. There are also two distinguished zones of operation: within the critical (red) values of functioning, and within the non-critical ones. In terms of non-critical means, the current marginality is the primary factor of source application. Conversely, in the case of critical values, this is the time per unit of change.

Table 7. Algorithm in a sequence for applying measures to regulate the microclimate.

Then for:	SR↓	T_A↓			v↑	
Possible sources	SR↓	T_1↓	T_2↓↓	T_3↓	AV_1↑	AV_2↑
Change in dependent parameters	RH↑	RH↑	RH↓, AV↑, O_2↑, GHG↓	RH↑	AFR↑ RH↓ AV↑ O_2↑ GHG↓	=T_2↓
Approved sources	SR↓	T_1↓	T_2↓↓	T_3↓	AV_1↑	→ T_2↓
Marginal costs, EUR/unit	0	MC (T_1)	0 (in case of NV)/MC (T_2)	-MC (T_3)	MC (AV_1)	n/d
Sequence of applied sources	3	1(2)—T_2↓, if NV or if MC (T_2) ≤ MC (T_1); 2(1)—T_1↓, if MC (T_1) < MC(T_2)		4	5	

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value; →—match with (amplification).

Accordingly, natural ventilation (NV) is the first priority, since opening vent holes is an inexpensive and relatively quick operation that provides cooling due to increased airflow speed (AV_1↑), increases the oxygen level (O_2↑), and reduces of gas emissions (GHG↓). Forced cooling (T_1↓) is the second priority as, despite its cost, it should reduce the means in the danger zones significantly. The next priority is shading from solar radiation, considering the marginality and speed of reducing the heat load (W×m^{-2}). Artificial lighting (T_3) can be quickly reduced. However, the dependence of this source on the total heat load is rather insufficient or inapplicable. In case of insufficient cooling, forced ventilation (AV_1↑) can also be applied. However, the recommendations for airflow velocity values may be significantly exceeded in the 13.00 time case.

3.3. 21.00 Time Case

Regardless of the fact that the accumulated heat load unit index (AHLU) was at a large negative value (Table 8), the current heat load index (HLI) exceeded the recommended range. Meanwhile, the level of acceptable pollution by one of the types of harmful gases was also exceeded.

Table 8. Microclimatic conditions and indices at 21:00.

Recommended Values	Parameter/Index	21:00
4–16	Dry-bulb temperature, °C	24
4–16	Black globe temperature, °C	34
-	Outdoor temperature, °C	14
50–80	Humidity, %	74
-	Outdoor humidity, %	61
≤74	THI	73
0.2–1.5	Airflow velocity, m/s	0.7
77–86	HLI	94
-	HLB	8
0	AHLU	−22
10–150 (×1000)	Airflow rate, m^3/h ×1000	79
≥20.95	Oxygen, O_2%	20.5
≤3	CO_2 (NH_3, H_2S, CO), ppm. ×1000	3.1
1–10	Illumination, Lx ×100	8.5

In the framework of the first approach (Table 9), general parameters for regulation are defined.

Table 9. Determining factors for change in the 21.00 time case.

Problems:		HLI↑		GHG↑
For correction	BGT↓	RH↓	AV↑	AFR↑
Current compliance with recommendations	+9 °C	Norm	Norm	Norm
Confirmed actions	BGT↓	RH↓	AV↑	AFR↑

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value.

As shown in Table 10, four sequential approaches were applied (approval, marginality, compatibility, and timing) in the selection and ranking of the influencing sources of the established climatic conditions. The source T_2/NV (ventilation) was the most prioritized for immediate changes, as it is complex and highly important in thermal regulation and gas exchange, which were beyond the normal values. Reducing the level of artificial illumination (T_3) was ranked second in the list, as this type of impact reduces costs. The SR source could also be applied first; however, it ended up ranking as the third most recommended application because, although not negative, it had zero relative marginality to a unit change. Practically speaking, it could be achieved via mechanical shading of the sunlight. In the event of insufficient actions for parameter normalization, the next step is forced ventilation (T_2↓), which can be used in conjunction with forced ventilation inside the room and air dehumidifiers (ranked 5th and 6th in the recommended order, respectively).

Table 10. Algorithm in a sequence for applying sources to regulate the microclimate.

Then for:		BGT↓				RH↓		v↑		AFR↑	
Possible sources	SR↓	T_1↓	T_2↓	T_3↓	H_1↓	H_2↓	H_3↓	AV_1↑	AV_2↑	AFR1↑	AFR2↑
Change in dependent parameter s	RH↑	RH↑	RH↓, AV↑ O_2↑ GHG↓	RH↑	n/d	Ta↑	=T_2↓ =H_3↓ =AV_2↑	AFR↑	=T_2↓ =H_3↓ =AV_2↑	=T_2↓ =H_3↓ =AV_2↑	=AV_1↑
Approved sources	SR↓	T_1↓	T_2↓↓↓↓	T_3↓	H_1↓	x	→ T_2↓	AV_1↑↑	→ T_2↓	→ T_2↓	→ AV_1↑
Marginal costs, EUR/unit	0	*n/d*	0 (NV)/MC (T_2)	-MC (T_3)	MC (H_1)		*n/d*	MC (AV_1)		*n/d*	
Sequence on applied sources	3		1—T_2↓ 4—T_2↓	2	6			5			

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value; →—match with (amplification).

4. Discussion

In all three cases, any of the microclimate parameters exceeding the recommended ranges is a formal reason for automatic, digital notification to bio-certification bodies. These organizations monitor compliance with organic regulations (Table 11).

Table 11. Causal relationships in the three considered cases.

Parameter/Index	Recommended Values	Hour (0–23) Case		
		3.00	13.00	21.00
Dry-bulb temperature, °C	*4–16*	7	30	24
Black globe temperature, °C	*4–16*	13	41	34
Ambient temperature, °C	-	2	19	14
Humidity, %	*50–80*	82	75	74
Outdoor humidity, %	-	67	55	61
THI	≤ 74	46	82	73
Airflow velocity, $m \cdot s^{-1}$	*0.2–0.5*	1.5	0.5	0.7
HLI	*77–86*	49	107	94
HLB	-	−28	21	8
AHLU	*0*	−64	−178	−22
Airflow rate, m^3/h ×1000	*10–150 (×1000)*	25	84	79
Oxygen, O_2%	≥ 20.95	21	19.8	20.5
CO_2 (NH_3, H_2S, CO), ppm. ×1000	≤ 3	1.21	2.35	3.1
Illumination, $100 \times Lx$	*1–1*	1.2	18.4	8.5
Recognition		High-risk threat	High-risk threat	Check
Response for CB *		Unannounced inspection; listed among the 10% [18]	Unannounced inspection; listed among the 10% [18]	Additional regular inspection; listed among the 5% [18]

* Based on methods for organic certification bodies [79].

The main document the bio-certification bodies follow is EU organic regulation 2018/848 of 30 May 2018 [79], which is an evolving document of revised European Commission Regulations 834/2007 and 889/2008. Thus, for the three cases (03:00; 13:00; 21:00), the proper code notifications for going beyond the norm may be written as (HLI − 7(r); H + 2(y); Av + 1(y)), (BGT + 25(r); THI + 8(r); Tdb + 14(y); HLI + 21(y)), and (HLI + 8(y); GHG + 100(y)), respectively, where (y) is a warning with a relatively low risk in the short term, while (r) is a current high-risk threat. One r-notification is a reason for immediate regulatory action, which automatically triggers an unannounced inspection. Lower risk levels may cause additional regular inspections in accordance with EU legislation [79].

Based on the results of the analysis, it is necessary to discuss the next point. Table 12 summarizes the sources for balancing microclimatic factors according to the recommendations. It is noteworthy that in all three cases, the highest-priority factor of regulation is the temperature, which is primarily regulated by the source of ventilation (T_2), i.e., air exchange with the outside air.

Table 12. Sources of microclimate regulation and their justified sequences in the observed cases.

3:00-Case						
Source	SR↑	T_1↑↑	T_2↑↑	T_3↑	H_1↓	AV_1↓
Sequence	4	5	1	3	6	2

13.00-Case						
Source	SR↓	T_1↓	T_2↓↓	T_3↓	x	AV_1↑
Sequence	3	1(2)	2(1)	4		5

21.00-Case						
Source	SR↓	x	T_2↓↓↓↓	T_3↓	H_1↓	AV_1↑↑
Sequence	3		1(4)	2	6	5

Legend: ↑↓—changing factor, increase (↑) or decrease (↓) in value.

Thus, the efficiency and optimality of microclimate regulation in the first place is directly dependent on the ventilation technology used in the livestock building. This is generally supported by other studies [94,95] and, in turn, indicates the correctness of the proposed technology.

However, there is another point of discussion. Despite a functioning algorithm, the impact on any of the climatic factors does not necessary indicate the type of energy applied (i.e., fossil fuels or renewable sources) or the sustainability of the consumed energy (i.e., energy system and manageable side effects) in the regulation of the microclimate. Based on an equal-weight scenario for financial, technical, environmental, and social criteria [91], an appropriate rank of the best energy alternatives was suggested as follows: (1) solar PV; (2) hydro; (3) wind; (4) geothermal; (5) biomass. However, each regional authority—such as the Rural Electricity Resource Council (http://rerc.org/aboutus.html; accessed on 20 September 2022)—could prioritize its own rankings based on the features of a region. Moreover, since ventilation (T_2), for example, can be natural or forced/mechanical (https://farm-energy.extension.org/ventilation-and-cooling-systems-for-animal-housing/; accessed on 20 September 2022) [96], the regulation is usually associated with mechanical methods and implemented mostly using electrical energy in animal housing [97,98]. However, the energy sustainability of mechanical ventilation also depends on the technology itself. Therefore, it is recommended to use the qualitative parameter of efficiency in technology with the ventilating efficiency ratio (VER) ($m^3 \times h^{-1} \times W^{-1}$) [99], where the higher the ratio the more efficiently a fan uses electricity. Thus, it is possible to create a subscale of enterprises according to these two factors (local priority of rank list and VER data of productions) for future organic certification and energy certification (formulating energy classes for a certification scheme for livestock buildings [97]).

5. Conclusions

The main idea behind this work is an attempt to numerically evaluate microclimatic factors and their interrelations that affect the health, welfare, and productivity of animals in controlled environments. Each microclimatic factor is presented as a set of separate physical indicators that can be monitored and effectively influenced. With a composition of certain indicators, the authors propose the analysis and ranking of relevant measures based on three main principles. The algorithm was created for mathematical substantiation of sources with sequential or parallel involvement during automatic regulation. A new initiative in this work is the third principle of transparency. Although this does not directly affect the sequence for switching the possible energy sources to regulate a certain climatic parameter, it does determine possible future interactions with certification bodies to improve the quality, sustainability and ethicality of products in systems of organic production. In addition, due to reporting to relevant committees on the efficiency of energy use, it also may contribute to the development of energy sustainability in the region—an incentive to reduce the levels of greenhouse gas emissions. Finally, the energy security and

sustainability aspects of centralized energy supplies are extremely relevant in the light of recent political events.

Other issues refer to the marginal costs of sources $f$mc ($X_{\text{last unit}}$) and connecting time values per unit changes of microclimatic variables ft ($X_{\text{last unit}}$). These are in high demand for the digital programming of automatic systems, which may be a reasonable subject for a separate study. These data are highly dependent on the applied technologies and are likely already available for equipment manufacturers; indeed, some attempts at applying simulation models have already been assessed in the academic literature [10].

However, the presented approach is based on objective physical laws that are supported by known equations. The practical outcome of this paper is hopefully to be a building block for pursuing the aim of finding a physical-based algorithm to manage the optimal microclimate under the terms of any farm with a controlled environment. In contrast with many published investigations, this work focuses not on the performance evaluation of a single regulatory method for microclimatic factors but, rather, on their analysis via three sequential principles (approval and compatibility, efficacy considering economic marginality, and transparency) to make the optimal choice on resources spent to maintain the conditions in a livestock building. Moreover, this technology should be tested through annual climate statistics, especially taking into account climatic extremes, long hot spells, and abnormally long frosts. In addition, for future fine-tuning of the algorithm, instead of commonly accepted but generalized indicators such as THI, HLI, HLB, or AHLU, it would be worth considering more personalized and accurate physiobiological indicators of animals.

This knowledge is potentially important for the subsequent digitalization processes in animal husbandry and the creation of an optimal digital template for an automatic algorithm that could be directly used in coding the commands for automatic regulation of the microclimate. The presented approach is highly likely to integrate into nature and bio-inspired algorithms within greenhouse control [100–102], as well as algorithms of artificial neural networks used for sustainable management in livestock systems [103].

In general, this paper does not present a specific algorithm for the automatic regulation of microclimatic conditions, since conditions can vary widely with different objects and types of livestock. Moreover, the final adaptation and implementation of the algorithm in areas of operation can be quite labor-intensive and time-consuming. It will be necessary to consider all conditions of a particular production system, including additional work with experimental methods on the verification of the algorithm. This study provides a reference for the indoor environmental regulation modeling of livestock housing. In the event that the experimental algorithm is not optimal, the health of animals may be negatively or even dangerously affected. The microclimate regulation modeling of such buildings should be supported with real tests on functioning facilities, and the control theory should be closely integrated with actual production systems.

