REVIEWS

Review
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Next-Generation Protective Gloves: Current Trends in Technological Solutions and Application Prospects (Scientific Review)

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Abstract
Introduction. Protective gloves are widely used in medicine to provide biological protection for patients and medical staff. However, if gloves are used improperly, there is a risk of healthcare-associated infections (HAIs) for both staff and patients. A significant problem is the resulting growth in medical waste and its disposal. Therefore, developing new approaches to ensure maximum protection for staff and patients, and minimize the risk of infection, by creating protective gloves based on biodegradable polymer materials with an antimicrobial coating, is an urgent epidemiological and environmental objective.
This paper discusses modern technologies and emerging issues in the creation of new materials for protective gloves with antimicrobial properties. These materials can be made using guanidine derivatives, quaternary ammonium compounds (QACs), chlorinated phenols, essential oils, iodine compounds, silver salts, metal oxides and metal nanoparticles and oxides, vegetable oil extracts, aniline dyes. The introduction of biofillers such as starch and nanocellulose will help improve biodegradability. They will also help maintain the necessary physical and chemical characteristics. The problem of synthetic rubber waste disposal can be solved by the development of new composite materials with improved biodegradation characteristics. These materials are in the form of thermoplastic elastomers (TPE), polylactide (PLA) and polylactone (PLC).
Conclusion. A review of the scientific literature revealed a significant global interest in the creation of protective gloves with antimicrobial properties made from biodegradable materials. However, in addition to directly suppressing the growth of pathogenic microflora, their use may also pose a number of problems related to their impact on human health and the ecosystem. The successful implementation of this direction hinges on the continuation of scientific research on imparting the declared properties to gloves. This research should use effective, reliable and safe technologies, as well as the development of unified methods and protocols for assessing antimicrobial activity. Once these are in place, the research can be implemented widely in practice. The production of biodegradable protective gloves offers significant potential, as it will help to reduce the risk of infection spreading in healthcare organizations and contribute to environmental protection.

Keywords: *protective gloves, antimicrobial properties, functional materials, review, biodegradable components*

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Научный обзор
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Защитные перчатки нового поколения: актуальные тенденции технологических решений и перспективы применения (научный обзор)

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Аннотация
Введение. Защитные перчатки широко используют в медицине, они обеспечивают уровень биологической защиты пациентов и медицинского персонала. Вместе с тем существует риск развития инфекций, связанных с оказанием медицинской помощи, у сотрудников и пациентов при их ненадлежащем применении. Значимой проблемой является рост медицинских отходов и их утилизация. В этой связи разработка новых подходов к обеспечению максимальной защиты персонала и пациентов, минимизации риска инфицирования, благодаря созданию защитных перчаток на основе биоразлагаемых полимерных материалов с антимикробным покрытием, является актуальной эпидемиологической и экологической задачей.
В статье обсуждаются современные технологии и возникающие проблемы при получении новых материалов для создания защитных перчаток с антимикробными свойствами при использовании производных гуанидина, четвертичных аммониевых соединений, хлорированных фенолов, эфирных масел, соединений йода, солей серебра, частиц и наночастиц металлов и их оксидов, экстрактов растительных масел, анилиновых красителей. Введение таких бионаполнителей, как крахмал и наноцеллюлоза, будет способствовать улучшению биоразлагаемых свойств при сохранении необходимых физико-химических характеристик. Разработка новых композитных материалов с улучшенными характеристиками биодеградации в форме термопластичных эластомеров, полилактида и поликапролактона позволит решить проблему утилизации отходов из синтетического каучука.
Заключение. Анализ современной научной литературы определил высокий интерес в мире к созданию защитных перчаток с антимикробными свойствами на основе биоразлагаемых материалов. Однако их применение, кроме непосредственного подавления роста патогенной микрофлоры, может дополнительно нести ряд проблем, связанных с влиянием на здоровье человека и экосистему. Для успешной реализации данного направления важно продолжать научные исследования по приданию перчаткам заявленных свойств с использованием эффективных, надёжных и безопасных технологий с разработкой унифицированных методик и протоколов оценки антимикробной активности для последующего широкого внедрения в практику. Создание биоразлагаемых защитных перчаток имеет большие перспективы, поскольку будет способствовать снижению риска распространения инфекций в медицинских организациях и внесёт существенный вклад в охрану окружающей среды.

