



Assessing the environmental impact of disposable polymer gloves: AGREEMIP criteria evaluations

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Abstract

This study aims to evaluate the environmental safety and material composition of disposable polymer gloves by examining the role of chemical additives and applying the Analytical GREENness Metric Index for Polymers (AGREEMIP) tool. A literature-based review was conducted on common chemical additives used in disposable gloves—including plasticizers, stabilizers, accelerators, and colorants—to assess their functional contributions to glove performance. Scanning electron microscopy (SEM) was used to observe the physical degradation of selected glove types. The environmental profile of three glove materials (latex, nitrile, and vinyl) was assessed using the AGREEMIP tool, which considers factors such as chemical toxicity, plastic waste generation, energy intensity, and degradability. Additives were found to significantly enhance glove elasticity, mechanical strength, and degradation resistance, though often at the cost of environmental sustainability. SEM analysis revealed microstructural degradation in used gloves, particularly latex types, indicating potential for biodegradation. The AGREEMIP assessment showed that nitrile gloves have the lowest environmental performance due to toxic additives and high energy consumption during production. Latex gloves demonstrated a superior profile in terms of biodegradability and lower ecological toxicity. The integration of performance-enhancing additives into disposable gloves improves usability but often compromises environmental safety. Latex gloves offer a more sustainable alternative compared to nitrile and vinyl. These findings support the need for greener design and procurement strategies in healthcare, food handling, and industrial applications to reduce the environmental impact of disposable glove use.

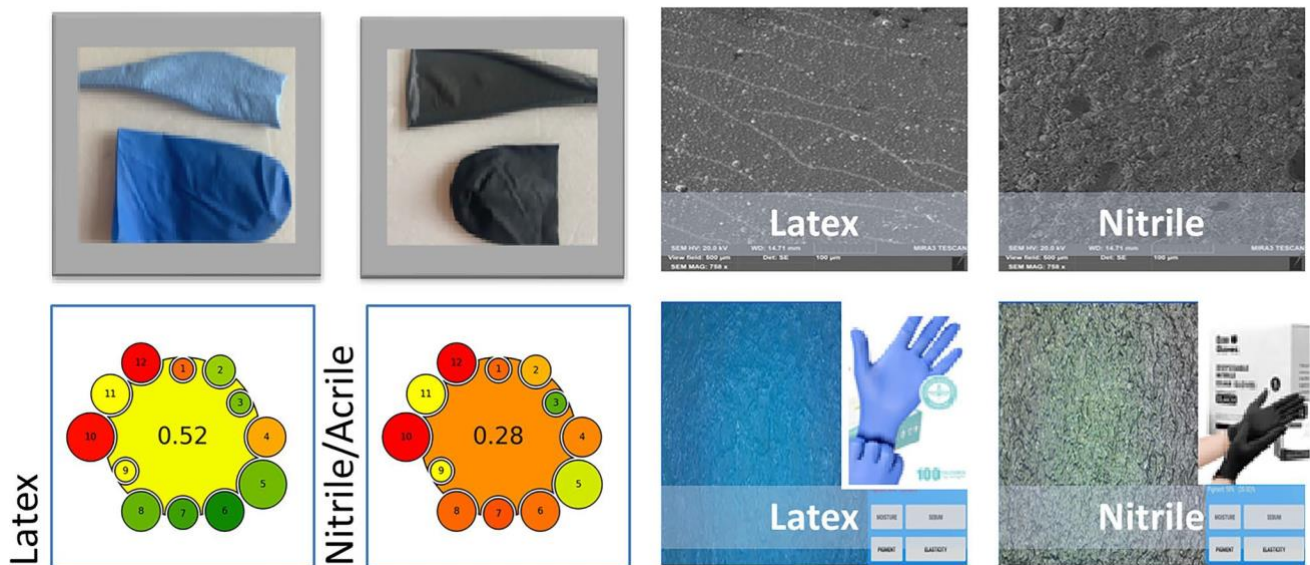
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Graphical Abstract

Microplastic pollution



Keywords Disposable polymer gloves · Chemical additives · Environmental impact · AGREEMIP tool · Degradability