Appendix A

The microclimatic parameters and indices are based on the data recorded from a livestock building on 27 April 2013 in Komarow (Poland) [8], with additions and simulations of the authors.

Recommended	Parameter/Index	Hour (0–23)																						
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
4–16	Dry-bulb temperature, °C	18	15	11	7	−1	5	9	10	12	16	20	23	25	30	30	31	32	32	30	28	25	24	23	21
4–16	Black globe temperature, °C	26	23	18	13	3	10	14	16	18	23	29	32	35	41	41	42	43	43	40	38	35	34	32	30
-	Ambient temperature, °C	9	7	5	2	−5	−1	2	4	6	8	10	13	16	19	20	20	23	22	20	19	18	14	13	12
50–80	Humidity, %	80	80	80	82	91	91	93	92	90	85	80	75	71	75	73	69	72	80	82	78	73	74	78	75
-	Outdoor humidity, %	60	62	64	67	80	81	85	86	85	79	72	65	59	55	60	60	61	65	65	64	61	61	65	64
≤74	*THI*	64	59	52	46	32	42	49	50	54	61	67	71	74	82	82	83	85	86	83	79	74	73	72	68
0.2-0.5	Airflow velocity, m/s	0.6	0.7	0.7	1.5	2.5	2.3	2.2	2.1	1.5	1.4	1.1	0.9	0.8	0.5	0.4	0.4	0.35	0.35	0.4	0.4	0.5	0.7	0.6	0.6
77–86	*HLI*	85	62	56	49	37	47	53	55	58	63	86	92	95	107	107	108	111	113	109	105	97	94	94	90
-	*HLB*	0	−15	−21	−28	−40	−30	−24	−22	−19	−14	0	6	9	21	21	22	25	27	23	19	11	8	8	4
0	*AHLU*	0	−15	−37	−64	−104	−134	−158	−180	−199	−213	−213	−207	−198	−178	−157	−135	−110	−83	−60	−41	−30	−22	−14	−10
10–150 (×1000)	Airflow rate, m³/h ×1000	20	18	24	25	32	35	45	58	62	65	71	75	79	84	89	95	98	98	97	92	85	79	75	68
≥20.95	Oxygen, O_2%	20.9	20.9	21	21	21	20.6	20.5	20.5	20.4	20.4	20.1	20	20	19.8	19.7	19.6	19.7	19.7	19.8	19.9	20	20.5	20.5	20.7
≤3	CO_2 (NH_3, H_2S, CO), ppm. ×1000	1	1.05	1.1	1.21	1.38	1.44	1.53	1.64	1.75	1.89	1.97	2	2.2	2.35	2.65	2.98	2.5	2.29	2	2.9	2.75	3.1	3.12	3.05
1–10	Illumination, 100× *Lx*	1	1	1	1.2	1.3	1.6	1.7	2	3.5	4.8	6.8	9.5	13.2	18.4	19.5	20.2	21.5	23	21	14.2	10.3	8.5	5.6	2.4

Developed by the authors; reference genotype: black Bos taurus/Angus steer; factors: no shade, manure management max = 50 mm, black coat color, healthy animal, water temperature = 20–30 °C, SR = 929 W/m^2; premises: S = 500 m^2, V = 2500 m^3, q = 15 steers; season: spring. The THI, HLI, HLB, and AHLU indices are calculated based on the input data. Blue: below the recommended minimum; orange: above/below the recommended value; red: critical (danger) values. n (hour): The environmental conditions when the regulation of microclimatic parameters is highly recommended.

References

1. Blood, D.C.; Radostits, O.M. Veterinary Medicine. In *A Textbook of the Diseases of Cattle, Sheep, Pigs, Goats and Horses*, 7th ed.; Baillière Tindall: London, UK, 1989; pp. 677–690.
2. Herbut, P. Air movement characteristics inside a cow barn with natural ventilation under no-wind conditions in the winter season. *Kom. Tech. Infrastruktury Wsi PAN O. W Krakowie* **2010**, *11*, 159–164.
3. Gauly, M.; Bollwein, H.; Breves, G.; Brugemann, K.; Danicke, S.; Das, G.; Demeler, J.; Hansen, H.; Isselstein, J.; Konig, S. Future consequences and challenges for dairy cow production system arising from climate change in center Europe—A review. *Animal* **2013**, *7*, 843–859. [CrossRef]
4. Nešporová, J.; Pavliš, V. Porovnání výše ztrát telat na vzdušném odchovu a v profylaktoriu ve VKK Kvasejovice. In *Sborník ze Semináře "Aktuální Problémy Odchovu Telat"*; ČSVTS: České Budějovice, Czech Republic, 1988; pp. 71–72.
5. Doležal, O.; Staněk, S.; Bečková, I. *Zemědělský Poradce ve Stáji II. Telata. Metodika*; Vyzkumny ustav zivocisne vyroby (VUZV), v.v.i.: Praha, Czech Republic, 2008; 63s.
6. Schauberger, G.; Piringer, M.; Petz, E. Steady-state balance model to calculate the indoor climate of livestock buildings, demonstrated for finishing pigs. *Int. J. Biometeorol.* **2000**, *43*, 154–162. [CrossRef] [PubMed]
7. Gao, L.; Er, M.; Li, L.; Wen, P.; Jia, Y.; Huo, L. Microclimate environment model construction and control strategy of enclosed laying brooder house. *Poult. Sci.* **2022**, *101*, 101843. [CrossRef]
8. Głuski, T.; Patro, M.; Marczuk, A.; Misztal, W.; Szwedziak, K.; Grzywacz, Z. 24-Hour Microclimate Conditions in Livestock Building. *Agric. Eng.* **2019**, *23*, 41–49. [CrossRef]
9. Andretta, I.; Kipper, M.; Schirmann, G.D.; Franceschina, C.S.; Ribeiro, A.M.L. Modeling the performance of broilers under heat stress. *Poult. Sci.* **2021**, *100*, 101338. [CrossRef] [PubMed]
10. Schauberger, G.; Hennig-Pauka, I.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Knauder, W.; Anders, I.; Andre, K.; et al. Efficacy of adaptation measures to alleviate heat stress in confined livestock buildings in temperate climate zones. *Biosyst. Eng.* **2020**, *200*, 157–175. [CrossRef]
11. Perez-Gonzalez, A.; Begovich-Mendoza, O.; Ruiz-Leon, J. Modeling of a greenhouse prototype using PSO and differential evolution algorithms based on a real-time LabViewTM application. *Appl. Soft Comput.* **2018**, *62*, 86–100. [CrossRef]
12. Taki, M.; Ajabshirchi, Y.; Ranjbar, S.F.; Rohani, A.; Matloobi, M. Heat transfer and MLP neural network models to predict inside environment variables and energy lost in a semi-solar greenhouse. *Energy Build.* **2016**, *110*, 314–329. [CrossRef]
13. Hasni, A.; Taibi, R.; Draoui, B.; Boulard, T. Optimization of greenhouse climate model parameters using particle swarm optimization and genetic algorithms. *Energy Procedia* **2011**, *6*, 371–380. [CrossRef]
14. Rivera-Ferre, M.G.; López-i-Gelats, F.; Howden, M.; Smith, P.; Morton, J.F.; Herrero, M. Re−framing the climate change debate in the livestock sector: Mitigation and adaptation options. *Wiley Interdiscip. Rev. Clim. Chang.* **2016**, *7*, 869–892. [CrossRef]
15. Kimball, B.A. Simulation of the energy balance of a greenhouse. *Agric. Meteorol.* **1994**, *11*, 243–260. [CrossRef]
16. Bot, G.P.A. Greenhouse Climate: Form Physical Processes to a Dynamic Model. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 1983.
17. Bai, X.; Wang, Z.; Sheng, L.; Wang, Z. Reliable data fusion of hierarchical wireless sensor networks with asynchronous measurement for greenhouse monitoring. *IEEE Trans. Control. Syst. Technol.* **2018**, *27*, 1036–1046. [CrossRef]
18. Joudi, K.; Farhan, A. A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse. *Energy Convers. Manag.* **2015**, *91*, 76–82. [CrossRef]
19. Su, Y.; Xu, L. Towards discrete time model for greenhouse climate control. *Eng. Agric. Environ. Food* **2017**, *10*, 157–170. [CrossRef]
20. Yang, H.; Liu, Q.F.; Yang, H.Q. Deterministic and stochastic modelling of greenhouse microclimate. *Syst. Sci. Control. Eng.* **2019**, *7*, 65–72. [CrossRef]
21. Daniel, Z. Wpływ mikroklimatu obory na mleczność krów. *Inżynieria Rol.* **2008**, *9*, 67–73.
22. Cincović, M.R. *Toplotni Stres Krava—Fiziologija i Patofiziologija*; Monografija, zadužbina Andrejević: Beograd, Serbia, 2010.
23. Hristov, S.; Stanković, B.; Joksimović-Todorović, M.; Bojkovski, J.; Davidović, V. Uticaj toplotnog stresa na proizvodnju mlečnih krava. *Zbornik Naučnih Radova* **2007**, *13*, 47–54.
24. Bernabucci, U.; Biffani, S.; Buggiotti, L.; Vitali, A.; Lacetera, N.; Nardone, A. The effects of heat stress in Italian Holstein dairy cattle. *J. Dairy Sci.* **2013**, *97*, 471–486. [CrossRef]
25. Spiers, D.E.; Spain, J.N.; Sampson, J.D.; Rhoads, R.P. Use of physiological parameters to predict milk yield and feed intake in heat-stressed dairy cows. *J. Therm. Biol.* **2004**, *29*, 759–764. [CrossRef]
26. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **2003**, *86*, 2131–2144. [CrossRef]
27. Kadzere, C.T.; Murphy, M.R.; Silanikove, N.; Maltz, E. Heat stress in lactating dairy cows: A review. *Livest. Prod. Sci.* **2002**, *77*, 59–91. [CrossRef]
28. Hansen, P.J. Exploitation of genetic and physiological determinants of embryonic resistance to elevated temperature to improve embryonic survival in dairy cattle during heat stress. *Theriogenology* **2007**, *68*, 242–249. [CrossRef] [PubMed]
29. Jaśkowski, J.M.; Urbaniak, K.; Olechnowicz, J. Stres cieplny u krów—Zaburzenia płodności i ich profilaktyka. *Życie Weterynaryjne* **2005**, *80*, 18–21.
30. MMM-RMO C2.2 Maatalouden tuotantorakennusten lämpöhuolto ja ilmanvaihto. In *Heating and Ventilation of Agricultural Production Houses*; Ministry of Agriculture and Forestry (MMM): Helsinki, Finland, 2022. (In Finnish)

31. Tarr, B. Cold Stress in Cows. 2007. Available online: http://www.omafra.gov.on.ca/english/livestock/beef/facts/07-001.htm (accessed on 12 September 2022).

32. Kic, P.; Brož, V. *Tvorba Stajoveho Prostředi*, 1st ed.; Institut vychovy a vzdělavani Ministerstva zemědělstvi Česke republiky: Praha, Czech Republic, 1995; p. 47.

33. Pedersen, S. Considerations over calf health in cold temperatures. UK. *Vet. Times* **2014**, *4*, 14–15.

34. Botto, Ľ. Ustajnenie a prostredie ošípaných. In *Návrh Optimalizovaných Parametrov Ustajnenia pre Hovädzí Dobytok, Ovce, Kone a Ošípané*; Brouček, J., Ed.; National Agricultural and Food Center, Animal Production Research Institute (EN): Nitra, Slovakia, 2012.

35. Hill, T.M.; Bateman, G.; Aldrich, J.M.; Schlotterbeck, R.L. Comparison of housing, bedding, and cooling options for dairy calves. *J. Dairy Sci.* **2011**, *94*, 2138–2146. [CrossRef]

36. McGuirk, S.M. Disease management of dairy calves and heifers. *Vet. Clin. N. Am. Food Anim. Pract.* **2008**, *24*, 139–153. [CrossRef] [PubMed]

37. Tuyttens, F.A.M. The importance of straw for pig and cattle welfare: A review. *Appl. Anim. Behav. Sci.* **2005**, *92*, 261–282. [CrossRef]

38. ASHRAE. *Handbook of Fundamentals*; America Society of Heating, Refrigeration and Air Conditioning Engineers: Atlanta, GA, USA, 2013.

39. DeShazer, J.A.; Hahn, L.; Xin, H. Chapter 1: Basic Principles of the Thermal Environment and Livestock Energetics. In *DeShazer, Livestock Energetics and Thermal Environment Management*, 1st ed.; James, A., Ed.; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2009; pp. 1–22.

40. Basharat, S. Effects of Air Velocity at Dairy Cow. Available online: https://www.linkedin.com/pulse/effects-air-velocity-dairy-cow-sohail-basharat?trk=public_profile_article_view (accessed on 12 September 2022).

