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ORIGINAL PAPER

THE EFFICIENCY OF NUISANCE RELIEF BY FILTERING FACEPIECE RESPIRATORS USED BY WORKERS EXPOSED TO AGRICULTURAL ODOURS

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Abstract

Background: The study aimed to evaluate the effectiveness of filtering facepiece respirators (FFRs) in reducing odour nuisances in agricultural work environment. Additionally, an assessment was conducted on the microbiological contamination of FFRs and the functionality of Time4Mask application in enhancing workplace safety. **Material and Methods**: Two types of FFRs were used for the study: with absorbing properties and reference ones. The research was carried out in 6 livestock rooms during a 1-week period in early spring (February–March 2021) on a farm in central Poland. The microclimate conditions (thermoanemometer), and particulate matter concentrations (laser photometer) were assessed. Additionally, the odour content in the studied rooms and the breathing zone of FFR users (gas chromatography with mass spectrometry) were evaluated. The number of microorganisms on the respirators was determined (cultivation method), followed by their identification (biochemical tests, taxonomic keys). Breakthrough curves were determined for both FFR types to assess absorption capabilities. **Results:** The average temperature in the livestock rooms was about 13°C, relative humidity – 53%, air flow velocity – 0.21 m/s, and particulate matter concentration – 0.216 mg/m^3. A significant variety of odorants was found in the environment and the breathing zone under the FFRs. Bacterial counts ranged between 2.4×10^1 and 2.6×10^2 CFU/cm^2, fungi between 3.2×10^0 and 5.4×10^1 CFU/cm^2, xerophilic fungi from 4.4×10^0 to 4.0×10^1 CFU/cm^2, mannitol-positive staphylococci between 1.6×10^1 and 1.0×10^2 CFU/cm^2, and haemolytic staphylococci from 2.2×10^1 to 4.5×10^1 CFU/cm^2, depending on the respirator type. Respirators were colonized by bacteria from the genera: *Bacillus*, *Staphylococcus*, actinobacteria *Streptomyces* sp., and fungi: *Candida*, *Absidia*, *Aspergillus*, *Mucor*, and *Penicillium*. Respirators with absorbing properties had over 8-times longer breakthrough time than reference ones. **Conclusions:** Respirators with activated carbon effectively improved work comfort when exposed to odours. Due to growth of microorganisms in the respirator materials, periodic replacement is necessary. It is crucial to provide workers with information about the safe-use time of respirators, considering environmental conditions. This is achievable using modern IT tools like Time4Mask application. Med Pr Work Health Saf. 2023;74(5):363–75.

Key words: agriculture, microbiological contamination, odour nuisance, filtering facepiece respirators, Time4Mask, worker safety and well-being

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INTRODUCTION

Agricultural work, due to its specific nature, i.e., complexity, seasonality, extended working day, fieldwork in the case of plant production and continuous cycle in the case of animal farming, exerts a significant impact on human health. Farm animals, plants, soil, and water serve as reservoirs for harmful factors in the referenced work environment. Allergy-inducing or toxic bacteria and fungi may develop in livestock housing premises. It is stimulated by the indoor temperature <30°C and air humidity >50%. Moreover, all substances of animal origin, such as feathers, fur, animal secretion and excretion, and substances of plant origin, such as litter and feed that farmers handle daily, may contain allergens and toxins [1,2]. The presence of such compounds in the indoor air contributes to the odour nuisance affecting both physical and mental well-being.

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Odour nuisance arises from sources emitting odorants that are detected by the olfactory receptors. The particles responsible for odours belong to 3 groups of chemical compounds, i.e., sulphur-, nitrogen- and carbon-based ones. Animal breeding and agriculture are the most onerous and common odorant emission sources. Odorants can have adverse effects on human health, primarily due to their negative impact on mental well-being. Long-term exposure to odour nuisance may trigger depression, weariness, respiration problems, nausea, and irritation of the mucous membranes of the eyes and throat. Considering the general population's rising awareness of the air quality's impact on health and well-being, the issue of odour nuisance in everyday life in the work environment has become the subject of intensive scientific research in Poland and globally in recent years [3,4]. Papers on deodorisation methods and tools used to determine the efficiency of systems that limit odour nuisance [5,6] deserve particular attention. The available literature applies to engineering solutions used in ventilation systems [7–9], but studies are also carried out on personal protective equipment intended for use in conditions where the maximum acceptable concentrations (MAC) of hazardous substances are not exceeded at the workstations [10]. This category of equipment includes filtering facepiece respirators (FFRs) with anti-odour properties. In addition to a system of polymer filtering materials with diversified efficiency, they also contain one or more layers of polymer-carbon non-woven which help limit the amounts of chemical substances penetrating the breathing zone. Considering the complex relationship between the concentration of chemical compounds, type of airborne odorants, microclimate conditions and individual smell sensitivity, developing an effective method to protect the human respiratory system will enhance occupational safety shall improve the occupational safety and comfort during activities related to livestock breeding. Evaluating the efficiency of odorant absorption by the filtering layers of FFRs, as well as their ability to block potentially pathogenic microorganisms, is crucial. Different methods are currently used for evaluating the odour impact and deodorisation efficiency. Brattoli et al. [11] described a broad literature review on the subject matter. She distinguished 2 basic categories of measurement methods:

– instrumental methods,
– olfactometric method.

Instrumental methods are based on the concentration measurement of each chemical compound using analytical chemistry methods (such as chromatography, colourimetry or sensor-based method) [12].

A human nose plays the role of a sensory item in olfactometric methods. This category includes, e.g., dynamic olfactometry, field tests and odour intensity scaling. The measurable values include odour concentration, hedonic quality and the frequency of the odour occurrence [13,14]. The olfactometric methods are suited to objectivise the evaluation of odour absorption by FFRs with anti-odour properties [15].