Abbreviations

PA	Polyamide
DEHP	Di(2-ethylhexyl) phthalate
DIDP	Diisodecyl phthalate
DEH	Diocetyl terephthalate
PBAT	Poly(butylene adipate terephthalate)
PH	Poly(hydroxy ether of bisphenol A)
PHA	Poly(hydroxyalkanoate)
PP	Poly(propylene)
PVC	Poly(vinyl chloride)
LDPE	Low density polyethylene
HDPE	High density polyethylene
PLA	Polylactide
BHT-Q	2,6-Di-tert-butyl-p-benzoquinone
IR	Isoprene rubber
CR	Chloroprene rubber
NBR	Acrylonitrile butadiene rubber
DINCH	Diisononyl adipate
MBT	Mercaptobenzothiazole
CBS	Cyclohexylbenzothiazole sulfenamide
DPB	Dibutyl phthalate
ZDEC	Zinc diethyldithiocarbamate
ZDBC	Zinc dibutyldithiocarbamate
TMTD	Tetramethylthiuram disulfide

Introduction

The increased production and use of disposable medical gloves in Ukraine has become critically important. This surge is further driven by the residual impact of the COVID-19 pandemic and the intensified health-care needs. The conflict has placed severe pressure on the healthcare infrastructure, creating an urgent need for enhanced medical support and protective equipment.

Armed conflicts typically lead to a sharp increase in casualties, necessitating expanded medical services and substantial supplies of disposable gloves to ensure hygiene and prevent cross-contamination. In Ukraine, the demand for medical gloves rose significantly during 2022–2024 (Hossain et al. 2024; Skorokhod et al. 2023; Martínez-García et al. 2023). These gloves are essential for maintaining sanitary conditions, limiting the spread of infections, and protecting both healthcare professionals and patients—particularly in times of increased medical emergencies. Field hospitals, humanitarian missions, and emergency response units rely heavily on glove availability to deliver safe and effective care.

In this context, efficient manufacturing and supply chain management are crucial to maintaining healthcare operations and avoiding secondary health crises.

As a result, Ukraine heavily relies on imports (Fig. 1) (Mylon et al. 2013; Garus-Pakowska et al. 2013; Salmanov et al. 2023). Nitrile gloves, in particular, are highly valued for their chemical and puncture resistance, and products from Malaysia and Thailand are widely praised for their consistent quality. In contrast, China supplies a diverse range of glove type's latex, nitrile, and cost-effective vinyl (PVC)—with product quality varying depending on the manufacturer and certification (<https://pro-consulting.ua/en/issledovanie-rynka/Analiz-rinku-medichnih-ta-specializovanih-rukavichok-v-Ukrayini-u-2021-roci>; <https://www.alliedmarketresearch.com/nitrile-medical-gloves-market>; Hashim 2013). Vietnam and Indonesia, traditionally focused on latex production, have recently increased nitrile glove manufacturing to meet global demand. Meanwhile, European producers such as Germany and Poland are known for high-quality gloves that comply with strict EU standards like EN 455, ensuring both safety and low allergenic potential.

According to the available data of the State Statistics Service of Ukraine, the main operators of the market of medical and specialized gloves in Ukraine are Medicare, Nitrylex, Igar, Care, Safetouch, MP Medplast, and Ambulance. The largest market share of domestic manufacturers in Ukraine is Medicare—48.2%. In second place is Nitrylex—28.5%. Other brands have smaller shares: Igar (6.0%), Care 365 (4.0%), Safetouch (3.9%), MP Medplast (2.9%), Ambulance (5.2%), and other brands 7.1% (Salmanov et al. 2023). Given that disposable medical gloves are a type of single-use polymer product and their widespread use leads to continuous accumulation and environmental pollution in Ukraine, it is crucial to evaluate and compare the "greenness" of their production by various suppliers exporting to the country. This includes an analysis of the chemical additives introduced