Ключевые слова: *защитные перчатки, антимикробные свойства, функциональные материалы, научный обзор, биоразлагаемые компоненты*

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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Introduction

The development of human potential and environmental protection are important objectives that define the domestic policy of the country and require the improvement of a set of measures to create conditions for strengthening the health of citizens, increasing life expectancy, reducing mortality and preventing infectious diseases, including healthcare-associated infections (HAIs), which have been identified as a biological threat by a Decree of the President of the Russian Federation[1].

Healthcare-associated infections (HAIs) are one of the key problems in global healthcare [1, 2]. Every day, 7 to 15 out of 100 patients acquire them in the hospital, and 1 in 10 cases result in death[2]. Issues of HAI prevention are traditionally of greatest significance in maternity hospitals [3, 4] and surgical departments [5]. Its relevance is increasing due to the complex demographic situation, as well as the rise in natural disasters, technological accidents and military conflicts. In the formation of HAI outbreaks, in addition to bacterial pathogens, whose resistance to antimicrobial drugs and biocides has become global, the significance of viruses is growing, including respiratory [6] and intestinal viruses [7]. The significance of the pathogens of blood-borne viral infections remains high [8]. The above suggests strengthening non-specific measures for HAI prevention, particularly improving personal protective equipment.

Modern issues in the use of protective gloves in medicine

Protective gloves are an essential attribute for every healthcare worker. As single-use personal protective equipment (PPE), they are designed to create a barrier between the patient and the healthcare worker while performing professional duties. Medical gloves, in addition to their basic protective properties (impermeability to microorganisms, airtightness, strength, safety for patient and staff health), should also have satisfactory consumer properties (comfort, high-quality packaging and labeling, ease of disposal, functionality)[3].

Depending on the degree of invasiveness of medical procedures and the risk of patient infection, protective gloves are divided into surgical and diagnostic/examination gloves. Surgical gloves must be sterile. Diagnostic/examination gloves can be sterile or non-sterile. Non-sterile gloves are used as standard precautions when working with patients infected and/or colonized with resistant strains of microorganisms and individuals infected with viruses that cause blood-borne infections (hepatitis B and C viruses, HIV, etc.).

Depending on the material, protective gloves are divided into latex, synthetic, and combined. Currently, most manufacturers of protective gloves use natural or synthetic latex as a base [9]. Natural latex (rubber) products are made from the sap of the *Hēvea brasiliēnswas* plant and are more comfortable [10–12]. In Russia, latex gloves are predominantly used. The material feels comfortable against the skin of the hands, which is ensured by its high elasticity and ability to absorb sweat. Despite its positive properties, natural latex often causes allergic reactions – up to 25% of nurses who use latex gloves report symptoms of dermatitis [13]. Due to this, most healthcare workers prefer gloves made of synthetic materials: vinyl, neoprene, polyurethane and nitrile. These materials are more durable and resistant to chemicals, while also being thinner, which provides high sensitivity for your fingertips. Nitrile gloves are used most often, followed by polyvinyl chloride and polychloroprene gloves [14, 15]. These gloves are pore-free, but they have less strength and elasticity than latex gloves; unlike latex gloves, their integrity is not restored after minor damage.

One type of high-strength gloves is chainmail gloves. They are still used in our country, but they only protect against cuts, not punctures. In this regard, the use of double gloves is being introduced in European medical institutions and some Russian hospitals. In this case, the risk of the surgeon's hands coming into contact with the patient's blood is reduced from 70% to 2%, and in 87% of cases where the outer glove is perforated, the inner glove remains intact [16]. When using two pairs of gloves worn one over the other, the skin is significantly better protected from blood exposure than when using a single pair of gloves. However, detecting damage while wearing double gloves is just as difficult as with single gloves.