Regarding another safety aspect of livestock breeding, exposure to microorganisms originating from animals and their dwelling environment, it is significant to select the adequate protection class of the protective equipment and determine the time of its safe use. Numerous studies confirmed that during a long-term use of respiratory protective equipment (RPE), microorganisms counts might increase and biofilm can be created in the filtering non-woven, which constitutes a potential hazard source for the equipment user [16–18]. The problem becomes critical when equipment is used multiple times or for extended periods, a common practice among self-employed individuals. The presence of carbon compounds in the filtering and absorbing layer of FFRs used for reducing odorant olfactory nuisance is a significant factor contributing to an increase in the dynamics of microorganisms' proliferation. It was demonstrated that the survival rate of the tested microorganisms – *Escherichia coli, Candida albicans,* and *Aspergillus niger* – in the non-woven depended not only on their type but also on dust composition, especially on the carbon to nitrogen ratio [16,17]. The dust in which the carbon to nitrogen ratio amounted to 98.64 created better conditions for the tested microorganisms' development than the dust with a low carbon to nitrogen ratio of approx. 10. This confirms that carbon constitutes a good food source enabling microorganisms' growth on FFRs, which can reduce the safe use period of equipment whose filtering layers contain carbon absorbing unpleasant odours. It is a challenging task for an individual user to determine the equipment replacement time because the proliferation of microorganisms in the filtering material of the FFRs without specialized microbiological tests. For this reason, an application was developed to provide information on the safe usage duration of RPE against biological factors. An easy-to-use mobile device app was designed to select and monitor the safe use time of RPE against bioaerosol. This application was utilized in an enclosed animal breeding facility.

This article aimed to evaluate the possibility of improving the respiratory comfort and safety of employees exposed to odorants and biological factors by using FFRs with layers absorbing unpleasant odours and indicating

their safe use time with the Time4Mask mobile application (Central Institute for Labour Protection – National Research Institute, Poland) . The tests were conducted in laboratory conditions and during work on a meat and dairy cattle farm. The paper characterises a selected workstation for the microclimate conditions and contamination level with PM and chemical substances to determine the uniformity of these parameters in the tested farm complex.

MATERIAL AND METHODS

Filtering facepiece respirators (FFRs)

The tests were carried out with 2 types of FFRs (MB Filter, Poland) with similar protection parameters and design. The essential protection and functional parameters of the FFRs are summarised in Table 1.

The FFRs marked as A (type MB 10 VC) had anti-odour properties, contrary to the FFRs labelled as B (type MB 20 V). The FFRs were designed as domes with an area of 184±7 cm^2. They featured 1 exhalation valve, a nose clip and 2 headbands. The FFRs' facepiece was made of a single layer of spun-bonded non-woven, a single layer of high-performance melt-blown non-woven, another layer of spun-bonded non-woven and calandered needled non-woven. The A FFR had an extra layer of polymer-carbon non-woven with a surface weight of 214 g/m^2 and 1.85 mm thick.

The employees who wore the FFRs, used the Time4Mask application to track the use time. The application's primary role was to monitor the respirators' use time. Thanks to the notification feature, the application informed users about the need to replace the respirator 15 min before the end of its safe use time. The application includes a tab that shows equipment usage history. The Time4Mask application is available free in Apple App Store and Google Play. Guided by the application's recommendations, users wore the FFRS while performing typical cow shed activities, such as distributing feed, milking, and cleaning manure.

Workplace characteristics

The tests related to the efficiency evaluation of FFRs were carried out in a meat and dairy cattle farm during a 1-week period in early spring. The FFRs were tested in animal breeding rooms characterized by intensive odour emissions, including the milking room, washing room, 4 cow sheds, and a barn. Odour generation stemmed from fermentation processes (decomposition of feed, urine, and faeces) as well as secretions from the animals' respiratory and digestive systems, and their skin. The farm was located in the village of Budy, in the Łódzkie region in Poland. The total cubature of the examined rooms amounted to 1670 m^3.

In the farm rooms, temperature, relative humidity, and air flow rate were measured at 6 different locations using the VelociCalc® Multi-Function Velocity Meter 9545 (TSI, USA) thermos anemometer. Airborne particulate matter (PM) concentration was gauged using the DustTrak™ DRX Aerosol Monitor 8533 (TSI, USA) laser photometer. The particle counter's probe was placed at a height of 1.5 m. The measurements were carried out in a continuous mode with a 5 s sampling interval for each sampling locations. The results were then averaged.

Quantitative and qualitative analysis of chemical contamination

The quantitative analysis of the air assessed concentrations of oxygen, carbon dioxide, and ammonia both in the environment and within the breathing zone of the FFRs under test. Oxygen and carbon dioxide concentrations were measured using the Servoflex Mini MP (Servomex, UK) analyser. The probe was placed at a height of 1.5 m. The measurements were carried out in a continuous mode with a 10 s sampling interval for 30 min. Ammonia concentration was determined using a colourimetric method with the Hach D2800 spectrophotometer (Hach Lange GmbH, Germany) with the wavelength range of 340–900 nm. Air samples were

Table 1. Essential protective and functional parameters of filtering facepiece respirators (FFRs)

FFR type	Declared protection class	Paraffin oil mist penetration* [%] (M±SD)	Resistance* [Pa] (M±SD)			CO_2 content in the exhaled air* [%] (M±SD)
			inhalation		exhalation	
			30 l/min	95 l/min	160 l/min	
MB 10 VC (A)	FFP1	1.56±0.07	27.60±1.42	91.94±3.98	122.72±2.99	0.77±0.05
MB 20 V (B)	FFP2	0.45±0.22	46.84±6.99	151.93±19.11	177.51±9.22	0.68±0.04

* Filtering facepiece respirators characteristics were measured acc. to EN 149:2001+A1:2009 [25].

collected with a laboratory pump into a 3 l volume glass bulb, filled with 0.5 l of distilled water, at a 10 l/min flow rate. Additionally, a qualitative analysis was carried out of air samples collected into Tedlar bags with an ESA1203 aspirator (Emio, Poland), using a gas chromatograph coupled with a mass spectrometer (Perkin Elmer, USA; Bruker Daltonics Inc., USA).