41. Romaniuk, W.; Overby, T.; Domasiewicz, T.; Głaszczka, A.; Mazur, K.; Wardal, W.; Rudnik, K.; Winnicki, S.B.; Eymontt, A.; Rasmussen, J.B.; et al. *Systems of Maintenance of Cattle*; Instytut Budownictwa, Mechanizacji i Elektryfikacji Rolnictwa, Duńskie Służby Doradztwa Rolniczego: Warsaw, Poland, 2005. (In Polish)

42. Lautner, M.; Miller, A.M. Kuehe lieben keine heissen Tage sondern kuhlen Kopf. *Nach-Richtsblatt. Besammungsbv Neust. D. Aisch.* **2003**, *149*, 23–25.

43. Solan, M.; Józwik, M. The effect of microclimate and management system on welfare of dairy cows. *Wiad. Zoot.* **2009**, *1*, 25–29. (In Polish)

44. Wathes, C.; Jones, C.; Webster, A. Ventilation, air hygiene and animal health. *Vet. Rec.* **1983**, *113*, 554–559. [PubMed]

45. Teye, F.; Hautala, M.; Pastell, M.; Praks, J.; Veermäe, I.; Poikalainen, V.; Pajumägi, A.; Kivinen, T.; Ahokas, J. Microclimate in cowsheds in Finland and Estonia. In Proceedings of the 13th International Congress in Animal Hygiene, Animal Health, Animal Welfare and Biosecurity, Tartu, Estonia, 17–21 June 2007; Aland, A., Ed.; pp. 83–88.

46. Broom, D.M. Environment as a significant factor influencing the welfare and production of farm animals. *Anim. Prod. Welf.* **2000**, 152–157.

47. Ministry of Agriculture and Food of the Republic of Belarus (MAFRB). Methodological Recommendations for Sanitary and Hygienic Assessment of a Poultry Factory. 2006. Available online: https://elib.belstu.by/bitstream/123456789/32293/1/metodicheskie_rekomendacii_po_sanitarno.pdf (accessed on 20 September 2022).

48. MSAH Haitalliseksi Todettu Pitoisuus arvot. In *Exposure Limits. Sosiaali- ja Terveysministeriön Oppaita*; Ministry of Social affairs and Health (MSAH): Helsinki, Finland, 2005. (In Finnish)

49. *MWPS-32 Midwest Plan Service Mechanical Ventilating Systems for Livestock Housing*; Iowa State University: Ames, IA, USA, 1990.

50. CEMAGREF. *CIGR Commission International du Génie Rural Aerial Environment in Animal Housing—Concencentration in and Emission from Farm Buildings*; CEMAGREF: Rennes, France, 1994.

51. CIGR Commission International du Genié Rural. *Climatization of Animal Houses*; Report of working group; Scottish Farm Buildings Investigation Unit: Aberdeen, Scotland, 1984.

52. Morris, T.C.M.; Wathes, D.R. Charles. *J. Agric. Sci.* **1994**, *125*, 123–148. [CrossRef]

53. RME (Rozporządzenie Ministra Środowiska), Regulation of the Minister of Environment of 24 August 2012. On the Levels of Certain Substances in the Air (Dz.U. 2012 poz. 1031), Warsaw, Poland. 2012. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20120001031/O/D20121031.pdf (accessed on 20 September 2022).

54. Gavan, C.; Motorga, V. The effect of supplemental light on milk production in holstein dairy cows. *Lucr. Ştiinţifice Zooteh. Şi Biotehnol.* **2009**, *42*, 261–265.

55. Doležal, O.; Cerná, D. Technika a technologie chovu skotu—Dojnice: Světlo ve stájích a dojírnách. In *Metodické Listy*; Výzkumný ústav živočišné výroby: Praha, Czech Republic, 2006; ISBN 80-86454-74-6.

56. Starby, L. *A Book on Lighting: A Basis for Planning Lighting Systems (En Bok om Belysning: Underlag för Planering av Belysningsanläggningar)*; Ljuskultur: Stockhol, Sweden, 2006.

57. *ASAE EP344.3*; Lighting for Agricultural Facilities. 53rd ed. American Society of Agricultural Engineers: St. Joseph. MI, USA, 2006.

58. Dimov, D.; Penev, T.; Marinov, I. Illumination levels in milking parlor in dairy cows freestall housing system. *Bulg. J. Agric. Sci.* **2020**, *26* (Suppl. 1), 78–82.

59. Lawrence, M.G. The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications. *Bull. Am. Meteorol. Soc.* **2005**, *86*, 225–233. [CrossRef]

60. Clapeyron, E. Mémoire sur la puissance motrice de la chaleur. *J. de l'École Polytechnique* **1835**, *XIV*, 90–153.
61. BRE. *Natural Ventilation in Non-Domestic Buildings*; BRE Digest; Building Research Establishment: Garston, UK, 1994.
62. Andonov, K.; Daskalov, P.; Martev, K. A New Approach to Controlled Natural Ventilation of Livestock Buildings. *Biosyst. Eng.* **2003**, *84*, 91–100. [CrossRef]
63. Moran, J. *Tropical Dairy Farming: Feeding Management for Small Holder Dairy Farms in the Humid Tropics*; Landlinks Press: 2005. Available online: http://www.publish.csiro.au/ebook/chapter/SA0501275 (accessed on 12 September 2022).
64. Thom, E.C. The discomfort index. *Weatherwise* **1959**, *12*, 57–59. [CrossRef]
65. Hahn, G.L. Management and housing of farm animals in hot environments. In *Stress Physiology in Livestock*; Yousef, M., Ed.; CRC: Boca Raton, FL, USA, 1985; pp. 151–174.
66. Akyuz, A.; Boyaci, S.; Cayli, A. Determination of critical period for dairy cows using temperature humidity index. *J. Anim. Vet. Adv.* **2010**, *9*, 1824–1827. [CrossRef]
67. Brügemann, K.; Gernand, E.; König von Borstel, U.; König, S. Defining and evaluating heat stress thresholds in different dairy cow production systems. *Archiv Tierzucht* **2012**, *55*, 13–24. [CrossRef]
68. Brown-Brandl, T.M.; Jones, D.D.; Woldt, W.E. Evaluating modelling techniques for cattle heat stress prediction. *Biosyst. Eng.* **2005**, *91*, 513–524. [CrossRef]
69. Mader, T.L.; Davis, M.S.; Brown-Brandl, T. Environmental factors influencing heat stress in feedlot cattle. *Anim. Sci.* **2006**, *84*, 712–719. [CrossRef] [PubMed]
70. FAO. Statistics2021. Available online: http://www.fao.org/3/S1250E/S1250E0s.htm (accessed on 12 September 2022).
71. Bond, T.E.; Kelly, C.F. The globe thermometer in agricultural research. *Agric. Eng.* **1955**, *36*, 251–255.
72. Castanēda, C.A.; Gaughan, J.B.; Sakaguchi, Y. Relationships between climatic conditions and the behaviour of feedlot cattle. *Proc. Aust. Soc. Anim. Prod.* **2004**, *25*, 33–36.
73. Gaughan, J.B.; Castanēda, C.A. *Refinement of Heat Load Index Based on Animal Factors*; Meat and Livestock Australia: North Sydney, NSW, Australia, 2003.
74. Buffington, D.E.; Collazo-Arocho, A.; Canton, G.H.; Pitt, D.; Thatcher, W.W.; Collier, R.J. Black globe-humidity index (bghi) as comfort equation for dairy cows. *Trans. ASAE* **1981**, *24*, 0711–0714. Available online: https://elibrary.asabe.org/abstract.asp??JID=3&AID=34325&CID=t1981v=24&i=3&T=1 (accessed on 12 September 2022). [CrossRef]
75. Swokowski, E.W. *Calculus with Analytic Geometry (illustrated ed.)*; Taylor & Francis: Boston, MA, USA, 1979; p. 370.
76. Gaughan, J.B.; Mader, T.L.; Holt, S.M.; Lisle, A. *A New Heat Load Index for Feedlot Cattle*; Faculty Papers and Publications in Animal Science, Lincoln: Dearborn, MI, USA, 2008; p. 613. Available online: https://digitalcommons.unl.edu/animalscifacpub/613 (accessed on 12 September 2022).
77. Edwards-Callaway, L.N.; Caitlin Cramer, M.; Cadaret, C.N.; Bigler, E.J.; Engle, T.E.; Wagner, J.J.; Clark, D.L. Impacts of shade on cattle well-being in the beef supply chain. *J. Anim. Sci.* **2021**, *99*, skaa375. [CrossRef]
78. *Introduction to the Recommendations for Animal Welfare*; Terrestrial Animal Health Code, Section 7 Animal Welfare; World Organisation for Animal Health: Paris, France, 2021.
79. Regulation (EU) 2018/848 of the European Parliament and of the Council on organic production and labelling of organic products and repealing Council Regulation (EC) No. 834/2007. *Off. J. Eur. Union* **2018**, *L 150*, 1–92.
80. Verified Beef Production Plus (VBP+). Producer Manual. Version 1.6. 2019. Available online: http://verifiedbeefproductionplus.ca/files/producer-resources/VBP_Producer_Manual_combined_V_1.6_and_V_7.8_Feb_13_2019.pdf (accessed on 1 April 2020).
81. Kononets, Y.; Konvalina, P.; Bartos, P.; Stokes, J.E. The Evolution of Organic Food Certification. *Front. Sustain. Food Syst.* 2022; submitted.
82. Paris, B.; Vandorou, F.; Tyris, D.; Balafoutis, A.T.; Vaiopoulos, K.; Kyriakarakos, G.; Manolakos, D.; Papadakis, G. Energy Use in the EU Livestock Sector: A Review Recommending Energy Efficiency Measures and Renewable Energy Sources Adoption. *Appl. Sci.* **2022**, *12*, 2142. [CrossRef]
83. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987–992. [CrossRef]
84. Leip, A.; Carmona-Garcia, G.; Rossi, S. Mitigation measures in the Agriculture, Forestry, and Other Land Use (AFOLU) sector. Quantifying mitigation effects at the farm level and in national greenhouse gas inventories. *JRC EC Tech. Rep.* **2017**, 6–8. [CrossRef]
85. European Commission. A European Green Deal: Striving to Be the First Climate-Neutral Continent. 2021. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 11 September 2022).
86. European Commission. *Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Brussels, Belgium, 2020.
87. Mintaș, O.S.; Mierliță, D.; Berchez, O.; Stanciu, A.; Osiceanu, A.; Osiceanu, A.G. Analysis of the Sustainability of Livestock Farms in the Area of the Southwest of Bihor County to Climate Change. *Sustainability* **2022**, *14*, 8841. [CrossRef]
88. Romaniuk, W.; Mazur, K.; Borek, K.; Borusiewicz, A.; Wardal, W.J.; Tabor, S.; Kuboń, M. Biomass Energy Technologies from Innovative Dairy Farming Systems. *Processes* **2021**, *9*, 335. [CrossRef]
89. John, C.A.; Tan, L.S.; Tan, J.; Kiew, P.L.; Shariff, A.M.; Abdul Halim, H.N. Selection of Renewable Energy in Rural Area Via Life Cycle Assessment-Analytical Hierarchy Process (LCA-AHP): A Case Study of Tatau, Sarawak. *Sustainability* **2021**, *13*, 11880. [CrossRef]

90. Saraswat, S.K.; Digalwar, A.K. Empirical investigation and validation of sustainability indicators for the assessment of energy sources in India. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111156. [CrossRef]

91. Lee, H.C.; Chang, C.T. Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. *Renew. Sustain. Energy Rev.* **2018**, *92*, 883–896. [CrossRef]

92. Fechet, R.; Petrariu, A.I.; Graur, A. Partial Discharge and Internet of Things: A Switchgear Cell Maintenance Application Using Microclimate Sensors. *Sensors* **2021**, *21*, 8372. [CrossRef]

93. Kim, S.-Y.; Kim, Y.-K. An Energy Efficient UAV-Based Edge Computing System with Reliability Guarantee for Mobile Ground Nodes. *Sensors* **2021**, *21*, 8264. [CrossRef]

94. Kiktev, N.; Lendiel, T.; Vasilenkov, V.; Kapralyuk, O.; Hutsol, T.; Glowacki, S.; Kuboń, M.; Kowalczyk, Z. Automated Microclimate Regulation in Agricultural Facilities Using the Air Curtain System. *Sensors* **2021**, *21*, 8182. [CrossRef]

95. Tikhomirov, D.; Vasilyev, A.N.; Budnikov, D.; Vasilyev, A.A. Energy-saving automated system for microclimate in agricultural premises with utilization of ventilation air. *Wirel. Netw.* **2020**, *26*, 4921–4928. [CrossRef]

96. Jones, D.D.; Friday, W.H.; Sherwood, S.; DeForest, P.E. *Environmental Control for Confinement Livestock Housing*; Purdue Extension Publication: West Lafayette, IN, USA, 1914. Available online: https://www.extension.purdue.edu/extmedia/AE/AE-96.html (accessed on 11 September 2022).

97. Costantino, A.; Fabrizio, E.; Biglia, A.; Cornale, P.; Battaglini, L. Energy Use for Climate Control of Animal Houses: The State of the Art in Europe. *Energy Procedia* **2016**, *101*, 184–191. [CrossRef]

98. Markou, G.; Balafoutis, T.; Mohamed, E.; Papadakis, G.; Michael, P.; Janssen, R. *The Cyprus Energy Profile for the Animal Sector: Current Situation and Energy Saving Measures in Combination with RES*; European Commission: Brussels, Belgium, 2017.