In 1993, double gloves with puncture indication appeared on the European market, which have now become widespread. The concept behind them is quite simple, but effective. The lower glove is different in color from the upper one. When the outer glove is damaged, liquid (blood, rinse water, etc.) gets between the gloves, and a contrasting spot forms in the area of the puncture, signaling a perforation. Thus, up to 97% of punctures are detected when using indicator gloves, while only 8% are detected when using a single layer of gloves [16].

Depending on the type of material, gloves must meet different standards. The ASTM D6319-19 "Stan-

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[1] Decree of the President of the Russian Federation dated 11.03.2019 No. 97 "On the Fundamentals of the State Policy of the Russian Federation in the field of chemical and biological safety for the period up to 2025 and beyond".

[2] WHO launches first ever global report on infection prevention and control. 2022. URL: https://www.who.int/news/item/06-05-2022-who-launches-first-ever-global-report-on-infection-prevention-and-control (дата обращения: 06.05.2022).

[3] MP 3.5.1.0113-16 "The use of gloves for the prevention of infections related to the provision of medical care in medical organizations" (approved by the Head of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare, Chief State Sanitary Doctor of the Russian Federation A.Yu. Popova 02.09.2016).

dard Specification for Nitrile Examination Gloves for Medical Application" applies for nitrile examination gloves, the ASTM D3578-19 "Standard Specification for Rubber Examination Gloves" applies for natural rubber examination gloves and the ASTM D5250-19 "Standard Specification for Poly(vinyl chloride) Gloves for Medical Application" applies for polyvinyl chloride gloves. The EN 374-2:2014 standard "Protective gloves against dangerous chemicals and microorganisms — Part 2: Determination of resistance to penetration, IDT)" presents a method for assessing resistance to penetration by microorganisms, providing a minimum protection level of 2 (a glove that is air and water-tight, having passed a leak test, is considered resistant to microorganisms). The updated standard introduced new requirements for testing to assess virus protection (in addition to fungi and bacteria), and ISO 16604 for assessing protection against contact with blood and biological fluids for both the finished product and the material itself.

No type of glove is completely impermeable to microorganisms. Infection can penetrate gloves through micro-injuries and pores, the sizes of which are comparable to that of microorganisms. The liquid that gets inside gloves is most often localized in the thumb area and at the fingertips, and only in 30% of cases are these defects noticed by users. The average frequency of such unnoticed punctures during surgical procedures is 34.7–92% [17]. The frequency of surgical glove damage during orthopedic surgeries can reach 26.1%, with 82% of these damages going unnoticed [18]. There are differences in the frequency of glove punctures among doctors and nurses. Thus, out of 1457 doctor's gloves examined, 17.3% were damaged, and out of 325 nurse's gloves, 23.7% were damaged [19].

Despite modern technology significantly improving the mechanical properties of gloves, even wearing two gloves on one hand cannot eliminate the penetration of microorganisms in case of punctures or other mechanical damage. M.N. Bardorf et al. evaluated the impact of punctures on the protective properties of surgical gloves made from materials such as latex, nitrile, and neoprene [20]. It was found that the penetration of microorganisms depended on the rigidity or elasticity of the material. In the study by A.N. Goldman et al., over 50% (out of 33 pairs) of outer gloves used during orthopedic surgeries had macro- or micro-perforations due to contact with surgical rotating instruments (drills) [21]. A. Wolfensberger et al. noted that in 14% of cases, microorganisms were transferred from gloves to hands during their removal [22]. In this regard, when choosing the type of surgical gloves, it is necessary to take into account the specific conditions of the types of surgical interventions, which can be met through the additional properties of the gloves.

Medical PPE manufacturers have proposed the introduction of gloves with an internal antibacterial coating as a highly effective measure for practical application. The protective mechanism of one type of such gloves is based on active coating technology containing chlorhexidine gluconate, which has a broad spectrum of antimicrobial action [23].