To identify volatile compounds in the air samples, we employed gas chromatography coupled with mass spectrometry (GC/MS). Analyses were performed using an Agilent 7890A gas chromatograph and mass detector MSD 5975C (Agilent, USA). Prior to GC analysis, air samples were gathered in 1 l Tedlar bags and subsequently extracted through the solid phase microextraction method. A StableFlex fibre coated with divinylbenzene/carboxene/polydimethylsiloxane 50/30 μm (1 cm length) was used for extraction. The needle with SPME fiber was introduced into the Tedlar bag through the septum valve and the fiber was slid out for direct exposure for 30 min (20°C). Before each sample extraction, the fiber was conditioned for 10 min at 260°C. After extraction fiber was removed and inserted into the GC injection port for desorption (5 min, 250°C, split ratio 1:1).

The fused silica capillary column (DB-1ms, 30 m × 25 mm × 25 μm [Agilent, USA]) was used to separate volatile compounds. The GC analysis employed a temperature ramp program: an initial 6 min at 30°C, a ramp at 5°C/min to 100°C, followed by a ramp at 20°C/min to 240°C, which was then held for 4 min. Helium was used as a carrier gas with a flow rate through the GC column of 1.1 ml/min. The transfer line temperature to the mass detector was set at 260°C, whereas the quadrupole and ion source temperatures were maintained at 150°C and 230°C, respectively. The mass spectrometer was operated with an ionization energy of 70 eV and in the mass/charge (m/z) range of 28–300 amu. Volatile compounds were identified by comparison of the mass spectra with those of the Wiley and NIST libraries as well as retention indices (RI) were calculated according to the formula proposed by van den Dool and Kratz [19] relative to a homologous series of n-alkanes from C5 to C23. Identifications were based on matches of mass spectra >75% and RI ±10. Data processing was conducted with Mass Hunter Workstation Software (Agilent, USA). Analyses of all samples were carried out in duplicate.

Quantitative and qualitative analysis of microbiological contamination of FFRs

Quantitative analysis

The FFRs were evaluated post-use by the study participants. Each tested FFRs was halved using sterile scissors. Both halves were used for the analysis and treated as the experiment's 2 repetitions. The FFRs were cut into smaller pieces and placed in bottles containing 90 ml of saline solution (0.85% NaCl). The samples were diluted from 10^{-2} to 10^{-4} in triplicates and plated onto media detailed in Table 2. Post-incubation, the colonies from each microorganism group on the plates were counted. These counts were then converted to represent colony-forming units per cm^2 of the FFR (CFU/cm^2).

Identification of microorganisms

Bacterial isolates from the TSA medium and yeast isolates from the MEA medium, both in pure culture, were macroscopically and microscopically characterized based on colony morphologies and selected biochemical tests, including Gram-staining, the catalase test, and the oxidase test. Subsequently, the isolates

Table 2. Media used for microbiological analysis

Medium	Supplier	Microorganism	Incubation temperature and time
Malt extract agar (MEA) medium with (0.1%) chloramphenicol	Merck KGaA, Germany	fungi	25±2°C, 7 days
DG18 LAB-AGAR™ (DG18 Agar)	BioCorp Sp. z o.o., Poland	*Xerophilic* fungi	25±2°C, 7 days
Tryptic soy agar (TSA) with (0.2%) nystatin	Merck KGaA, Germany	total bacteria	30±2°C, 48 h
Columbia blood agar with (0.2%) nystatin	Oxoid, Ltd, France	haemolytic *Staphylococci*	37±2°C, 24–48 h
Pochon's agar with (0.2%) nystatin	Labo-Mix, sp. j., Poland	*Actinomycetes*	25±2°C, 5–7 days
Chapman agar with (0.2%) nystatin	Merck KGaA, Germany	mannitol-positive *Staphylococci*	37±2°C, 24–48 h
King B medium with (0.2%) nystatin	Himedia Ltd, India	*Pseudomonas fluorescens*	30±2°C, 48 h
Violet red bile glucose agar (VRBG LAB-AGAR) with (0.2%) nystatin	BioCorp Sp. z o.o., Poland	*Enterobacteriaceae*	37±2°C, 24–48 h

were categorized into strains and identified using API tests (BioMérieux, France), namely API 50 CH, API STAPH, and API 20 NE. Yeast identification was performed using the API C AUX test (BioMérieux, France). Mould identification was based on macroscopic and microscopic observations after culturing on CYA (Czapek Yeast Extract Agar, USA) and YES (Yeast Extract with Supplements) media, guided by taxonomic keys [20,21].