99. The Bioenvironmental and Structural System (BESS) Laboratory Data, Agricultural Ventilation Fans, University of Illinois, Department of Agricultural and Biological Engineering. 2022. Available online: http://bess.illinois.edu/type.asp (accessed on 11 September 2022).

100. Oliveira, P.M.; Solteiro Pires, E.J.; Boaventura-Cunha, J. Evolutionary and Bio- inspired Algorithms in Greenhouse Control: Introduction, Review and Trends. *Intell. Environ.* **2017**, *22*, 39–48. [CrossRef]

101. Oliveira, P.M.; Pires, E.S.; Boaventura-Cunha, J.; Pinho, T.M. Review of nature and biologically inspired metaheuristics for greenhouse environment control. *Trans. Inst. Meas. Control* **2020**, *42*, 2338–2358. [CrossRef]

102. Li, B.M.; Wang, Y.; Zheng, W.C.; Tong, Q. Research progress in environmental control key technologies, facilities and equipment for laying hen production in China. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 212–221.

103. Salah, L.B.; Fourati, F. A greenhouse modeling and control using deep neural networks. *Appl. Artif. Intell.* **2021**, *35*, 1905–1929. [CrossRef]

2 Cíl a hypotézy práce

Cílem dizertační práce *Monitoring mikroklimatických podmínek v intenzivních chovech hospodářských zvířat s technologií nucené a přirozené ventilace* je objektivní posouzení produkce emisí NH_3 a NH_4 a revize dostupných metodik pro jejich stanovení. Práce je zaměřena zejména na intenzivní chovy hospodářských zvířat, které jsou provozovány na území ČR a svým charakterem jsou součástí integrovaného registru znečišťování životního prostředí či se uvažuje o jejich zařazení.

Výzkumné hypotézy

V oblasti vědecko-výzkumné byly formulovány tři hypotézy:

> H1: Metodika pro stanovení emisí NH_3 *výpočet měřením koncentrace NH_3 a výkonu ventilace* uvedená v Závěry o BAT (2017) je dostačující z pohledu matematického vyhodnocení dat z 24hodinového měření.

> H2: Stanovené emisní faktory pro NH_3 z ustájení intenzivního výkrmu prasat uvedené v MŽP ČR (2012) odpovídají současným provozním podmínkám.

> H3: Dodržení stanoveného počtu a rozložení monitorovacích dnů uvedených v metodice Závěry o BAT (2017) je klíčové při odhadu emisí NH_3 z intenzivního výkrmu prasat metodou *výpočet měřením koncentrace NH_3 a výkonu ventilace.*

Cíle pro praxi

Pro vypracování dizertační práce jsou stanovené cíle, které budou aplikovány v praxi:

> C1: Ověřit, zda vybrané intenzivní chovy prasat splňují limity BREF pro emise NH_3 pro jednotlivé kategorie chovaných zvířat.

> C2: Stanovení vhodné metodiky pro měření emisí NH_3 a CH_4 z přirozeně větraných hal pro ustájení skotu.

3 Metodika a výsledky

3.1 Publikovaná rešerše k dané problematice

První publikace **Kunes, R**. a kol. (2002a). *A Review: Comparison of Approaches to the Approval Process and Methodology for Estimation of Ammonia Emissions from Livestock Farms under IPPC, Atmosphere,* je rešeršního charakteru a zabývá se problematikou metod pro stanovení či přesněji řečeno odhad emisí NH_3 z intenzivních chovů hospodářských zvířat, na které se aktuálně vztahuje směrnice IED. Dle uvedené směrnice jsou to chovy s kapacitou nad 40 000 kusů drůbeže, 750 prasnic nebo 2 000 kusů prasat na výkrm. Podklady pro rešerši byly získány v období roku 2019–2020 a zaměřují se na všechny členské státy EU.

Spolehlivé metody pro odhad emisí NH_3 jsou v zemích EU nezbytné pro určování účinnosti strategií zmírňování emisí na národní a regionální úrovni. Podle závěrů o nejlepších dostupných technologií (BAT) směrnice IED lze odhad provádět podle tří přístupů:

1. *Odhad s použitím emisních faktorů* – Emisní faktor je stanoven na základě vědeckých poznatků a liší se podle kategorie a technologie ustájení zvířat. Výpočty se berou v úvahu pro každý cyklus manipulace s hnojem (ustájení, skladování, aplikace na pole). Do výpočtu lze také implementovat technologie pro snížení emisí. Emisní faktory jsou převzaté z evropských nebo národních legislativ.

2. *Odhad s použitím hmotnostní bilance podle vyloučení celkového dusíku* – Emise NH_3 jsou odhadovány na základě množství dusíku vyloučeného zvířaty (celkový tok dusíku či amoniakálního dusíku) a koeficientu vyprchání za každou fázi zpracování hnoje (ustájení, skladování, aplikace na pole). Koeficient vyprchání lze převzít z evropských nebo národních legislativ.

3. *Výpočet měřením koncentrace NH_3 a výkonu ventilace* – Při monitoringu je nutné se držet zásad pro odběr vzorků a to tak, aby se ve sledované hale provedlo nejméně šest dní měření rozložených do období jednoho roku a to následovně:

   a) Stabilní produkce emisí (nosnice, prasnice) – měření se doporučuje jednou každé dva měsíce během jednoho roku.

b) Lineární produkce emisí (prasata na výkrm) – tři měření se doporučují uskutečnit v prvním chovném cyklu a tři měření v druhém chovném cyklu. Dny monitorování v druhé polovině chovného cyklu se rovnoměrně rozloží po celý rok.

c) Exponenciální produkce emisí (brojleři) – jedno měření provést v prvním chovném cyklu, dvě měření v druhém chovném cyklu a tři měření ve třetím chovném cyklu. Dny monitorování ve třetím období chovného cyklu je třeba rovnoměrně rozložit po celý rok (Závěry o BAT, 2017).

Měření koncentrace NH_3 se provádí souběžně na vstupu a výstupu vzduchu z chovné haly kontinuálně po dobu minimálně 24 hodin. Koncentrace NH_3 pro výpočet emisí se stanový rozdílem koncentrace NH_3 naměřené na výstupu a koncentrace NH_3 naměřené na vstupu do chovné haly. Výsledná koncentrace NH_3 se poté násobí výkonem ventilace, která je měřena pomocí rychlosti proudění vzduchu či je zaznamenávána řídící jednotkou. Denní průměr emisí se vypočítá jako průměr za všechny dny odebírání vzorků. Z denního průměru emisí NH_3 lze vypočítat roční průměrné emise vynásobením počtu dnů obsazenosti chovné haly (Závěry o BAT, 2017).

Z uvedené publikace vyplývá, že v ČR mohou provozovatelé chovů, na které se vztahuje směrnice IED využít podle Metodického pokynu MŽP ČR k odhadu emisí NH_3 *odhad s použitím emisních faktorů* (BAT 25.c), nebo *výpočet měřením koncentrace NH_3 a výkonu ventilace* (BAT 25.b). Povolovací orgán nicméně nemůže *výpočet měřením koncentrace NH_3 a výkonu ventilace* nařídit podle BAT 25.b (Závěry o BAT, 2017).

Jednotlivé členské země EU používají odlišné přístupy. Je to dáno rozdílným přístupem legislativ z pohledu ochrany životního prostředí. Důležitými faktory jsou také rozdíly v klimatických podmínkách a používaných technologiích chovů, které mají vliv na produkci zmíněných emisí. Ty se promítají zejména do výpočtových koeficientů používaných při odhadů emisí s použitím *emisních faktorů* či *hmotnostní bilance podle vyloučeného celkového dusíku*. Tyto faktory či koeficienty jednotlivé státy EU přebírají z evropské legislativy, či si je upravují podle národních zákonů. Z tohoto důvodu mohou při stejně zvolené metodice (odhad emisí NH_3 podle *emisních faktorů*) vykazovat rozdílné hodnoty.

Nejméně používanou variantou odhadu emisí NH_3 je pomocí *výpočtu měřením koncentrace NH_3 a výkonu ventilace*. Je to zejména z důvodu časové a finanční náročnosti a používá se zejména pro vědecko-výzkumné účely. Nejpoužívanější metodou je *odhad*

s použitím bilance podle vyloučení celkového dusíku. Tato metoda se ještě dělí na přístup výpočtu pomocí metody Tier 1 a Tier 2. Uvedená metoda je přesnější, protože do výpočtu zahrnuje detailnější postup při stanovení koloběhu dusíku než *odhad s použitím emisních faktorů*, ale je náročnější na provedené výpočty. Někteří provozovatelé si je nedokáží sami zpracovat a jsou nuceni si pro tyto výkazy najímat externí zpracovatele.

Z výše uvedených informací lze říci, že metodika pro odhad emisí NH₃ z intenzivních chovů hospodářských zvířat, na které se vztahuje směrnice IED se liší podle legislativ členských zemí EU. Z tohoto důvodu i na výsledné emise NH₃, které vykazují jednotlivé členské státy, musí být nahlíženo zejména z pohledu metodiky, podle které byly odhadnuty. Detailní přehled přístupů jednotlivých zemí pro odhad emisí NH₃ je uveden ve zmíněné publikaci na stránkách 13 a 14 v kapitole 3.2.

3.2 Metodika pro měření emisí amoniaku z intenzivních chovů prasat

Druhá publikace Kriz, P., **Kunes, R**., a kol. (2021). ***Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming***, *Agriculture*, se zabývá tvorbou metodiky zejména z pohledu vyhodnocení naměřených dat. Před prováděním experimentálních měření emisí NH₃ autoři konstatovali, že metodika pro odhad emisí NH₃ *výpočet měřením koncentrace NH₃ a výkonu ventilace*, která je popsána v dizertační práci kapitole 3.1 odstavec 3 sice detailně stanovuje kolikrát a v jakém období u kterých kategorií zvířat provádět měření a jak správně odebírat vzorky, ale více se nezabývá problematikou vyhodnocení naměřených hodnot, respektive jak statisticky stanovit průměrnou denní hodnotu emisí NH₃ z 24hodinového monitoringu. Na základě této problematiky různí autoři či výzkumné týmy volí rozdílný přístup pro následné vyhodnocení naměřených dat. Hlavní motivací pro autory uvedené výzkumné publikace bylo stanovení vhodné metodiky pro vyhodnocení dat z pohledu jejich reprezentativnosti.

Stanovení emisí NH₃ je založeno na měření rozdílu koncentrace NH₃ vstupujícího a vystupujícího ze stáje. Dalším měřeným parametrem je průtok vzduchu prostorem stáje, ze kterého je určen výkon ventilace. Pro měření koncentrace NH₃ autoři používali plynový analyzátor INNOVA 1412, který může analyzovat vzorky až z 12 odběrových míst. Přístroj analyzuje vzorky postupně, proto nelze v jeden okamžik znát koncentraci NH₃ vstupující a vystupující z haly. Nezávisle na měření koncentrace NH₃ jsou také získávána data o průtoku vzduchu ventilací (výkon ventilace). Z principiálních omezení použitého přístroje vyplývá, že není možné získat v jeden okamžik data odpovídající pro aktuální

vstupní i výstupní koncentraci vzduchu a výkonu ventilace. Z tohoto důvodu je nutné počítat výsledné emise NH_3 z více nezávisle měřených dat všech vstupních proměnných během vhodně zvoleného časového intervalu (časového okna). Volba časového okna je klíčová pro výslednou přesnost měření.

Postup pro testování statistických metod pro stanovení vhodného časového intervalu byl aplikován na reálných datech pořízených z experimentálního měření, která jsou prezentována ve výše uvedené publikaci na obrázku 3. Jak již bylo uvedeno, vstupní data (koncentrace amoniaku vstupující a vystupující ze stáje, rychlost proudění vzduchu), nejsou vzájemně závislé veličiny, proto byl z těchto reálných hodnot vytvořen jednoduchý model simulující stabilní situaci. Postup tvorby modelu je detailně popsán v textu publikace, který reprezentují data v obrázku 4. Tento model byl ještě rozšířen o tři uměle upravené časové intervaly, které simulují maximální možné chybové zatížení při vyhodnocování parametru E (emisní tok NH_3 v $mg \cdot s^{-1}$) v důsledku nemožnosti měřit všechny vstupní proměnné současně (vypnutá ventilace, skokové nárůsty zapříčiněné provozními podmínkami). Upravená data modelu jsou v grafu na obrázku 5. Svislé zelené čáry označují intervaly, ve kterých byla modelová data uměle upravena.

Referenční hodnota E byla stanovena pro testování vyvinuté metodiky hodnocení. Metodické testy byly rozděleny na dvě části. V každé z nich byla použita navržená metodika vyhodnocení E. V první části byl zkoumán vliv časového okna na průměrné emise NH_3 za 24 h. Délka časového okna byla postupně volena ze série 15 min, 20 min, 30 min, 45 min, 60 min, 90 min, 2 h, 3 h, 4 h, 6 h, 8 h a 12 h. Rozdíly mezi jednotlivými vypočtenými hodnotami byly testovány pomocí analýzy ANOVA a Tukeyho HSD testu. Rozdíly mezi vypočtenými emisemi daných délek časových oken pro oba modely byly testovány také Studentovým t-testem. Hladina významnosti každého statistického testu byla stanovena 0,05.