A serious mistake that medical staff often make when working with gloves (especially powdered ones) is treating them with alcohol solutions. According to surveys (questionnaires), the proportion of employees who do not change gloves after treating them with alcohol-based sanitizers, or who only change gloves when in contact with blood, is 6.5% [24]. It is known that alcohols destroy the upper protective layer of gloves, making them permeable to microorganisms and forming a compress of powder in the form of a mixture of skin antiseptic and "glove juice", which can lead to postoperative adhesions in the patient and negatively affect wound healing. Powder from laboratory staff gloves getting into a biological sample can also lead to false-negative results when testing blood serum for HIV [16].

It is not recommended to treat gloves with sanitizers and disinfectants, which has been confirmed by experimental studies. Penetration of *Escherichia coli* and *Staphylococcus aureus* through latex medical gloves without antiseptic was established after 30 minutes in 15% of cases, after 60 minutes in 25%, and through gloves of the same types but treated with sanitizer, in 29.2% and 45.5% respectively [25].

A significant problem remains the practice of staff washing their hands with soap while wearing gloves between assisting different patients or between procedures on the same patient, which is not recommended but occurs quite frequently in practice. Hands can also come into contact with the potentially contaminated outer surface of the gloves during removal. Study conducted by A.R. Tenorio et al. on vancomycin-resistant enterococci found that despite the use of gloves, these pathogens were detected on the hands of staff after glove removal in 30% of cases [26].

It can be concluded that the hand protection provided by modern types of protective gloves is insufficient for medical staff and patients, and that antimicrobial agents need to be added to the PPE. The increase in the number of antibiotic-resistant microorganisms dictates the necessity to search for new antimicrobial fillers against which resistance will develop to a lesser extent. First and foremost, this concerns inpatient departments with high circulation of nosocomial strains of microorganisms, where the use of antimicrobial protective gloves will be most in demand.

The Growth of Medical Waste as a Leading Environmental Problem

In medical facilities, single-use gloves are subject to disinfection/decontamination after use as medical waste of the corresponding class (usually classes B or

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C, in certain cases D or E)[4]. Presenting an epidemiological hazard, medical waste is a far more significant threat than most other production and consumption waste [27]. Changes in patient diagnostic and treatment methods, and a sharp increase in the demand for single-use medical instruments have significantly impacted the morphological composition of hospital waste, its generation rate and accumulation.

Medical waste is complex and diverse, and many of its components are hazardous in terms of their microbiological composition. Not only is sanitary and epidemiological safety important, but also the economic efficiency of their disinfection/neutralization. Ensuring the epidemiological and environmental safety of medical waste management requires active interdepartmental cooperation and legal regulation [28].

According to the WHO, the generation of medical waste worldwide is increasing annually and by 2021 had already reached 2.27 kg per person per day. Developing countries generate 2–3 times more medical waste than developed countries [29]. According to the US Environmental Protection Agency, approximately 20% of medical waste is generated in hospitals, 15% in laboratories, 35% in nursing homes, and 30% in urgent care clinics and other healthcare facilities. Alongside this, in 2020, as noted in the UN report, 30% of healthcare facilities in developed countries and 60% in the least developed countries lacked waste disposal equipment [30]. In Russia in 2021, approximately 8.448 billion tons of waste were generated [31], of which 3.5 million tons were medical waste [32].

The application of PPE based on synthetic materials (polypropylene, polyurethane, and polyacrylonitrile in masks, as well as latex, vinyl, polyethylene, and nitrile in gloves) poses a serious environmental problem of pollution in the form of not only solid waste but also plastic particles formed as a result of their fragmentation. These particles are non-biodegradable, can persist in the environment for a long time, and pose a serious threat to aquatic and terrestrial fauna and flora. For example, according to the estimates of experts, the number of disposable face masks that ended up in the World Ocean in 2020 alone was estimated at 1.56 billion units [33].

Progress in medical technology is inevitable, but it leads to a significant increase in medical waste. In this regard, research is being conducted on both new technologies for neutralization and destruction, as well as principles for waste quantity management. Open burning of medical waste or burning in any other improper manner leads to the release of dioxins, furans and particulate matter into the air, polluting the environment [34].

In this regard, the objective of giving protective gloves not only antimicrobial properties but also the maximum possible biodegradable components is one of the most important preventive and environmental measures for minimizing the risks of infectious diseases arising and spreading, and for preserving public health in a safe and comfortable living environment.