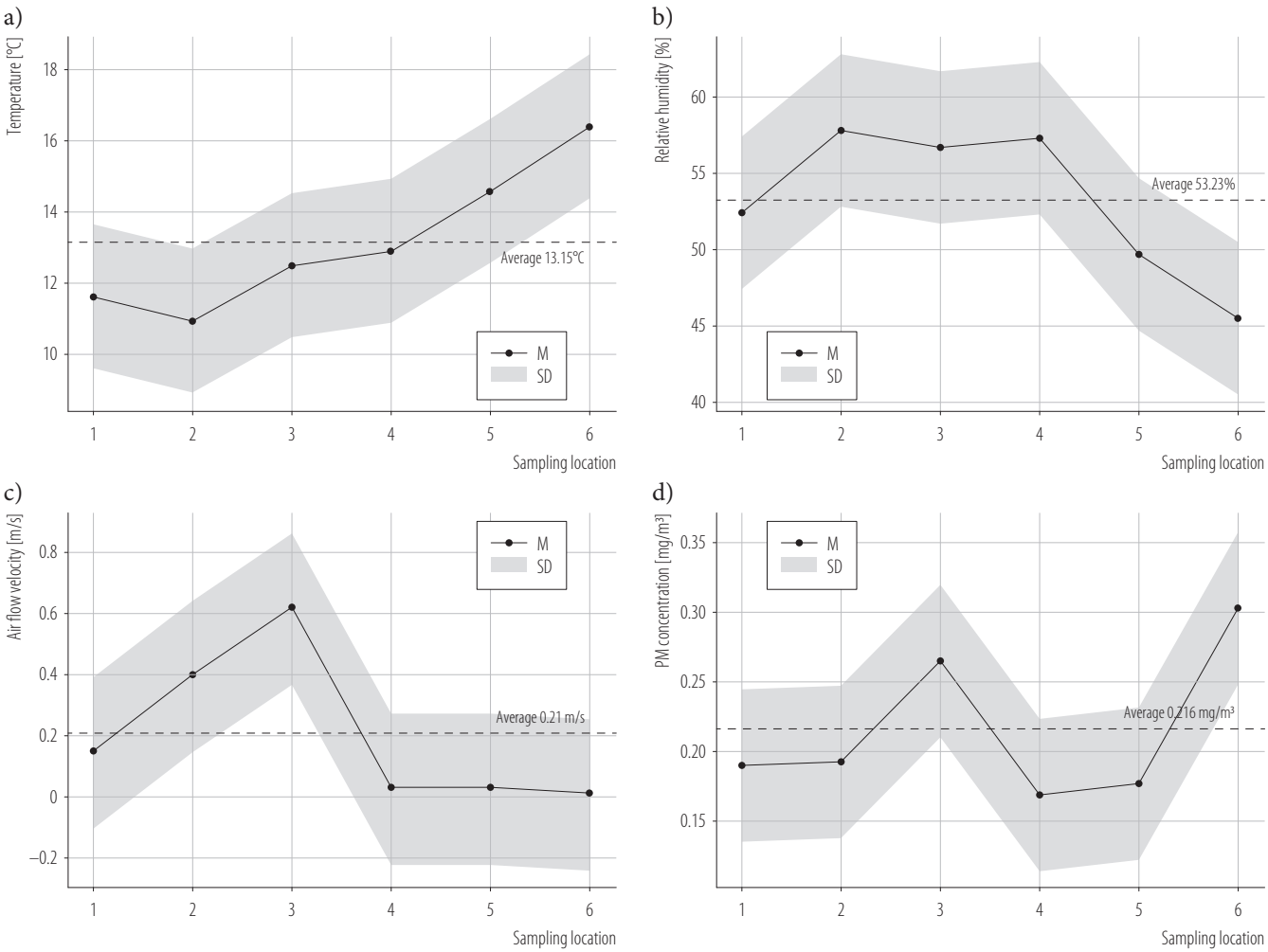
Adsorption characteristics of FFRs

Breakthrough experiments were carried out using cyclohexane vapours as a challenge substance at a test stand described in by Okrasa et al. [22]. During the test, dry compressed air was delivered to the system through a particulate filter equipped with a pressure reducer allowing an adjustment in the range of 0–8 bar. It was then divided into 2 lines, one that was used for temperature and relative humidity regulation; and the second one that was used to adjust the concentration of the test substance in the test chamber. Air at a given temperature and relative humidity was combined with the challenge vapours in a mixing chamber. This mixture was then channelled into the test chamber where the sample was securely placed in a pneumatic holder. We recorded the concentrations of the challenge vapour both upstream (C_{in}) and downstream (C_{out}) of the sample using the X-am 7000 Multi-Gas meters (Dräger, Germany). The temperature and relative humidity in the test chamber were monitored using the VelociCalc® Multi-Function Meter 9545 1 (TSI, USA).

RESULTS

Microclimate conditions and PM concentration

The results of microclimate test results are summarised in Figure 1 together with the results of comparative statistical analysis.



1–6 – different sampling locations at the testing site.

Figure 1. Variation a) temperature, b) relative humidity, c) air flow velocity and d) PM concentration at different sampling locations

The health and dynamics of microbial ecosystems are profoundly influenced by environmental conditions. Across different sampling locations, the average temperature was found to be approx. 13.2°C. Temperature is a critical factor for microbial activity, with most microorganisms having an optimal temperature range for growth. A deviation from this range can either slow down their metabolic activities or halt their growth altogether. The relative humidity, another essential factor for microbial survival, averaged around 53.2% across the locations. High humidity levels can provide the necessary moisture for microbial growth, while an environment that is too dry can inhibit microbial proliferation. Air flow, with an average velocity of 0.21 m/s, can influence the distribution of microorganisms, potentially aiding in their dispersion or settlement. Lastly, the PM concentration, an indicator of potential microbial transporters, averaged at 0.216 mg/m^3. The predominant fraction of PM had aerodynamic diameters <1 μm. The size of airborne particulates plays a pivotal role in determining their ability to penetrate the human respiratory system. This, in turn, affects their retention time and subsequent toxicity to the human body. Hence, airborne particles are typically classified by magnitude to determine their MAC values at workstations. In Europe, there are 2 primary benchmarks for occupational exposure limits:

- those established by the European Agency for Safety and Health at Work on behalf of the European Union,
- national limits set by individual member states.

Notably, these European limits can differ from those in non-European countries [23]. The PM concentrations at the workstations remain within acceptable limits as per legal regulations, eliminating the mandatory need for respiratory protection against particles. Consequently, the choice to use such protection becomes discretionary. When opting for protective gear, the primary consideration is the user's comfort during work. This flexibility allows for the selection of any FFR, even those with odour-neutralizing properties, irrespective of its designated protection class.

The results presented above could suggest varying microbial loads across different locations, especially if these particulates are organic in nature. Such environmental variations could lead to unique microbial communities at each sampling location, influencing conditions for fermentation processes occurring in the animal feed and faeces, which in turn could affect the quantitative composition of odorants released in these processes.

Qualitative and quantitative analysis of chemical contaminants

Table 3 displays the results of the assessment of oxygen, carbon dioxide, and ammonia concentrations in both the environment and the breathing zone for the reference FFRs (B) and the anti-odour FFR (A).

A qualitative analysis of other airborne compounds is presented in Figure 2.