Výsledná data byla podrobně zpracována do grafů, které reprezentují obrázky 6, 7, 8 a 9. K těmto obrázkům jsou detailně popsány výsledky testovaných metodik.

Frekvenci odběru vzorků nelze neúměrně zvýšit, protože je také omezena měřicím zařízením. Pokud se jedno zařízení používá ke zjišťování koncentrace NH_3 na několika místech odběru vzorků současně, je nutné zajistit dostatečnou dobu na vyčištění pro výměnu vzduchu v měřicí komoře. Pro taková zařízení se zdá být dostatečná četnost odběru vzorků 10 za hodinu. To znamená, že hodnota koncentrace NH_3 je zaznamenána přibližně každých 6 minut.

Z výsledků je patrné, že navrhovaný algoritmus vykazoval minimální rozdíly pro časová okna od 15 minut do 3 h, ale odchylka měření se znatelně zvyšuje pro delší časová okna. Nicméně s klesající délkou časového okna se průměruje méně hodnot a výsledný průměr je citlivější na případná výrazně vychýlená nebo dokonce chybná měření. V případě 15minutového časového okna se jedná maximálně o tři hodnoty, což je relativně malý počet. V případě 30minutového okna se zprůměruje pět hodnot a jedna výrazně vychýlená hodnota ovlivní průměr méně.

Proto na základě provedených testů metodiky na modelových datech a uměle modifikovaných modelových datech se jako ideální řešení jeví časové okno dlouhé 30 minut. Při reálných měření existují krátkodobé změny ve stáji, které se projevují zvýšenými nebo sníženými emisemi NH_3 během dne. Při použití delších časových oken by nebylo možné monitorovat odchylky od běžného průběhu emisních křivek a bylo by prakticky nemožné reagovat na situace, které se z různých důvodů objevují ve stáji, ať už z důvodů provozních podmínek, nebo pouze technologicky souvisejících s metodikou měření.

3.3 Porovnání tří přístupů pro stanovení emisí amoniaku v intenzivních chovech prasat na výkrm s ohledem na IPPC: Případová studie pro Českou republiku

Třetí publikace **Kunes, R**. a kol. (2022b). *Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic, Atmosphere,* porovnává tři zvolené přístupy pro odhad emisí NH_3 z intenzivních chovů prasat na výkrm v ČR. Jako vstupní data sloužily výstupy v rámci řešení funkčního úkolu pro MZe ČR, které proběhlo v letech 2017 a 2018 a jsou uvedeny v Dolan a kol., (2017) a Dolan a kol., (2018.) Pro účely odborné publikace byla zvolena experimentální měření ze čtyřech chovů, jejichž technologie ustájení odpovídala BAT 30.a0 (garantované snížení emisí NH_3 o 25 %) a v jednom chovu s technologií ustájení odpovídající BAT 30.a8, který negarantuje žádné snížení produkovaných emisí NH_3. Monitorované chovy používali krmná aditiva garantující snížení emisní NH_3 v rozmezí 22–48 %.

První přístup pro odhad roční měrné emise NH_3 z intenzivního chovu prasat na výkrm byla zvolena metoda *výpočtu měřením koncentrace NH_3 a výkonu ventilace* (Závěry o BAT, 2017). Odběr vzorků probíhal v souladu s metodou s tím rozdílem, že místo šesti vzorkovacích dní, byl zvolen pouze jeden vzorkovací den a monitoring byl prováděn

ve finální fázi výkrmu (při hmotnosti prasat mezi 90–102 kg). Tento přístup byl zvolen zejména z toho důvodu, že autoři studie chtěli ověřit vliv počtu vzorkovacích dní a jejich provedení během roku na odhad výsledných emisí NH_3. Pro výpočet roční měrné emise NH_3 byla využita metodika Kříž a kol. (2021), která je uvedena v kapitole 3.2 a příslušné publikaci.

Druhý přístup pro odhad roční měrné emise NH_3 z intenzivního chovu prasat na výkrm byla zvolena metoda *výpočtu měřením koncentrace NH_3 a výkonu ventilace* podle (Závěry o BAT, 2017). Odběr vzorků probíhal v souladu s touto metodou, kdy je nezbytné uskutečnit 6 měření. Polovina měření se provede v první půlce chovného cyklu a zbytek ve druhé půlce chovného cyklu. Dny odebírání vzorků v druhé polovině chovného cyklu se rovnoměrně rozloží po celý rok (stejný počet měření za sezónu). Z vědeckovýzkumných účelů bylo provedeno během roku monitorování čtyř chovných cyklů, v každém 5 měření tj. 20 dní, ve kterých bylo měření realizováno. Pro výpočet roční měrné emise NH_3 byla využita metodika Kříž a kol. (2021), která je uvedena v kapitole 3.2 dizertační práce a příslušné publikaci.

Třetím zvoleným přístupem byla metoda *odhadu NH_3 s použitím emisních faktorů* (Závěry o BAT, 2017). Emisní faktory byly v ČR stanoveny v minulosti na základě experimentálních měření, která reprezentují místní podmínky chovu. Provozovatel chovu hospodářských zvířat musí vždy při výpočtu započíst i dílčí emisní faktory pro sklady exkrementů a dílčí emise pro zapravení exkrementů do půdy i v případě, že tyto suroviny předává jiné oprávněné osobě. Pro účely publikace byly porovnávány pouze dílčí emisní faktory reprezentující emise NH_3 z ustájení. Emisní faktor pro ustájení v chovu prasat na výkrm je 3,2 kg NH_3 · zvíře^{-1} · rok^{-1} (MŽP ČR, 2012). Dle platné legislativy lze stanovený emisní faktor snížit o procentuálně vyjádřenou účinnost technologie, která je využita pro snížení emisí NH_3. Tato technologie musí být schválena v legislativě jako BAT a pro výpočet lze využít jen jednu technologii s nejvyšší účinností.

Z přehledové tabulky 7 výše zmíněné publikace, která vychází z provedených experimentálních měření uvedených v tabulkách 5 a 6 lze předpokládat, že emisní faktory jsou stanoveny pro podmínky hospodaření, které nepoužívají žádnou BAT. Z uvedených dat je patrné, že naměřené hodnoty se ve většině případů nepřibližují ke stanovenému emisnímu faktoru. Z teoretického hlediska je možné, že kombinace BAT pro ustájení a krmení vede k výraznějšímu snížení emisí, než mohou zemědělci zohlednit v konečných výpočtech, kde mohou uplatnit pouze procentuální snížení pro účinnější BAT.

Z uvedených dat rovněž vyplývá, že objektivnější je použít metodiku uvedenou v Závěrech o BAT podle směrnice 2010/75/EU (Závěry o BAT, 2017), kdy je podmínkou, aby se v chovu provedlo během roku šest měření, z nichž tři se provádí v první polovině a tři v druhé polovině výkrmu. Například jedno měření provedené na začátku výkrmu v chladnějších podmínkách, se může značně lišit od měření provedeného za letního počasí. Tyto rozdíly mohou být výraznější s délkou výkrmu. Je zajímavé, že i chovné sekce v jedné výkrmové hale s obdobnými mikroklimatickými podmínkami a stejnou technologií chovu a výkrmu vykazují rozdíly v emisích NH_3. Na obrázku 1 a 2 tuto odchylku reprezentují čísla měření A4/A14, A5/A15, A7/A17 a A10/A20. Při podrobném zkoumání bylo zjištěno, že vnitřní podmínky byly na hranici mírného tepelného stresu při měřeních A4/A14, A5/A15 a A7/A17. To mohlo způsobit, že každá skupina prasat reagovala na tento jev odlišně. Studie také ukázala, že klimatické a mikroklimatické podmínky mohou ovlivnit emise NH_3, zejména hodnoty ze sledování celých výkrmových cyklů. Vzhledem k tomu, že sledování prvního chovného cyklu bylo prováděno od února do června a druhého chovného cyklu v období od června do listopadu, lze tyto hodnoty považovat za průkazné a přisuzovat ročnímu období nezanedbatelný vliv na produkci emisí NH_3.

Z výše uvedených údajů lze potvrdit robustnost metodiky *odhadu NH_3 s použitím emisních faktorů* uvedené v závěrech o BAT podle směrnice 2010/75/EU (Závěry o BAT, 2017). Zejména z pohledu potřeby provádění odběrů vzorků v různých fází výkrmu a během celého roku.

Při použití metody *odhad s použitím emisních faktorů*, nastává otázka, jestli emisní faktory, které byly stanoveny před několika lety, stále odpovídají reálné produkci emisí NH_3. Odvětví živočišné produkce je stále inovováno (šlechtění, výživa, konverze krmiv, technologie ustájení, využívaní BAT), ale emisní faktory zůstávají stejné. Jelikož je tato metoda pro odhad emisí NH_3 v ČR nejrozšířenější z důvodu její časové nenáročnosti a nízké obtížnosti výpočtu, bylo by vhodná její revize pro získávání reprezentativních dat.

3.4 Technologie regulace mikroklimatu v energeticky udržitelné živočišné výrobě

Čtvrtá publikace Havelka, Z.; **Kunes, R**., a kol. (2022). ***Technology of Microclimate Regulation in Organic and Energy-Sustainable Livestock Production***, *Agriculture,* se věnuje problematice stanovení vhodného systému pro řízení mikroklimatických podmínek v intenzivní živočišné produkci s ohledem na energetickou udržitelnost. Cílem publikace

bylo na základě teoretických poznatků vytvořit podklady pro tvorbu algoritmu pro řízení technologií ovlivňující mikroklimatické podmínky.

Z literární rešerše byly stanoveny základní parametry ovlivňující mikroklimatické podmínky a jejich doporučené hodnoty (rozmezí hodnot), které splňují welfare zvířat. Mezi uvedené parametry byla zvolena teplota, relativní vlhkost, rychlost proudění vzduchu, výměna vzduchu, intenzita osvětlení a koncentrace CO_2, NH_3, H_2S, CO a prachových částic. Vzhledem k tomu, že se jednotlivé parametry navzájem ovlivňují a nejde na ně pohlížet jako na jednotlivé součásti, byly také definovány společné faktory, jako je například teplotně-vlhkostní index (THI), index výměny vzduchu, index tepelné zátěže (HLI), kumulovaná tepelná zátěž (AHL). V publikaci je na obrázku 1 uvedeno schéma, kde jsou znázorněny jednotlivé parametry ovlivňující mikroklimatické podmínky a možnosti jejich mechanické regulace pomocí stájových technologií.

Požadavky na algoritmus řídicího systému byly upozornění na překročení určených limitů, které snižují kvalitu welfare chovaných zvířat a automatizovaný odhad nákladů na úpravu mikroklimatických podmínek. Na základě výstupů algoritmu by řídicí jednotka automaticky regulovala vnitřního mikroklima zejména s ohledem na ekonomické náklady v bilanci s kvalitou vnitřního prostředí.

Vyvinutý algoritmus byl testován na vybraných datech z 24 h monitorování v chovu výkrmových býků plemene Angus. Hodnoty z vybraného monitorovacího období jsou uvedeny v příloze publikace na straně 24. Uvedená studie definuje nejoptimálnější algoritmy pro řízení mikroklimatických podmínek s ohledem na přijatelný komfort zvířat. Algoritmus se dá upravovat s ohledem na individuální potřeby chovaných zvířat.

Výsledky uvedené v publikaci splnily požadavky pro teoretické stanovení faktorů ovlivňující mikroklimatické podmínky a návrhu obecného algoritmu pro jejich řízení. Pro zpřesnění navrhnutého algoritmu je třeba provést experimentální měření v jednotlivých chovech a adaptovat na jednotlivé chovné technologie.

4 Naplnění cílů práce a diskutovaní stanovených hypotéz

V této kapitole budou diskutovány stanovené výzkumné hypotézy a dosažení cílů vymezených pro potřeby této dizertační práce. Z důvodů finanční a časové náročnosti při monitorování emisí se ne vždy podařilo získat dostatečné množství dat, proto, aby dané hypotézy šlo posoudit na základě statistických metod, proto je většina hypotéz postavena na praktickém ověření.

Výzkumné hypotézy

H1: Metodika pro stanovení emisí NH$_3$ *výpočet měřením koncentrace NH$_3$ a výkonu ventilace* **uvedená v Závěrech o BAT (2017) je dostačující z pohledu matematického vyhodnocení dat z 24hodinového měření.**

Uvedená metodika velmi detailně popisuje postup při plánování monitorovacích dní, provádění monitoringu v praxi (rozmístění odběrových sond) a jeho doby (24 hodin). V metodice se ale dále neuvádí, jakým matematickým postupem vyhodnocovat naměřená data. Proto mezi vědeckou komunitou v publikovaných odborných článcích lze objevit různé přístupy. Mezi nejběžnějšími přístupy je vyhodnocení průměrováním všech naměřených hodnot (24hodinový průměr). Dalším přístupem je průměr hodnot z vybraných časových intervalů (den a noc, hodinové intervaly). Výše uvedené rozdílné přístupy mohou mít za následek odchylku v interpretaci výsledků.