New materials for producing gloves with antimicrobial properties

Antimicrobial components that could be incorporated into the material of protective gloves made of natural or synthetic rubber include guanidine derivatives (chlorhexidine salts and polyhexamethylene biguanide), quaternary ammonium compounds, chlorinated phenols (triclosan), essential oils (farnesol, phenoxyethanol, octoxyglycerin), iodine compounds, silver salts, metal nanoparticles and their oxides, as well as extracts from certain plant oils (purple gentian), aniline dyes (brilliant green), chitosan-based compounds, turmeric and similar substances [35]. By covalently bonding an antibacterial agent to polymer surfaces, a lasting effect and self-disinfection of the material can be achieved. Metals and their oxides, particularly silver particles, zinc oxide, copper, as well as composite materials based on them, are considered as potential antimicrobial components [36–38].

In a study by X. Chen et al., calcium carbonate whiskers (CaCOw), tetrapod-like zinc oxide whiskers (T-ZnOw), and magnesium oxysulfate whiskers in the form of needles and irregularly shaped particles (MgOSw) were added to natural latex (before vulcanization) to impart antimicrobial properties [39]. Antimicrobial activity was studied using the Oxford cup method and the suspension method. *E. coli*, *S. aureus*, *Pseudomonas aeruginosa*, and *Staphylococcus epidermidis* were used as test microorganisms. The best results for all microorganisms were obtained for samples containing zinc oxide. Antimicrobial activity was noted in materials containing calcium carbonate. Samples based on magnesium oxysulfate showed an antimicrobial effect only against *P. aeruginosa*. The results obtained confirmed the fact that T-ZnOw activates the active oxidizing group (OH), leading to the death of microorganisms.

E. Smiechowicz et al. proposed using cellulose fiber to create protective gloves [40]. Silicon nanoparticles with immobilized silver nanoparticles were introduced into the fibers. The authors limited themselves to only the results of the material's properties (strength, vapor permeability, resistance to mechanical impact and pH changes), without indicating its antimicrobial activity.

[4] Section X of SanPiN 2.1.3684-21 "Sanitary and epidemiological requirements for the maintenance of territories of urban and rural settlements, for water bodies, drinking water and drinking water supply, atmospheric air, soils, residential premises, operation of industrial and public premises, organization and conduct of sanitary and anti-epidemic (preventive) measures" (approved by the Head of the Federal Service for on supervision in the sphere of consumer rights protection and human well-being, by the Chief State Sanitary Doctor of the Russian Federation A.Yu. Popova on January 28, 2021).

In a study by T. Arpornwichanop et al., a partial antimicrobial effect of an additive to natural latex in the form of N,N,N-trimethylchitosan, adsorbed on poly(methyl methacrylate) and stabilized with silica nanoparticles, was established against Gram-positive and Gram-negative microorganisms [41]. The pronounced antimicrobial effect of this composition was established only for the Gram-positive *S. aureus*.

Graphene oxide, as well as its derivatives, have a broad spectrum of antiviral activity against DNA and RNA viruses, including enveloped and non-enveloped viruses. Laser-induced graphene-based materials exhibited antibacterial properties [42]. Studies on their effectiveness have been conducted exclusively in laboratory settings to date, and there is no literature data confirming their effectiveness when tested in practical conditions.

Strong antibacterial properties were found when silver particles, deposited on graphene oxide, were introduced into natural latex. The antimicrobial activity of the composite materials by T. Li et al. was evaluated based on the area of the growth inhibition zones of the test microorganisms *E. coli* and *S. aureus* in an experiment with these additives [43]. The synthesized materials demonstrated high antibacterial activity, but the authors were unable to establish a correlation between the size of the growth inhibition zones and the concentration of the synthesized additive. The mechanism of antimicrobial action was explained by the active release of silver ions (Ag^+) and their interaction with thiol groups (SH) within the protein molecules of microorganisms.