For all detected substances, the concentration varied between the environment (background) and the breathing zone beneath the tested FFRs. However, there were no significant concentration differences between the reference FFR (B) and the one equipped with a carbon fibre non-woven layer (A). The qualitative analysis results show that oxygen deficiency did not occur in the environment. Carbon dioxide quantity did not deviate from the standard composition of atmospheric air. A drop in oxygen content <15% volume can impair human physiological and cognitive functions. If oxygen deficiency is caused by neutral gases, the effect can be negligible for a human being. A further decrease in oxygen content to ca. 10% oxygen volume in the air typically causes loss of consciousness, and when it drops to ca. 8% volume, death may occur due to suffocation. Oxygen concentration under the FFRs was lower than in the environment. The effect resulted from the presence – under the facepiece – of carbon dioxide exhaled by the subject

Table 3. Concentration of selected chemical compounds in ambient air and breathing zone

Compound	Concentration depending on sampling location (M±SD)		
	ambient	MB 10 VC (A)	MB 20 V (B)
Oxygen [% vol.]	21.55^a±0.04	18.85^b±0.55	18.35^b±0.64
Carbon dioxide [% vol.]	0.035^a±0.01	2.62^b±0.95	2.93^b±0.63
Ammonia [mg/m^3]	1.95^a±0.56	0.62^b±0.05	0.74^b±0.38

$^{a, b}$ Statistically significant differences are observed for the mean concentrations marked with different letters within same compound (ANOVA, α = 0.05; Tukey's HSD test, α = 0.05).

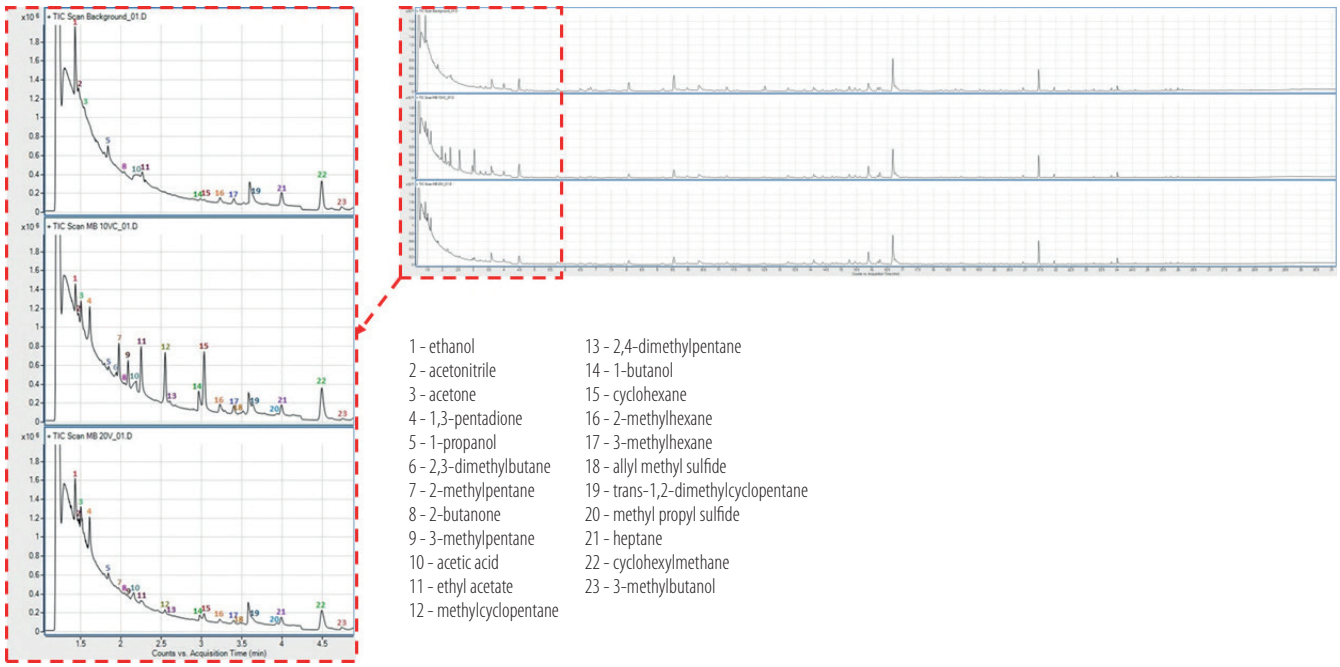


Figure 2. Qualitative comparison of air composition in the environment and in the breathing zone under the tested facepiece respirators

and its mixing with the inhaled air. In both respirators, the carbon dioxide concentration under the facepieces was elevated, surpassing the threshold established in laboratory tests as per EN 149:2001+A1:2009 [24]. It can have resulted from a short air sampling period from under the facepiece. Ammonia concentration in the environment did not exceed the MAC of the substance at the workstation (14 mg/m^3) [25]. Under the reference FFR and anti-odour FFR, it was respectively 62% and 68% lower than the values measured in the environment.

A qualitative analysis of the air indicated a rich variety of odorants within the breathing zone beneath the FFRs. The quantity of the identified compounds was higher for the anti-odour FFR than for the reference one, which could have been caused by higher breathing resistance impeding gas exchange with the environment. Most of the identified compounds originated from the employee's respiratory system. Only 1-butanol, ethanol and cyclohexane occurred under the facepiece and in the environment.

Quantitative and qualitative analysis of FFRs' microbiological contamination

On anti-odour FFRs, bacteria counts ranged 1.2×10^2–2.6×10^2 CFU/cm^2, fungi count –3.2×10^0–1.3×10^1 CFU/cm^2, xerophilic fungi count – 4.4×10^0–1.4×10^1 CFU/cm^2, mannitol positive staphylococci count – 1.6×10^1–1.0×10^2 CFU/cm^2, and haemolytic *Staphylococci* count – 2.2×10^1–4.5×10^1 CFU/cm^2 (Figure 3a). For FFRs lacking a carbon fibre layer bacteria count ranged 2.4×10^1–7.6×10^1 CFU/cm^2, fungi count – 4.0×10^0–5.4×10^1 CFU/cm^2, xerophilic fungi count – 2.4×10^1–4.0×10^1 CFU/cm^2, mannitol positive staphylococci count – 1.8×10^1–2.8×10^1 CFU/cm^2, and haemolytic staphylococci count – 6.3×10^0–2.8×10^1 CFU cm^{-2} (Figure 3b). No *Enterobacteriaceae*, *Actinomycetes* or *Pseudomonas fluorescens* were detected on any FFR type.