V odborné publikaci Kriz, P., **Kunes, R**., a kol. (2021). *Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming, Agriculture,* se autor práce podílel na stanovení vhodného postupu při zpracování naměřených dat. Na reálných datech z experimentálních měření, do kterých byly implementovány hodnoty reprezentující nestandartní situace, byly pomocí statistických analýz testovány zvolené časové intervaly (15 min, 20 min, 30 min, 45 min, 1 h, 1,5 h, 2 h, 3 h, 4 h, 6 h, 8 h a 12 h). Z výsledných hodnot uvedených na obrázku 6 výše zmíněné publikace je patrné, že navrhovaný algoritmus nevykazoval znatelné rozdíly pro časová okna od 15 minut do 3 h, ale odchylka se znatelně zvyšuje se zvětšením doby časového okna. Nicméně s klesající délkou časového okna se průměruje méně hodnot a výsledný průměr je citlivější na případná výrazně vychýlená nebo dokonce chybná měření. V případě 15 min časového okna se jedná maximálně o tři hodnoty, což je relativně malý počet; v případě 30 min okna se zprůměruje pět hodnot a jedna výrazně vychýlená hodnota ovlivní průměr méně.

Z výsledků provedených testů metodiky na modelových datech a uměle modifikovaných modelových dat se jako ideální řešení jeví časové okno 30 minut. Na základě uvedených informací lze tvrdit, že diskutovaná metodika *výpočet měřením koncentrace NH₃ a výkonu ventilace* uvedená v Závěrech o BAT (2017) není dostatečně definována z pohledu matematického vyhodnocení naměřených dat.

H2: Stanovené emisní faktory pro NH₃ z ustájení intenzivního výkrmu prasat uvedené v MŽP ČR (2012) odpovídají současným provozním podmínkám.

Pro experimentální měření byl vybrán chov, kde byly během roku monitorovány čtyři chovné cykly. Bylo provedeno 20 monitorovacích dní (tabulka 3.6 v kapitole 3.5.1) a dle metodiky uvedené v Závěry o BAT (2017) stanovené výrobní měrné emise NH₃. Výsledná měrná výrobní emise $0{,}91 \pm 0{,}02$ kg NH₃ $\cdot$ ks^{-1} $\cdot$ rok^{-1} a $1{,}03 \pm 0{,}03$ kg NH₃ $\cdot$ ks^{-1} $\cdot$ rok^{-1} byla hluboko pod emisním faktorem 3,6 kg NH₃ $\cdot$ ks^{-1} $\cdot$ rok^{-1}, včetně jednotlivých dílčích výrobních emisí.

Tento rozdíl může být způsobený tím, že v chovu jsou používané BAT v podobě ustájení a fázové výživy s krmnými aditivy. Jejich účinnost nelze přesně definovat, protože chovatel používá krmná aditiva garantující snížení emisí NH₃ o 23–48 %. Dle platné legislativy může chovatel pro stanovení emisí snížit emisní faktor o procentuálně vyjádřenou účinnost technologie, která je využita pro snížení emisí NH₃ (pouze o jednu s nejvyšší účinností). V uvedeném případě to může být o 46 %, tedy výsledný emisní faktor by chovatel mohl vykázat 1,66 kg NH₃ $\cdot$ ks^{-1} $\cdot$ rok^{-1}. I v tomto případě se emisní faktor jeví jako nadhodnocený.

Na základě prováděných monitorovacích měření lze předpokládat, že emisní faktory už nemusí odpovídat reálným podmínkám. To lze předpokládat i z ostatních měření uvedených v kapitole (3.5.1). Na tuto skutečnost také autor a jeho řešitelský tým upozorňoval v článku **Kunes, R**. a kol. (2022a) *Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic*. *Atmosphere,* publikovaném 10. 12. 2022.

Dne 28. 11. 2022 vyšla aktualizovaná verze vydání Věstníku, kde je metodický pokyn, v kterém jsou uvedeny aktualizované emisní faktory pro drůbež, prasata a skot (MŽP, 2022). Ve většině případů byl emisní faktor výrazně snížen.

Na základě výše zmíněných informací autor uvádí, že stanovené emisní faktory pro NH$_3$ z ustájení intenzivního výkrmu prasat uvedené v MŽP ČR (2012) neodpovídají současným provozním podmínkám a hypotéza se nepotvrdila. Uvedené tvrzení lze podložit také reakcí MŽP ČR na tuto problematiku a vydáním aktualizované verze Věstníku s revizí u emisních faktorů.

Autor by v této problematice také navrhoval revizi z pohledu snižování vykazovaných emisí pomocí procentuálního snížení nejúčinnějšího BAT. Autor předpokládá, že při využití více vhodných BAT může dojít k větší efektivitě při snižování reálné produkce emisí a tento faktor by měl být také reflektován v legislativě. Tím by došlo k podpoře chovatelů, kteří již efektivně využívají BAT. Dále by bylo vhodné po určitém období provádět přezkum emisních faktorů, aby se zpřesnil celkový odhad emisí NH$_3$. Jedním z důvodů je také to, že metoda *odhadu emisí pomocí emisních faktorů* je v ČR nejrozšířenější. Tyto změny by byly nejenom v zájmu chovatelů, ale i orgánů státní správy, při vykazování celkové produkce emisní NH$_3$.

H3: Dodržení stanoveného počtu a rozložení monitorovacích dnů uvedené v metodice Závěry o BAT (2017) je klíčové při odhadu emisí NH$_3$ z intenzivního výkrmu prasat metodou *výpočet měřením koncentrace NH$_3$ a výkonu ventilace*

Podle dokumentu Závěry o BAT (2017) je pro stanovení emisí NH$_3$ metodou *výpočet měřením koncentrace NH$_3$ a výkonu ventilace* nutné pro kategorii prasata na výkrm provést nejméně šest měření rozložených do jednoho roku, tak aby tři měření byla prováděna v prvním chovném cyklu a tři měření v druhém chovném cyklu. Jelikož jsou měření finančně a časově náročné, tak se v uvedené hypotéze pracuje s variantou, jestli je možné zkrátit počet monitorovacích dnů. Tímto předpokladem se zabývaly výstupy z publikace **Kunes, R**. a kol. (2022b). *Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic, Atmosphere*, kde se porovnávaly různé způsoby odhadu emisí NH$_3$.

První přístup pro odhad roční měrné emise NH$_3$ z intenzivního chovu prasat na výkrm byl zvolen metodou *výpočtu měřením koncentrace NH$_3$ a výkonu ventilace* (Závěry o BAT, 2017). Odběr vzorků probíhal v souladu s metodou s tím rozdílem, že místo šesti vzorkovacích dní, byl zvolen pouze jeden vzorkovací den a monitoring byl prováděn ve finální fázi výkrmu bez ohledu na roční období (při hmotnosti prasat mezi 90–102 kg). Druhý přístup pro odhad roční měrné emise NH$_3$ z intenzivního chovu prasat na výkrm

byla zvolena metoda *výpočtu měřením koncentrace NH₃ a výkonu ventilace* podle Závěry o BAT (2017) a odběr vzorků probíhal v souladu s touto metodou. Z vědecko-výzkumných účelů bylo provedeno během roku monitorování čtyř chovných cyklů, v každém 5 měření tj. 20 dní, ve kterých bylo měření realizováno. Pro výpočet roční měrné emise NH₃ byla využita metodika Kříž a kol. (2021), která je uvedena v kapitole 3.2 a příslušné publikaci.

Na základě provedených experimentálních měření v intenzivních chovech prasat na výkrm lze tvrdit, že stanovený počet monitorovacích dnů a jejich rozložení do jednotlivých fází výkrmu je důležité pro získání reprezentativních dat. S růstem prasat na výkrm se mění jejich hmotnost, spotřeba krmiva a denní aktivita což jsou parametry, které mají vliv na produkci emisí NH₃. Z naměřených hodnot uvedených ve výše zmíněné publikaci v tabulce 6 podle metodiky Závěry o BAT (2017) je patrné, že pro získání reprezentativních dat, které vypovídají o produkci emisí NH₃, je nutné zvolit minimálně 6 měření rozložených rovnoměrně mezi výkrmové fáze. Je to dáno zejména z důvodu, že výsledné emise NH₃ se značně liší v počáteční fázi výkrmu (po odstavu) a ve finální fázi výkrmu před porážkou. V porovnání s výsledky uvedenými v tabulce 7 je zřejmé, že omezit počet dnů či je směrovat jen do finální fáze výkrmu může výrazně zkreslit produkci emisí během celého výkrmu.

Z tabulky 6 a 7 je zřejmé, že ověření hypotézy na základě standardních statistických metod se jeví jako problematické, protože bylo s ohledem na finanční náročnost každého měření stanoveno pouze 20 hodnot, ze kterých je závěr vyvozován. Nicméně výsledky těchto měření vynesené do tabulky indikují, že dodržení stanoveného počtu a rozložení monitorovacích dnů uvedené v metodice Závěry o BAT (2017) je klíčové při odhadu emisí NH₃ z intenzivního výkrmu prasat a stanovená hypotéza je potvrzena.

Cíle pro praxi

C1: Ověřit, zda vybrané intenzivní chovy prasat splňují limity BREF pro emise NH₃ pro jednotlivé kategorie chovaných zvířat

V roce 2017 a 2018 bylo realizováno celkem 77 měření emisí NH₃ v intenzivních chovech prasat (30 v kategorii prasnice plemenné a prasnice k připuštění/březí, 33 v kategorii prasata na výkrm a 14 v kategorii selata v dochovu). Cílem experimentálních měření bylo zhodnotit co nejvíce českých chovů (chovných technologií) z pohledu plnění limitů BREF pro emise NH₃. Jelikož jsou měření časově náročná, nebylo provedeno šest měření

pro jednotlivý chov a kategorii, ale jednotlivá měření, která reprezentovala daný chov. Na základě naměřených hodnot byly vypočteny výrobní měrné emise NH_3, které byly následně porovnány s limitem uvedeným v BREF. Ze souhrnných tabulek číslo 3.2 až 3.7 uvedených v dizertační práci vyplývá, že emisní limity NH_3 uvedené v BREF pro intenzivní chovy prasat nebyly v žádném z posuzovaných chovů překročeny.

C2: Stanovení vhodné metodiky pro měření emisí NH_3 a CH_4 z přirozeně větraných hal pro ustájení skotu

Stanovení metodiky pro odhad emisí měřením koncentrace NH_3 a CH_4 z přirozeně větraných hal pro ustájení skotu je problematické právě z důvodu absence jasně definovaného proudění vzduchu do a ze stáje. Provedením rešerše dostupných přístupů lze tvrdit, že existuje shoda ve stanovení proudění množství vzduchu do a ze stáje pomocí bilanční metody CO_2, i když se jednotlivé přístupy částečně liší zvolenými proměnnými pro výpočet produkce metabolického CO_2. Z pohledu stanovení počtu a rozmístění odběrových sond v prostoru stáje se přístupy značně odlišují. Na tento faktor lze pohlížet jako největší nedostatek při sestavování vhodné metodiky, protože vhodný počet a rozmístění odběrových sond je klíčový pro získání reprezentativních dat. Tato problematika je také limitována měřicí technikou a technologií chovné haly.

Po navržení obecné metodiky provedl autor s výzkumným týmem pilotní monitorování emisí NH_3 a CH_4 v intenzivních chovech skotu s cílem stanovit doporučení pro zlepšení navržené metodiky. Ke stanovení klíčových parametrů jako je umístění odběrových sond a stanovení místa pro monitoring vnějších klimatických podmínek bylo využito dostupných technologií. Před prováděným monitoringem bylo provedena detailní analýza převládajícího proudění vzduchu na základě větrných růžic dostupných na Českém hydrometeorologickém ústavu a lokálních měření v okolí farmy pomocí meteorologických stanic. Na základě lokálních měření byly vytvořeny CFD modely proudění vzduchu ve stáji, pro přesnější stanovení míst pro umístění odběrových sond.

Výsledky z monitorování jsou uvedeny v publikaci Kuneš (2022c) a Kuneš (2004). Výsledné hodnoty emisí NH_3 a CH_4 z intenzivních chovů skotu jsou v rozmezí, které je uváděno pro produkci skotu chovaného v podmínkách střední Evropy. Na základě výše zmíněných informací lze tvrdit, že autor splnil zadání pro stanovení vhodné metodiky pro měření emisí NH_3 a CH_4 z přirozeně větraných hal pro ustájení skotu. Chtěl by ale zmínit, že navržená metodika má zatím obecný charakter a v budoucnu by se chtěl věnovat jejímu adresnějšímu využití pro odlišné technologie intenzivních chovů skotu v ČR.