L.A. Alshabanah et al. conducted research on a polymer composite material that also contained silver nanoparticles with a size of 17–51 nm [44]. Polyvinyl alcohol or thermoplastic polyurethane were used as the matrix. Antimicrobial properties were evaluated similarly based on the zones of inhibition of microbial growth (*S. aureus* and its methicillin-resistant variant (MRSA), *E. coli*, *Acinetobacter baumannii*, and *Klebsiella pneumoniae*). High antimicrobial activity of the polyurethane-based material containing 4% silver nanoparticles was established against all tested strains.

M. Kahar Bador et al. described a method for imparting antimicrobial properties to nitrile gloves by applying polyhexamethylene biguanide hydrochloride to their surface [45]. The effectiveness assessment was conducted with the involvement of medical staff from the intensive care unit. The number of colony-forming units (CFU/mL) of microorganisms that grew on nutrient agar was determined as a result of seeding samples (glove swabs) after staff performed four procedures (intravenous administration of solution, oral care for the patient, physiotherapy, changing bed linen). The studies were conducted in parallel using standard nitrile gloves without polyhexamethylene biguanide hydrochloride (control). In the first three out of four types of manipulations, antibacterial gloves had less pronounced bacterial contamination compared to the control. No significant difference in bacterial contamination of gloves was observed between the groups when changing bed linen.

S. Ali et al. studied the antimicrobial effect of polyhexamethylene biguanide hydrochloride on the survival of *Streptococcus pyogenes*, carbapenem-resistant *E. coli*, MRSA and *K. pneumoniae* [46]. 15 minutes after applying the suspension (10 μL) containing 10^4 CFU/mL of bacterial culture to untreated gloves (1 cm^2), regardless of the type of contamination, the listed bacteria maintained their initial concentration level. Gloves treated with polyhexamethylene biguanide hydrochloride reduced the level of microbial contamination by 99.99% within 10 minutes of contact. However, the antimicrobial properties of such gloves were strongly dependent on the presence of biological contaminants (blood, organic compounds, etc.).

In a study by M. Suchomel et al., the effect of chlorhexidine bigluconate on the survival of microorganisms on the hands of surgeons after wearing gloves for 3 hours was investigated [47]. The hands were pre-treated with a skin antiseptic containing 60% (v/v) *n*-propanol. Wearing surgical gloves containing chlorhexidine bigluconate resulted in a 2.67 log10 reduction in the number of microorganisms. With untreated gloves, the degree of reduction was less pronounced (from 1.96 log10 to 1.68 log10, $p \leq 0.01$).

In a similar study (with chlorhexidine biguanide), J. Leitgeb et al. found a high degree of antimicrobial hand protection after wearing gloves for 2 hours [48]. The experiment involved 16 healthy adult volunteers. They wore a glove with chlorhexidine biguanide on one hand (experimental) and one without it (control) on the other. After wearing them for 2 hours, they performed specific finger movements and then removed the gloves from their hands. Subsequently, test microorganisms *S. aureus* (ATCC 6538) or *K. pneumoniae* (ATCC 4352) were applied to the inner surface of the cut-off fingers of the gloves at a concentration of 10^8 CFU/mL. The main evaluation criterion was considered to be the average number of viable forms, expressed in CFU, after 5 minutes of contact with the test microorganisms. In glove samples treated with chlorhexidine biguanide, the average number of *S. aureus* was 6.24 log10 lower compared to the control group, and *K. pneumoniae* was 6.22 log10 lower.

Quaternary ammonium compounds are an effective additive to natural latex. A. Arakkal et al. found that the addition of quaternary poly(4-vinylpyridine) to the polymer precursor provided the necessary degree of protection (99.99%) against clinical isolates of *P. aeruginosa* (PAO1) and *A. baumannii* (C80) [49].

In several scientific papers, W. Moopayak et al. used mangosteen rind to give gloves antimicrobial properties [50]. The active components were xanthones – secondary metabolites also found in plants, fungi

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and lichens. Xanthones are attributed with antioxidant, anticancer, anti-inflammatory, antiallergic, antibacterial, antifungal and antiviral properties. Natural rubber was used as a biofiller. Adding mangosteen rind powder improved the antimicrobial properties of rubber gloves without compromising their physical and mechanical characteristics. At the same time, the toxicity of the material was significantly lower compared to samples with silver nitrate.