In this study, the microbiological contamination levels of FFRs were consistent with data from a combined heat and power station processing plant biomass [26]. Nevertheless, the microbial counts were lower than those reported by Jachowicz et al. [18] in an agricultural setting, where a half-mask worn by a combine harvester operator harboured up to 10^5 CFU/4 cm^2 of both bacteria and fungi after just an hour of use. Such discrepancies suggest that FFR contamination can vary based on the specific workplace and its microclimatic conditions, such as humidity and air temperature. Jachowicz et al. also highlighted a strong correlation between environmental dust levels and microbial counts on FFRs [18]. In this study, the average air temperature in livestock rooms was around 13°C, and PM concentrations adhered to legal guidelines, aligning with the findings of low FFR microbial contamination in this setting.

Bacteria belonging to three genera: *Bacillus* (*B. licheniformis, B. subtilis*), *Staphylococcus* (*S. caprae, S. lentus,*

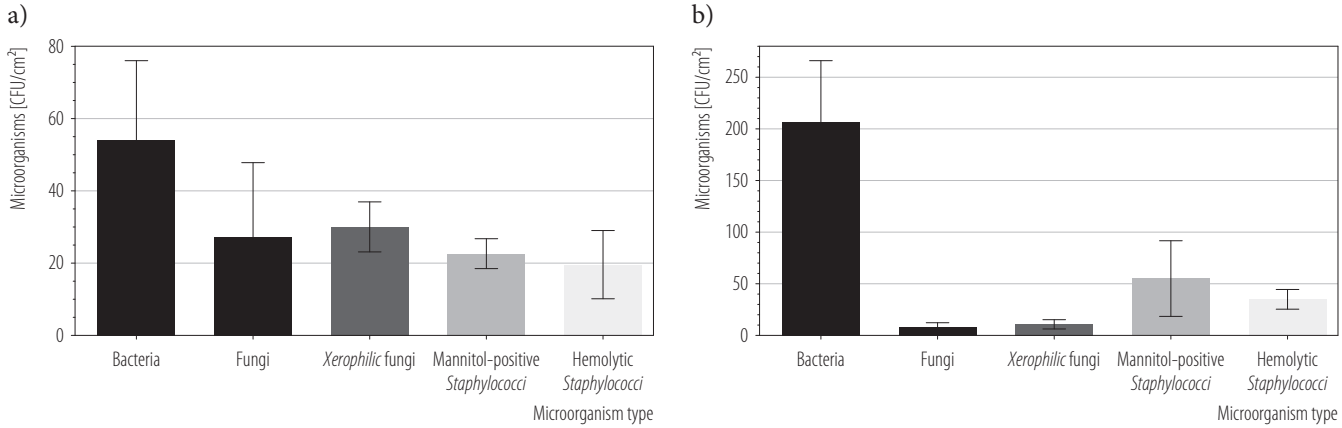


Figure 3. Microorganisms counts depending on filtering facepiece respirators (FFR) type: a) MB 10 VC (A), b) MB 20 V (B)

S. xylosus) and *Streptomyces* sp. were isolated from the tested filtering respirators (Table 4). Bacteria of the genus *Bacillus* are ubiquitous microorganisms in the environment, often isolated from the air or soil [27]. *Streptomyces* are actinomycetes characteristic of the soil environment [28]. In turn, the source of *Streptococcus* is most likely man – his skin and mucous membranes. These bacteria include species associated with the natural human microflora [29].

One species of yeast (*Candida guilliermondii*) and 9 species of mould (*Absidia corymbifera, Aspergillus candidus*, *A. flavus*, *A. fumigatus*, *A. niger*, *A. unguis*, *Mucor*

Table 4. Microorganisms detected in tested filtering facepiece respirators (FFRs)

Microorganism type	FFRs			
	frequency % (M±SD)		% (M±SD)	
	MB 10 VC (A)	MB 20 V (B)	MB 10 VC (A)	MB 20 V (B)
Bacteria				
Bacillus licheniformis	33.3±38.2	66.7±14.4	5.9±9.7	12.7±3.8
Bacillus subtilis	25.0±0.0	91.7±14.4	1.9±1.7	31.4±10.2
Staphylococcus caprae	16.7±14.4	16.7±28.9	0.2±0.2	1.2±2.1
Staphylococcus lentus	25.0±43.3	41.7±28.9	2.7±4.6	8.0±10.2
Staphylococcus xylosus	100.0±0.0	100.0±0.0	86.1±7.5	44.1±1.3
Streptomyces sp.	41.7±14.4	41.7±14.4	3.2±1.3	2.7±2.7
Fungi				
Candida guilliermondii	66.7±14.4	50.0±50.0	36.4±9.9	36.1±37.6
Absidia corymbifera	0.0±0.0	25.0±25.0	0.0±0.0	4.7±7.5
Aspergillus candidus	0.0±0.0	41.7±38.2	0.0±0.0	11.6±10.4
Aspergillus flavus	8.3±14.4	0.0±0.0	1.5±2.5	0.0±0.0
Aspergillus fumigatus	91.7±14.4	75.0±25.0	50.7±1.3	24.3±23.8
Aspergillus niger	0.0±0.0	8.3±14.4	0.0±0.0	0.2±0.4
Aspergillus unguis	8.3±14.4	8.3±14.4	1.0±1.8	1.0±1.7
Mucor racemosus	0.0±0.0	41.7±52.0	0.0±0.0	21.0±33.8
Penicillium expansum	8.3±14.4	0.0±0.0	2.1±3.6	0.0±0.0
Penicillium oxalicum	16.7±28.9	16.7±28.9	8.3±14.4	1.1±1.9

racemosus, *Penicillium expansum* and *P. oxalicum*) were identified on the FFRs (Table 4).

However, the most common species of mould found on the tested respirators were *A. fumigatus*. It belongs to the second hazard group and if it is present in the work environment, it can be harmful to the health of workers [30]. This suggests that FFRs of protection classes FFP1 and FFP2 might not offer adequate protection against *A. fumigatus*. To confirm this, it would be necessary to check the possibility of multiplication of this species on the filtering materials used in the FFRs' construction. Other mould species found on FFRs also have the potential to cause allergic reactions in humans. The genera *Aspergillus*, *Mucor* and *Penicillium* are among the most important moulds in the etiology of allergies [31].