Závěr

Aktuálně probíhá v Evropské komisi diskuze jednotlivých států k připravované revizi směrnice IED. V případě, že by byl návrh schválen v podobě tak, jak je uveden v literární rešerši, znamenalo by to veliký zásah do sektoru živočišné produkce nejenom v ČR. Z uvedených dat vyplývá, že snížení prahové hodnoty na 150 DJ a rozšíření o kategorii chovu skotu by znamenalo enormní nárůst počtů podniků, které by musely splňovat nařízení IPPC až o 700 %. Uvedené legislativní opatření v environmentální oblasti ve spojení s aktuální situací rostoucích ekonomických nákladů, hrozících onemocnění (prasečí mor, ptačí chřipka) by mohla přímo ekonomicky ohrozit chovatele, protože už dnes jsou určitá odvětví živočišné produkce na hraně finanční rentability. Další snižování tuzemské produkce v oblasti živočišné výroby by mělo negativní vliv na potravinovou soběstačnost. V roce 2021 byla podle MZe ČR (2023) míra soběstačnosti v produkci vepřového masa alarmujících 51,3 %. Dalšími faktory by bylo narušení řetězce cirkularity zemědělství v podobě ztráty kvalitního organického hnojiva pro rostlinou produkci, jenž by muselo nahradit syntetické hnojivo.

Z výsledků provedených vědecko-výzkumných aktivit a výstupů dizertační práce by autor chtěl uvést možná doporučení pro praxi v oblasti stanovení emisí z intenzivních chovů hospodářských zvířat:

- sjednotit metodiky pro odběr a vyhodnocení emisí pomocí *výpočtu měřením koncentrace NH_3 a výkonu ventilace* podle dokumentu Závěry o BAT (2017), z důvodu lepšího porovnání monitorovaných dat,
- revize emisních faktorů po určitém časovém období pro metodu *odhadu emisí s použitím emisních faktorů* podle dokumentu Závěry o BAT (2017) z důvodu zpřesnění výsledků,
- revizi legislativy při podávání hlášení do integrovaného registru znečišťovatelů při *odhadu emisí s použitím emisních faktorů* podle dokumentu Závěry o BAT (2017) umožněním procentuálního snížení celkových emisí nejenom o nejúčinnější BAT, ale částečně i o další využívané BAT.

Seznam použité literatury

Bartoš P., Celjak I., Dolan A., Havelka Z., Kuneš R. (2017). Emise amoniaku a zápachu z intenzivních chovů drůbeže a prasat ve vztahu k Závěrům o BAT Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-q338565---Lxx4M2Xe/zprava-o-mereni-emisi-amoniaku-z-chovu?_linka=a273127

Dolan A., Dolan A., Havelka Z., Celjak I., Kuneš R., Kříž P., Šístková M., Bartoš P. (2018). Zpráva o měření emisí amoniaku z chovů prasat. Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-q338461---9ITI7ODd/zprava-o-mereni-emisi-amoniaku-z-chovu?_linka=a273057

Dolan A., Dolan A., Celjak I., Havelka Z., Kuneš R., Šístková M., Bartoš P. (2017). Zpráva o měření emisí amoniaku z chovů prasat. Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-q338565---Lxx4M2Xe/zprava-o-mereni-emisi-amoniaku-z-chovu?_linka=a273127

Havelka, Z., Olšan, P., Kuneš, R., Stehlík, R., Bumbálek, R., Zoubek, T., Filip, M., Šístková, M., a Bartoš, P. (2021). Referenční dokument o nejlepších dostupných technologiích pro intenzivní chovy drůbeže a prasat. České Budějovice: Jihočeská univerzita v Českých Budějovicích, Zemědělská fakulta. ISBN: 978-80-7394-889-4. Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-q338509----1TIonqE/nejlepsi-dostupne-techniky-v?_linka=a273089

Havelka Z., Kuneš R., Bumbálek R., Zoubek T., Olšan P., Celjak I., Šístková M., Filip M., Dolan A., Bartoš P. (2019). Zpráva o současném stavu v oblasti využití BAT technologií v chovech drůbeže a prasat spadajících do režimu IPPC za rok 2019. Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-q338447---hLJJxugv/zprava-o-soucasnem-stavu-v-oblasti?_linka=a273047

Havelka, Z.; Kunes, R.; Kononets, Y.; Stokes, J.E.; Smutny, L.; Olsan, P.; Kresan, J.; Stehlik, R.; Bartos, P.; Xiao, M.; Kriz, P.; Findura, P.; Roztocil, D. (2022). Technology of Microclimate Regulation in Organic and Energy-Sustainable Livestock Production. *Agriculture*, *12*, 1563.

Kriz, P., Kunes, R. a kol. (2021). Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming. *Agriculture*, 11, 1073.

Kunes, R., Havelka, Z. a kol. (2022a). A Review: Comparison of Approaches to the Approval Process and Methodology for Estimation of Ammonia Emissions from Livestock Farms under IPPC. *Atmosphere*, 13, 2006.

Kunes, R., Havelka, Z. a kol. (2022b). Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic. *Atmosphere*, 13, 2084.

Kuneš, R., a kol. (2023). Monitoring emisí amoniaku a metanu z intenzivních chovů skotu pomocí experimentálních měření a matematických modelů proudění plynů. Funkční úkol pro Ministerstvo zemědělství. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/mze/potraviny/bezpecnost-potravin/environmentalni-techniky-a-technologie/ippc/zpravy-studie-k-vyrobnim-cinnostem/tps-kategorie-6-6/monitoring-emisi-amoniaku-a-metanu-z-intenzivnich-chovu-skotu-pomoci-experimentalnich-mereni-a-matematickych-modelu-proudeni-plynu

Kuneš, R., a kol. (2022c). Rešerše dopadů významných změn v souvislosti s revizí směrnice Evropského parlamentu a Rady 2010/75/EU o průmyslových emisích. [online] [cit. 10. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/mze/potraviny/bezpecnost-potravin/environmentalni-techniky-a-technologie/ippc/zpravy-studie-k-vyrobnim-cinnostem/tps-kategorie-6-6/reserse-dopadu-vyznamnych-zmen-v

MPO ČR (2022). Aktuality IPPC. [online] [cit. 20. 7. 2022]. Dostupné z: https://www.mpo.cz/cz/prumysl/ippc-integrovana-prevence-a-omezovani-znecisteni/aktuality/navrh-revize-smernice-o-prumyslovych-emisich-ied-a-narizeni-o-evropskem-registru-uniku-a-prenosu-znecistujicich-latek-e-prtr--267067/

MZe ČR (2023). Panorama potravinářského průmyslu 2021. [online] [cit. 20. 1. 2024]. Dostupné z: https://eagri.cz/public/portal/-a37942---cVnwaWyv/publikace-panorama-potravinarskeho-prumyslu-2021?_linka=a554102

MŽP ČR (2012). Metodický pokyn odboru ochrany ovzduší ke klasifikaci chovů hospodářských zvířat podle zákona č. 201/2012 Sb., o ochraně ovzduší, pro výpočet emisí znečišťujících látek z těchto stacionárních zdrojů a k seznamu technologií snižujících emise NH_3 z těchto stacionárních zdrojů. [online] [cit. 25. 1. 2022]. Dostupné z: https://eagri.cz/public/web/file/564268/Publikace_Emise_amoniaku_a_zapachu.pdf

MŽP ČR (2022) Metodický pokyn odboru ochrany ovzduší ke klasifikaci chovů hospodářských zvířat podle zákona č. 201/2012 Sb., o ochraně ovzduší, pro výpočet emisí znečišťujících látek z těchto stacionárních zdrojů a k seznamu technologií snižujících emise NH_3 z těchto stacionárních zdrojů. [online] [cit. 25. 12. 2022]. Dostupné z: https://www.mzp.cz/C1257458002F0DC7/cz/zemedelstvi/$FILE/OOO-MP_chovy_28_11_2022_Final-20221202.pdf

Závěry o BAT (2017). BAT Conclusions under Directive 2010/75/EU of the European Parliament and of the Council, for the Intensive Rearing of Poultry or Pigs. Strana 39. [online] [cit. 5. 12. 2022]. Dostupné z: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D0302&from=EN

ŽIVOTOPIS

Ing. Radim Kuneš

Narozen: 3. 1. 1991 ve Strakonicích
Adresa: Profesora Skupy 907, 386 01 Strakonice
Telefon: + 420 606 263 674
e-mail: kunesr@jcu.cz

Vzdělání:

Od 2015 — Jihočeská univerzita v Č. Budějovicích, Zemědělská fakulta, doktorské studium
Obor: **Obecná zootechnika** (Disertační práce: Monitoring mikroklimatických podmínek v intenzivních chovech hospodářských zvířat s technologií nucené a přirozené ventilace)

2013 - 2015 — Jihočeská univerzita v Č. Budějovicích, Zemědělská fakulta, Katedra agroekosystémů
Obor: **Agroekologie – Ing.** (Diplomová práce: Využití nízko-potenciálního odpadního tepla produkovaného JE Temelín pro zemědělskou produkci)

2010 - 2013 — Jihočeská univerzita v Č. Budějovicích, Zemědělská fakulta, Katedra zemědělské, dopravní a manipulační techniky
Obor: **Dopravní a manipulační technika – Bc.** (Bakalářská práce: Využití odpadního tepla z bioplynových stanic)

2006 - 2010 — Střední průmyslová škola ve Strakonicích.
Obor: **Počítačová grafika a CNC technika** (Závěrečná práce: Porovnání drsnosti vzorků oceli)

Pracovní zkušenosti:

Od 2017 — Jihočeská univerzita v Č. Budějovicích, Zemědělská fakulta
od 04/2017 - odborný asistent

Charakteristika odborné činnosti:

Stanovení emisí zátěžových plynů a zápachu z intenzivních chovů hospodářských zvířat a vývoj a ověřování nových nejlepších dostupných technik (BAT).
Vývoj a testování technologií pro živočišnou produkci.

Jazykové znalosti:

anglický jazyk - úroveň B2

Počítačové a jiné schopnosti:

➢ MS office (Word, Excel, Power Point, Access),
➢ 3D tisk, 3D grafika (autoCAD, Solid Works),
➢ Programování - CNC obráběcích strojů, platformy Arduino/Raspberry Pi.

Publikační činnost:

Impaktované publikace

Bojana Petrović, Roman Bumbálek, Tomáš Zoubek, **Radim Kuneš**, Luboš Smutný, Petr Bartoš (2024). Application of precision agriculture technologies in Central Europe-review, Journal of Agriculture and Food Research, 101048, ISSN 2666-1543. https://doi.org/10.1016/j.jafr.2024.101048 (Q1; I.F. 3,8)

Sramhauser, K., Naprstkova, N., Hren, I., Spalek, F., Vlach, T., **Kunes, R.** , Tupy, O. (2023). Wear Analysis of Indexable Inserts after Machining of Austenitic Steel 1.4404. Manufacturing Technology, 23, https://doi.org/917-26.10.21062/mft.2023.094 (Q3; I.F. 0,91)

Řezáč, I., Kernerová, N., Komosný, M., **Kuneš, R**., Havrdová, N., Poborská, A., Zábranský, L. Possibilities for dealing with large litters of piglets. *Journal of Central European Agriculture* **2023**, *24*(1), 61-71. https://doi.org/10.5513/JCEA01/24.1.3867 (Q4; I.F. 0,7)

Kunes, R.; Havelka, Z.; Olsan, P.; Dolan, A.; Stehlik, R.; Petrovic, B.; Smutny, L.; Bartos, P.; Xiao, M.; Kriz, P.; Cerny, P. Comparison of the Three Approaches for Determining Ammonia Emissions in the Intensive Breeding of Fattening Pigs with Respect to the Integrated Pollution Prevention and Control: Case Study for the Czech Republic. *Atmosphere* **2022**, *13*, 2084. https://doi.org/10.3390/atmos13122084 (Q2; I.F. 3,110)

Kunes, R.; Havelka, Z.; Olsan, P.; Smutny, L.; Filip, M.; Zoubek, T.; Bumbalek, R.; Petrovic, B.; Stehlik, R.; Bartos, P. A Review: Comparison of Approaches to the Approval Process and Methodology for Estimation of Ammonia Emissions from Livestock Farms under IPPC. *Atmosphere* **2022**, *13*, 2006. https://doi.org/10.3390/atmos13122006 (Q2; I.F. 3,110)

Havelka, Z.; **Kunes, R**.; Kononets, Y.; Stokes, J.E.; Smutny, L.; Olsan, P.; Kresan, J.; Stehlik, R.; Bartos, P.; Xiao, M.; Kriz, P.; Findura, P.; Roztocil, D. Technology of Microclimate Regulation in Organic and Energy-Sustainable Livestock Production. *Agriculture* **2022**, *12*, 1563. https://doi.org/10.3390/agriculture12101563 (Q1; I.F. 3,408)

Kříž, P.; Hořcičková, M.; Bumbálek, R.; Bartoš, P.; Smutný, L.; Stehlík, R.; Zoubek, T.; Černý, P.; Vochozka, V.; **Kuneš, R**. Application of the Machine Vision Technology and Infrared Thermography to the Detection of Hoof Diseases in Dairy Cows: A Review. Appl. Sci. **2021**, 11, 11045. https://doi.org/10.3390/app112211045 (Q1; I.F. 2,679)

Kriz, Pavel, **Radim Kunes**, Lubos Smutny, Pavel Cerny, Zbynek Havelka, Pavel Olsan, Maohua Xiao, Radim Stehlik, Antonin Dolan, and Petr Bartos. Methodology for Measurement of Ammonia Emissions from Intensive Pig Farming. *Agriculture* **2021**, no. 11: 1073. https://doi.org/10.3390/agriculture11111073 (Q1; I.F. 2,925)

Kunes, Radim; Bartos, Petr; Iwasaka, Gustavo K.; Lang, Ales; Hankovec, Tomas; Smutny, Lubos; Cerny, Pavel; Poborska, Anna; Smetana, Pavel; Kriz, Pavel; Kernerova, Nadezda. In-Line Technologies for the Analysis of Important Milk Parameters during the Milking Process: A Review. *Agriculture* **2021**, no. 3: 239. https://doi.org/10.3390/agriculture11030239 (Q1; I.F. 2,925)

Recenzované publikace a konference

Bumbálek R., Zoubek T., Štindlová L., Havelka Z., Olšan P., Bartoš P., **Kuneš R.,** Stehlík R., Dolan A. Comparison of the Performance of Convolutional Neural Networks YOLOV5 ans YOLOV8 for Appliacation in Agricultural Technologies. TECHNOFORUM 2023 „New Trends in Machines and Technologies for Biosystems," pp.24, 2023. DOI: 10.15414/2023.9788055226033. ISBN: 978-80-552-2603-3.