A composite material based on mangosteen powder and zinc oxide is described by M. Luengchavanon et al. [51]. The antimicrobial component was applied to the surface of standard nitrile gloves. The minimum inhibitory concentration for MRSA was 160 μg/mL. High inhibitory activity against *K. pneumoniae* was established. Despite the high effectiveness of the method presented by the authors, achieving the effect required prolonged contact of the microorganisms with the surface — at least 30 minutes, which is difficult to achieve in real-world conditions.

Aloe extract is considered one of the promising antimicrobial components of plant origin. In an experiment, H. Khanzada et al. established the high antimicrobial effectiveness of polyvinyl acetate fibers with aloe extract against *S. aureus* and *E. coli* using the electrospinning method [52].

The introduction of antimicrobial additives into the composition of gloves can, in some cases, contribute to expanding their functionality. Thus, C. Salvadores Fernandez et al. applied a composite material containing zinc oxide to nitrile gloves and integrated flexible electrical contacts into the glove material, creating a highly sensitive layer on the fingertips that, according to the authors, can be used as a diagnostic tool [53]. They successfully used such gloves to study pig sphincter damage in an *ex vivo* experiment.

A new approach to creating self-disinfecting protective gloves, based on the action of an electric current generated by friction between nylon and silicone rubber, has been proposed by S. Bayan et al. [54]. A small bioelectric device (2 × 2 cm) made of silicone rubber and nylon (applied to nitrile) generated over 20 V of transient voltage or 41 μW of output power, which was sufficient to charge a capacitor to 65 V in just ~50 seconds. The energy released was used to destroy microorganisms that land on the surface. Thus, to reduce the number of *P. aeruginosa* and *E. coli*, the method's effectiveness was 50–70%.

E.M. Klupp et al. studied the antimicrobial activity of examination gloves with light-activated properties [55]. The experiment was conducted under practical conditions on Gram-positive microorganisms. Glove surfaces were contaminated according to a standardized method (ASTM D7907) with a suspension of *Enterococcus faecium* (ATCC 6057) and its vancomycin-resistant variant, as well as MRSA (ATCC 43300). The results indicated insufficient activity of the applied method against the strains used. The level of contamination reduction was less than 1 $\log_{10}$ after 10 minutes of light exposure. The authors concluded that the method was ineffective.

In a study by D. Patil et al., a method for imparting antimicrobial properties to a nitrile without adding an active substance is described [56]. A specific nanotopographic pattern resembling a cicada wing was created on the surface of the gloves using reactive ion etching. The altered surface structure led to the death of over 85% of *P. aeruginosa* isolates, with the effectiveness of the material's antimicrobial properties showing a clear dependence on the surface structure.

Modern approaches to creating biodegradable protective gloves

Polymeric materials, including synthetic rubber, take a significant amount of time to decompose naturally — around 3 years [57]. One of the reasons for their long persistence in the environment in an unchanged form is the synthetic origin of rubbers, for the production of which raw materials from fossil fuels are used. The variety of monomers used for rubber synthesis has led to the creation of numerous types of synthetic rubbers, but their disposal remains difficult. Managing rubber waste at the end of its life cycle is a global environmental problem of our time.

The rate of decomposition of gloves in nature, like any other material, is influenced by numerous factors, including the types of soil microorganisms present, temperature, pH of the environment, and the presence of chemical additives in the material composition. It is known that synthetic rubber can be combined with thermoplastics. The resulting thermoplastic elastomers will possess both thermoplastic and elastomeric properties. Their thermoplastic properties will allow for more effective processing.

Certain thermoplastics — polylactic acid (PLA) and polycaprolactone (PCL) — contain hydrolyzable ester bonds, which allow materials based on them to exhibit good hydrolytic degradation [58]. Adding these compounds into synthetic rubber can enhance the product's biodegradability. Currently, PLA, being a bio-based polymer (produced from corn or sugar beets), is widely used in the development of eco-friendly plastics, 3D printing filaments, and as a component of polymer blends. A thermoplastic poly(ether urethane) derived from PCL, hydrogenated 4,4'-methylene diphenyl diisocyanate, and chain extenders of varying lengths (e.g., 2-ethynyl urea diol obtained from an amino acid) completely degrades within 100 days in an alkaline solution [59].