Adsorption characteristics of FFRs

The efficiency of FFRs in reducing odour nuisance is considerably influenced by their design and the materials they incorporate. A FFR without a carbon fibre layer showed a significantly short breakout time (<3 min) indicating its limited capacity for odour neutralization. In contrast, the inclusion of a carbon layer extended the breakout time to approx. 25 min, highlighting the carbon's pivotal role in absorbing and neutralizing odours (Figure 4). These findings underscore the importance of the filter's breakout time, which directly correlates with its odour absorption capacity, in determining the equipment's effective duration at workstations [22].

When it comes to mitigating odour nuisance, the duration for which a respirator can efficiently absorb and neutralize odours becomes paramount. However, it's essential to approach these breakout times with caution. Laboratory conditions offer a controlled environment, often differing from real-world scenarios. Several factors in actual settings, such as temperature fluctuations, varying humidity levels, differing odorant concentrations, and the presence of volatile substance mixtures, can impact the odorant sorption capacity of the respirator's carbon material. These variations might result in discrepancies between lab-measured and actual breakout times. Moreover individual olfactory sensitivity of the user plays equally important role [15]. Given these considerations, it's imperative to comprehensively assess the work environment's conditions. Understanding these conditions and their potential effects on the respirator's protective action duration is crucial. Tools that facilitate the selection of appropriate RPE, tailored to specific hazards and conditions at workstations, are invaluable in this context.

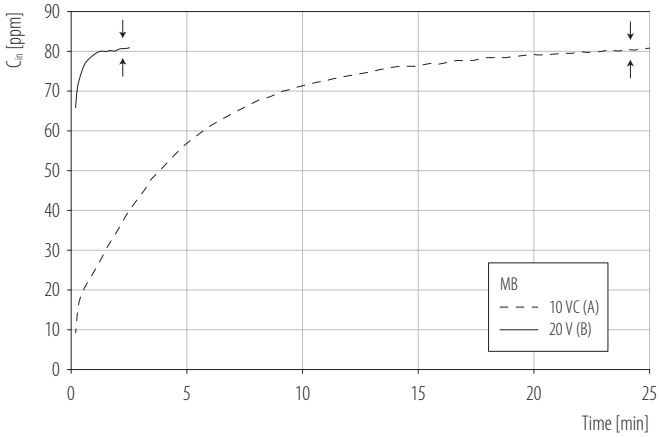


Figure 4. Avareged breakthrough curves for cyclohexane depending on filtering facepiece respirators (FFRs) type

In conclusion, while FFRs with anti-odour properties, especially those with a carbon layer, offer a promising solution to combat odour nuisances, a holistic approach considering both the equipment's specifications and the work environment's unique challenges ensures optimal protection and user comfort.

DISCUSSION

Numerous studies indicate widespread colonisation of FFRs by microorganisms, which can lead to a situation in which the filtering equipment becomes a secondary source of hazard for employees [32,33]. This situation arises when microorganisms, trapped in the filtering non-woven, re-enter the respiratory air stream. In practice, equipment items at workstations are replaced when the airflow resistance increase because of contaminants' deposition, making breathing difficult for the employee. It means that the employee individually decides about the equipment use period, having no knowledge about microorganisms' growth which occurs when FFRs are used. Such a practice can contribute to the employee's health issues.

As far as the environmental aspect is concerned, one shall remember that microorganisms which are harmful biological factors dominate in a bioaerosol form. The number, types, and survival rates of microorganisms are closely tied to the specific nature of the workplace. The essential elements characterising a particular work environment should include the location (indoor or outdoor), properties of the premises (ventilation, air-conditioning, type of construction materials, insolation intensity, hygienic conditions, frequency

of venting and cleaning) and microclimate parameters (temperature, relative humidity of the air, dustiness). The parameters will vary depending on the work environment. In an indoor environment, the highest accumulation of microorganisms can be expected in dark, damp places, with no ventilation, poor hygienic conditions and highly dusted. Temperatures of ca. 20°C and relative humidity of the air >50% foster a high microorganisms count.

The presence of building partitions with traces of flooding and fungi development often constitutes an additional source of microorganisms penetrating the air. It was confirmed by previous studies carried out by the authors in breeding rooms [10]. Employees' activities and behaviours also influence the prevalence and survival of microorganisms at workstations. Human factors stimulating the proliferation of microorganisms include, e.g., a high number of staff members, intensive employee traffic, inadequate personal hygiene, incorrectly used personal protective equipment, body secretions (sweat, saliva) and ill health (infections, carrier state) [34].

The analysis above reveals that the impact of environmental factors on microorganisms' survival in workstations and in FFRs is very complex and hard to define unequivocally. Hence, there was a crucial need to develop a user-friendly application for selecting and estimating the safe use duration of RPE based on data related to the work environment. Tests helped create a database of physicochemical and biological hazards occurring at the selected workstations related to animal breeding. Characteristics of physicochemical and biological hazards were prepared as the input data for the application helping select the equipment protecting the respiratory system from biological hazards.

The Time4Mask application provides a range of features for users. Firstly, it allows for the selection of the appropriate type and class of RPE equipment based on the data entered by the user. Additionally, the application offers guidelines on how to correctly put on, fit, and take off the chosen RPE. For safety purposes, it displays warning messages related to the proper and safe use of the equipment. Moreover, it has a monitoring system that keeps track of the duration of equipment use, notifying users when it's time to replace it with a new one. Lastly, users can also access a record of their equipment usage history within the application.

Algorithms were developed for selecting the appropriate type of RPE (such as FFR, a filter with a facepiece, or a full respirator). These algorithms facilitate decisions related to the safe use period of the RPE under specific work conditions. Such conditions include parameters like air temperature, air humidity, air flow rate, dust concentration, types and counts of microorganisms in the air, types of metabolites in the dust, cytotoxicity of dust, bacterial biodiversity, and fungal biodiversity. A comprehensive description of the underlying algorithm, including its development, can be found in the authors' separate [35].