Šístková, M., **Kuneš, R**., Hankovec, T., Lang, A., Bumbálek, R., Filip, M. (2019) Vliv typu míchacího krmného vozu na přesnost nakládky. *Náš chov*, 79(11), 82 - 86. ISSN 0027-8068

Kuneš, R., Bartoš, P., Celjak, I., Havelka, Z., Šístková, M. a Šoch, M. (2017). Technology for Intensive Poultry Production as a Source of Odour Emissions with Time-Varying Intensity. *Acta Technologica Agriculturae*, 4:91-95.

Kuneš, R., Bartoš, P., Celjak, I., Havelka, Z., Šístková, M. a Šoch, M. Dynamická olfaktometrie jako metoda pro vyhodnocení zátěže pachovými látkami vyprodukovanými v zemědělských chovech. In *VIDIECKÉ STAVBY V EURÓPSKYCH REGIÓOCH IV Architektúra – konštrukcie – technológie – bezpečnost – logistika*. Nitra : Slovenská poľnohospodárska univerzita v Nitre, Technická fakulta, 2017, s. 92-97. ISBN 978-80-552-1707-9.

Celjak I., **Kuneš R**., Havelka Z., Bartoš P., Šístková M., 2016: Problematika velkochovů drůbeže jako zdrojů pachových látek, Náš chov 10, roč. LXXVI, s. 80-82, ISSN 0027-8068.

Celjak I., **Kuneš R**., Šístková M., Havelka Z., 2016: Problematika emisí prachových látek z velkochovů drůbeže, Náš chov 12, roč. LXXVI, s. 42-43, ISSN 0027-8068.

Kuneš R., Bartoš P., 2015: Využití nízkopotenciálního odpadního tepla z JE Temelín pro zemědělskou produkci, Energetika 11, roč. LXIV, s. 586-591, ISSN 0375-8842.

Vědecko-výzkumná činnost:

NAZV QK1910174 - Zvyšování kvality mléka a jeho ekonomických ukazatelů využitím automatizovaného systému sledování vybraných parametrů v reálném čase (člen řešitelského týmu) 01/2019 - 12/2023

MPO TRIO FV30234 – Výzkum a vývoj procesu laserového potisku skleněných ploch malého až velkého formátu pro potřeby současného stavebnictví **(**člen řešitelského týmu**)** 01/2018 – 12/2020

MPO TRIO FV40316 - Vývoj komplexu modulárního systému robotizovaného dojení za současného hodnocení parametrů chovu aplikací metod umělé inteligence (člen řešitelského týmu) 01/2019 - 12/2022

MPO TRIO FW01010391 - Vývoj systému pro nepřetržitou identifikaci a etologické sledování zvířat v chovech skotu s využitím metod umělé inteligence (člen řešitelského týmu) 01/2020 - 12/2023

MPO TRIO FW03010447 - Vývoj inteligentního systému pro zvyšování užitkovosti dojeného skotu s využitím metod umělé inteligence (člen řešitelského týmu) 01/2020 - 12/2023

TAČR Delta 2 TM02000027 - Výzkum a vývoj chytrých technologií pro chovy skotu a prasat založených na pokročilých výpočetních postupech (člen řešitelského týmu) 05/2021 - 05/2023

TAČR Delta 2 TM04000023 - Výzkum a vývoj klíčových technologií pro chovy drůbeže – systém pro monitorování zvířat a prostředí a inteligentní management chovu (člen řešitelského týmu) 01/2023 - 12/2025

GAJU 094/2016/Z - Optimalizace produkčních funkcí a environmentálních dopadů zemědělství (člen řešitelského týmu) 01/2016 - 12/2017

MPO OPPIK CZ.01.1.02/0.0/0.0/17_102/0011495 – Inovace procesů při vývoji nových technických řešení pro chovy skotu (člen řešitelského týmu) 07/2018 – 12/2020

MPO INOVAČNÍ VOUCHER - VÝZVA III OP PIK CZ.01.1.02/0.0/0.0/17_205/0015174 - Posouzení a rozpracování systému „Chytrý skleník'' (člen řešitelského týmu) 11/2018 - 11/2019

MPO INOVAČNÍ VOUCHER - VÝZVA III OP PIK - Realizace měření parametrů stájového prostředí (člen řešitelského týmu) 2017 - 2018

MPO INOVAČNÍ VOUCHER - VÝZVA III OP PIK - Měření koncentrace amoniaku pomocí fotoakustického analyzátoru INNOVA a stanovení dalších souvisejících parametrů stájového prostředí (člen řešitelského týmu) 01/2018 - 10/2018

JIHOČESKÝ PODNIKATELSKÝ VOUCHER - Kvalitní analýza mléka (člen řešitelského týmu) 01/2020 - 31/01/2021

Patenty:
ISOTHERM s.r.o., JU. Povrchová úprava transparentního plošného konstrukčního dílu a způsob její výroby. Původci: Bartoš P., Fekete L., Filip M., Goldfinger M., Chlaň I., **Kuneš R**., Minařík J., Rajchard J., Smolík P., Zoubek T. Česká republika. Patent č. 308218, 2020.

AGROSOFT Tábor s.r.o., JU. Zařízení pro automatizaci dojíren s manuální obsluhou dojících strojů . Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Lang A., Olšan P., Smutný D., Smutný L., Stehlík R., Špalek F., Zoubek T.. Česká republika. Patent č. 309824, 2023.

Funkční vzorky:

Smolík, Pavel., Fekete, Ludvík., Goldfinger, Michal., Chlaň, Ivo., Minařík, Jiří., Zoubek, Tomáš., Filip, Martin., **Kuneš, Radim**., Bartoš, Petr., Havelka, Zbyněk. Potisk skleněného materiálu malého formátu. 2018. P.FV30234.

Smolík, Pavel., Fekete, Ludvík., Goldfinger, Michal., Chlaň, Ivo., Minařík, Jiří., Zoubek, Tomáš., Filip, Martin., **Kuneš, Radim**., Bartoš, Petr., Havelka, Zbyněk. Potisk skleněného materiálu středního formátu. 2019. P.FV30234.

Smolík, Pavel., Fekete, Ludvík., Goldfinger, Michal., Chlaň, Ivo., Minařík, Jiří., Zoubek, Tomáš., Filip, Martin., **Kuneš, Radim**., Bartoš, Petr., Havelka, Zbyněk. Potisk skleněného materiálu velkého formátu. 2020. P.FV30234.

Smolík, Pavel., Fekete, Ludvík., Goldfinger, Michal., Chlaň, Ivo., Minařík, Jiří., Zoubek, Tomáš., Filip, Martin., **Kuneš, Radim**., Bartoš, Petr., Havelka, Zbyněk. Transparentní plošný konstrukční díl. 2020. P.FV30234.

Užitné vzory:

Jihočeská univerzita v Českých Budějovicích. Multifunkční identifikační čip. Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Olšan P., Smutný L., Stehlík R., Špalek F. Zoubek T. Česká republika. Užitný vzor č. 37059, 2023

Jihočeská univerzita v Českých Budějovicích. Systém pro monitorování zdravotního stavu paznehtů dojnic. Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Olšan P., Smutný L., Stehlík R., Špalek F. Zoubek T. Česká republika. Užitný vzor č. 37058, 2023

Jihočeská univerzita v Českých Budějovicích. Systém pro monitorování zdravotního stavu vemene dojnic. Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Olšan P., Smutný L., Stehlík R., Špalek F. Zoubek T. Česká republika. Užitný vzor č. 37057, 2023

Jihočeská univerzita v Českých Budějovicích. Systém pro využití rozboru obrazového záznamu k řízení chovu skotu. Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Lang A., Olšan P., Smutný L., Smutný D., Stehlík R., Špalek F. Zoubek T. Česká republika. Užitný vzor č. 36612, 2022

Jihočeská univerzita v Českých Budějovicích. Zařízení pro automatizaci dojíren s manuální obsluhou dojících strojů. Původci: Bartoš P., Bumbálek R., Filip M., Havelka Z., **Kuneš R**., Lang A., Olšan P., Smutný L., Smutný D., Stehlík R., Špalek F., Zoubek T. Česká republika. Užitný vzor č. 36572. 15. 11. 2022.

Funkční úkoly:
Ministerstvo zemědělství – Dolan A., Celjak I., Havelka Z., **Kuneš R**., Šístková M., Bartoš P. (2017). Zpráva o měření emisí amoniaku z chovů prasat.

Ministerstvo zemědělství - Bartoš P., Celjak I., Dolan A., Havelka Z., **Kuneš R**. (2017). Emise amoniaku a zápachu z intenzivních chovů drůbeže a prasat ve vztahu k Závěrům o BAT.

Ministerstvo zemědělství – Dolan A., Havelka Z., Celjak I., **Kuneš R**., Kříž P., Šístková M., Bartoš P. (2018). Zpráva o měření emisí amoniaku z chovů prasat.

Ministerstvo zemědělství – Havelka Z., **Kuneš R**., Zoubek T., Bumbálek R., Filip M., Olšan P., Hankovec T., Lang A., Šístková M., Bartoš P. (2018). Rešerše o přístupu členských států ke stanovování emisních limitů ve vztahu k IPPC.

Ministerstvo zemědělství – Havelka Z., **Kuneš R**., Bumbálek R., Zoubek T., Olšan P., Celjak I., Šístková M., Filip M., Dolan A., Bartoš P. (2019). Zpráva o současném stavu v oblasti využití BAT technologií v chovech drůbeže a prasat spadajících do režimu IPPC za rok 2019.

Ministerstvo zemědělství – Havelka Z., Olšan P., **Kuneš R**., Stehlík R., Bumbálek R., Zoubek T., Filip M., Šístková M., a Bartoš P. (2020). Nejlepší dostupné techniky v intenzivních chovech drůbeže a prasat (BREF).

Ministerstvo zemědělství – **Kuneš R**., Havelka Z., Dolan A., Kříž P., Bartoš P. (2022). Rešerše dopadů významných změn v souvislosti s revizí směrnice Evropského parlamentu a Rady 2010/75/EU o průmyslových emisích.

Ministerstvo zemědělství – **Kuneš R**., Havelka Z., Dolan A., Kříž P., Blažek J., Bartoš P. (2023). Monitoring emisí amoniaku a metanu z intenzivních chovů skotu pomocí experimentálních měření a matematických modelů proudění plynů.

Uvedené funkční úkoly jsou uvedeny na webových stránkách Ministerstva zemědělství ČR - https://eagri.cz/public/portal/mze/potraviny/bezpecnost-potravin/environmentalni-techniky-a-technologie/ippc/zpravy-studie-k-vyrobnim-cinnostem/tps-kategorie-6-6

Knihy:

Havelka, Z., Olšan, P., **Kuneš, R**., Stehlík, R., Bumbálek, R., Zoubek, T., Filip, M., Šístková, M., a Bartoš, P. (2021). Referenční dokument o nejlepších dostupných technologiích pro intenzivní chovy drůbeže a prasat. České Budějovice: Jihočeská univerzita v Českých Budějovicích, Zemědělská fakulta. ISBN: 978-80-7394-889-4

Zahraniční stáž:
2018 – Industrial technical instructor training program TCNR - Taichung, Taiwan (2 měsíce)
2022 - Teaching mobility - Kazakh Agrotechnical University, Nur-Sultan, Kazachstán (7 dní)
2022 - Technical training - Riga Technical University, Riga, Lotyšsko (14 dní)
2023 - Teaching mobility - Agriculture and Forestry University, Bharaptur, Nepál (7 dní)
2023 - Technical training - Riga Technical University, Riga, Lotyšsko (14 dní)
2023 - Cooperation mobility - Nanjing Agricultural University, Nanjing, Čína (10 dní)

Další aktivity:

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