Polyesters of 1,4-butanediol, 1,3-propanediol, and/or 2,3-butanediol can also be used as materials for biodegradable films, in combination with various organic acids such as lactic, sebacic, itaconic, and succinic acid [60].

G.Y. Yew et al. pointed out the possibility of using other biological supplements derived from food products and plants (algae) [61]. Works have been published on the application of biofillers in elastomers made from cellulose, starch, chitosan, PLA or polyglycolic acid [62].

Starch has been proposed as a biofiller for latex. S. Daud et al. conducted experimental studies with sago starch to improve the biodegradability of natural rubber films [63]. Sago starch with sulfate-ester groups was obtained by treating it with an aqueous solution of sulfuric acid for 7 days at room temperature. The initial starch particle size was 1.233 μm, and after the acid hydrolysis process, it decreased to 0.313 μm, which allowed for the production of latex films with uniformly incorporated starch particles. The biodegradability of such films was up to 25% within 3 weeks.

R. Blanchard et al. described the use of nanocrystalline cellulose as a biofiller for natural rubber [64]. However, the authors did not present convincing data on the antimicrobial activity of such films.

Conclusion

Protective gloves are an essential piece of PPE widely used in various fields, primarily in medicine. The choice of glove type depends on the specific tasks being performed and the requirements of quality standards. The most common materials for making gloves are nitrile, natural latex, and polyvinyl chloride, which meet their respective safety and effectiveness standards. Modern international standards, such as ASTM and ISO, provide a high level of protection against the penetration of microorganisms, including viruses, bacteria, and fungi. However, research shows that even when all precautions are taken and modern technology is used, there is a risk of microorganisms penetrating damaged gloves, especially during complex procedures involving sharp instruments.

Despite significant advancements in the production of protective gloves, there remains a necessity for further improvement in quality control methods and the development of new approaches to ensure maximum worker protection. This includes raising staff awareness of safe glove use guidelines and implementing innovative solutions to minimize the risk of infection.

The problem of synthetic rubber waste disposal is becoming increasingly relevant due to its difficulty in decomposing naturally. Despite the variety of synthetic rubbers, their long-term presence in the environment poses serious ecological problems. Modern research is focused on developing materials with improved biodegradation characteristics, such as thermoplastic elastomers containing hydrolyzable ester bonds, which will significantly accelerate the decomposition process. The use of biopolymers like PLA and PCL opens up prospects for creating environmentally friendly materials suitable for a wide range of applications, including the production of disposable gloves. The adding of biofillers such as starch and nanocrystalline cellulose will improve the biodegradability of materials while ensuring the preservation of the necessary physical and mechanical characteristics. Research in the field of modifying the composition and structure of synthetic rubbers to increase their biodegradation rate is necessary to address the global environmental problem associated with the management of rubber waste. The use of composite materials that include both traditional synthetic components and biodegradable additives appears to be a promising scientific direction for the development of the polymer materials industry.

An analysis of current scientific literature has demonstrated a significant increase in interest in the development of protective gloves with antimicrobial properties. Despite the obvious appeal of the idea of giving gloves antibacterial properties, its implementation faces a number of serious technical and medical challenges. It is important to consider not only the effectiveness of antimicrobial components but also their potential impact on the health of medical staff, patients and the environment. The need to develop unified criteria for assessing antimicrobial activity and identifying risks requires a comprehensive risk-based approach that takes into account the interests of all stakeholders. The lack of standardized testing methods makes it difficult to compare the results of different studies and hinders the development of general recommendations for the use of antimicrobial additives.

Thus, for the successful promotion of the idea of creating antiseptic gloves, it is important to conduct further scientific research aimed at developing reliable and safe methods for introducing active substances, and to develop standard protocols for assessing antimicrobial activity for subsequent implementation in healthcare practice.

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