After selecting the RPE's type and grade, the application user had the opportunity to learn the equipment characteristics, comments on limitations related to the referenced equipment use and marking/labelling that should be visible on the equipment's facepiece and the view of a sample equipment item. A timer was a unique feature of the application counting down the time left to replace the user's RPE. The time left to replace the equipment item was calculated based on the data entered in the form and on fifteen algorithms developed to calculate the safe use time of FFRs in the given work conditions. It was possible to stop counting down the time of the FFR's use and its resuming and collecting the information about the FFR usage date and time recorded by the timer until the end of its operation. The application was used on iOS and Android smartphones (Figure 5).

Based on empirical research from prior studies, specific parameters were incorporated into the application's form. These include the designation of the work environment as "agriculture," and the work setting being classified as "indoor." Additionally, the oxygen content was stipulated to be greater than or equal to 19%. The application also accounts for the absence of vapours and gases above the MAC. The environmental conditions are delineated with temperatures <20°C and a humidity range <50–75%. The dust concentration is established to be less than the MAC value, while the type of microorganisms is categorized under risk group 2. Furthermore, the concentration of these microorganisms is demarcated within a range of 1–4 times the limit value.

The application advocated for the utilization of a respirator belonging to the FFP1 or FFP2 classification. The stipulated maximum operational duration was delineated at 4 h, congruent with the insights derived from an extensive compendium of scholarly and developmental research conducted by the team. However, this is not in line with the common practice of using the equipment throughout the entire work shift. Considering

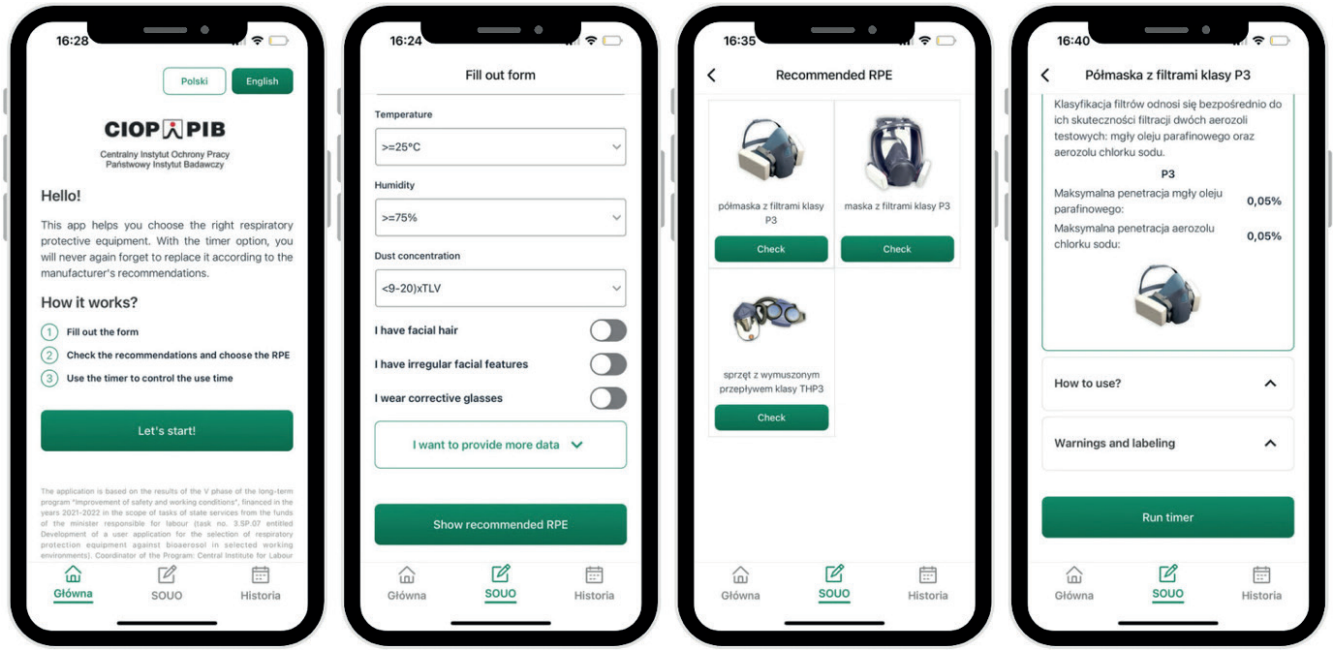


Figure 5. Time4Mask application – user interface

this, especially in environments rich in bioaerosols, it is recommended to reduce the duration of FFR usage to ensure optimal protection and efficacy.

CONCLUSIONS

The study evaluated the possibility of using instrumental methods employed for assessing odour impact to evaluate the anti-odour efficiency of FFRs at the workstation. Tests revealed a high diversity of microclimate conditions in different rooms of the farming complex, creating varied conditions for fermentation processes occurring in animal feed and excrements and potentially resulting in variable qualitative and quantitative composition of odorants emitted in these processes. The MAC of dust and airborne chemical compounds at the workstations was exceeded in none of the examined rooms. This suggests that the lowest protection class of anti-odour FFRs (FFP1) can effectively shield the respiratory system from odorants without causing undue breathing resistance. It is significant for the comfort of working in enclosed livestock rooms where the microclimate conditions are unfavourable for breathing.

For all identified substances, differences were demonstrated in the substances' concentration between the environment and the breathing zone under the tested FFRs, but no significant differences were revealed between the reference FFR and the one with a carbon fibre non-woven layer. Quantitative analysis highlighted a diverse range of odorants in the breathing zone when using FFRs. The amount of the identified compounds was higher for the FFR with polymer-carbon non-woven than for the reference FFR without such a layer. This proves that a standard FFR complying with EN 149 provides sufficient protection against inhaling onerous odorants. The protection class of FFRs is a vital aspect. The higher the class, the more efficiently it stops all harmful and onerous compounds present in livestock premises' atmosphere.

The possibility of reaching for an easy-to-use application for iOS and Android based devices is a significant aspect improving work safety and comfort in cattle breeding. The application informs about the need to replace the FFR with a new one. It results from the potential of quick proliferation of potentially pathogenic microorganisms in the FFRs during use in favourable microclimate.

Author contributions

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