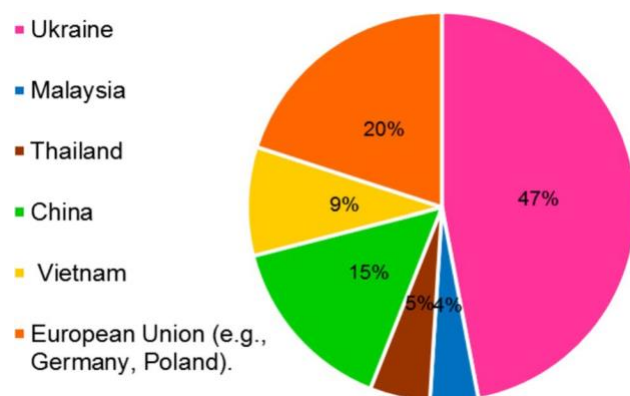


Fig. 1 Production and distribution of disposable gloves in Ukraine

during the manufacturing process. Assessing the environmental friendliness of different glove materials involves considering several key aspects: resource consumption, environmental impact during production, biodegradability, and potential for recycling. Such an approach not only emphasizes the importance of medical gloves as a protective measure but also highlights their role in strengthening the sustainability of Ukraine's healthcare system under challenging conditions. (Nakamura et al. 2003; Chauhan et al. 2024; Shenoy et al. 2024; Zhao et al. 2023; Wang et al. 2022; Phalen et al. 2014; Gee 2023; Brundage et al. 2018). The evaluation of disposable glove materials requires a comprehensive understanding of their environmental friendliness, environmental impact, and greenness level, as these parameters directly reflect the sustainability of their production and post-use disposal. Considering these aspects is essential for identifying environmentally responsible alternatives and minimizing the ecological footprint of single-use medical products. Therefore, the paper assessed environmental sustainability (Brundage et al. 2018; Moldan et al. 2012; Kurul et al. 2025), environmental impact (Pajula et al. 2017; ISO 2006; Klüppel 2005; Adawy et al. 2024), and greenness (Wojnowski and Pena-Pereira 2020; Marć et al. 2024; Phalen et al. 2020).

Environmental sustainability refers to the extent to which a product, process, or activity minimizes harm to the environment. This typically refers to the use of sustainable resources, the reduction of pollution, and the preservation of ecosystems throughout the life cycle of the product or process (ISO 2006).

Environmental impact describes the measurable impact of a material, product, or process on the environment. This includes emissions to air, water, and soil; resource depletion; energy consumption; and waste generation throughout its life cycle (Klüppel 2005; Adawy et al. 2024).

Greenness is a broader measure often used to assess the overall sustainability or "greenness" of a chemical process or product. It combines several measures, such as nuclear economy, toxicity, energy efficiency, waste generation, and environmental sustainability. Tools such as the AGREE, AGREEprep, or AGREEMIP measures help quantify this level in a structured and reproducible way (Wojnowski and Pena-Pereira 2020; Marć et al. 2024; Phalen et al. 2020).

This focus of research underscores not only the importance of medical gloves as a protective tool but also the resilience of Ukraine's healthcare system amidst challenging conditions. But also highlights their role in environmental pollution and the accumulation of disposable plastic in the European region. In this work, the use of different materials and their influence on the environmental friendliness and environmental impact of medical disposable gloves was carried out. To compare the different materials, the work employs literature data and disposable glove manufacturing

technology information in the analytical tool for evaluating the greenness of polymer synthesis (AGREEMIP).

Materials and methods

The evaluation the greenness of polymer synthesis of medical disposable gloves by uses analytical tool AGREEMIP. The assessment can be performed using user-friendly open-source software, freely downloadable from mostwiedzy.pl/agreemip (Marć et al. 2024; Phalen et al. 2020). The greenness assessment of glove materials was conducted using the AGREEMIP (Analytical GREENness Metric Index for Polymers) framework. AGREEMIP is a multi-criteria evaluation tool based on the principles of green chemistry, designed to assess the environmental performance and sustainability of polymeric materials across their life cycle (Wojnowski and Pena-Pereira 2020; Marć et al. 2024; Phalen et al. 2020). This methodology evaluates materials across 12 criteria, each reflecting a core aspect of green chemistry and environmental impact:

- Renewable feedstocks—use of bio-based vs. fossil-based raw materials
- Toxicity—toxicity to human health and the environment
- Process safety—risk of accidents, flammability, or instability during production
- Energy efficiency—energy demand of the manufacturing process
- Waste generation—amount and hazard level of generated waste
- Atom economy—proportion of reagents converted to the final product
- Chemical yield—efficiency of polymer synthesis
- Number of synthetic steps—complexity and intensity of synthesis
- Use of auxiliary substances—solvents, catalysts, and other non-reactive reagents
- Degradability—biodegradability or degradability in natural conditions
- Recyclability—feasibility of mechanical or chemical recycling
- End-of-life fate—long-term environmental behavior, e.g., microplastic generation

Table 1 Comparison of glove types by their projected usage between 2019 and 2030 (Moldan et al. 2012)

Type of glove	2019 usage	2030 usage
Nitrile	High	Very high
Vinyl	Low	Medium
Latex	Low	Medium

Table 2 Comparison of medical gloves made of different materials (Ogawa et al. 2024; Xu et al. 2008; Restelatto et al. 2024a, b; Esmizadeh et al. 2021; Yew et al. 2019; Kruželák et al. 2017; Fleischmann et al. 2018; Allergy 2018; Reitzel et al. 2009; Alleged Allergenicity of Latex Gloves 2006; Patrawoot et al. 2021)

Material properties	Latex	Nitrile	Vinyl
Protection against chemicals	Average	High	Low
Solvent protection	Low	High	Low
Protection against hydrocarbons	Low	High	Low
Protection against acids and alkalis	High	High	Average
Protection against alcohol	Average	High	Low
Biodegradability	High	Low	Low

Each material (latex, nitrile, vinyl) was scored individually for all criteria. Evaluation was based on available literature data (Jędruchiewicz et al. 2021; Banaee et al. 2024; European Union Number (EN) International Organization of Standards (ISO) 2016; Norhanifah et al. 2024; Herkins and Cornish 2024; Ogawa et al. 2024; Xu et al. 2008; Restelatto et al. 2024a, b; Esmizadeh et al. 2021), industrial reports, and publicly available safety and environmental data (ECHA, PubChem, REACH dossiers). Scoring was performed using a semi-quantitative color code:

Green: low impact / high sustainability (desirable), Yellow: moderate impact (acceptable under certain conditions), Red: high impact/low sustainability (undesirable).

All criteria were assigned equal weight in this study to ensure a balanced comparison.

The evaluation of Criteria 2–10 within the AGREEMIP framework—namely, Functional Monomer, Template, Cross-Linking Agent, Porogen/Solvent, Other Reagents/Adjuvants/Carriers, Core/Particle Preparation, and Surface Modification—was conducted using principles adapted from the Derivatisation Agent Selection Guide (DASG), developed as part of green chemistry tools for the rational selection of reagents. The DASG was originally designed to assist in choosing derivatisation agents in analytical chemistry but has since been used as a decision-making matrix for evaluating reagent sustainability. It assesses chemical substances based on multiple hazard-related and environmental parameters, including: Acute and chronic toxicity (e.g., carcinogenicity, mutagenicity, reproductive toxicity), Volatility and risk of inhalation, Persistence, bioaccumulation, and degradability, Corrosivity and reactivity, Occupational safety classifications (GHS hazard codes, pictograms), Environmental hazard (aquatic toxicity, ozone depletion). In the context of this study, these parameters were mapped to the relevant components used in glove production (e.g., acrylonitrile, phthalates, accelerators, stabilizers, pigments, surfactants, etc.). Scoring for each sub-criterion was determined based on available data from reliable databases such as REACH, ECHA, and PubChem, with penalties assigned for high-risk



Fig. 2 Types of medical gloves are used in medical practice (Esmizadeh et al. 2021; Yew et al. 2019; Kruželák et al. 2017; Fleischmann et al. 2018; Allergy 2018)

or non-compliant substances and bonuses for the use of safer or biodegradable alternatives. This approach ensures that each evaluated criterion in AGREEMIP not only reflects chemical efficiency or function but also aligns with broader sustainability and safety goals. By using DASG principles, the assessment becomes more transparent, reproducible, and grounded in established green chemistry methodology.

Glove materials and types of medical gloves

The most widely used materials for medical disposable gloves are nitrile, vinyl (polyvinyl chloride-based), and natural rubber latex. Each of these materials has distinct chemical and physical properties that determine their suitability for different applications. Nitrile (nitrile butadiene rubber, NBR) is a synthetic elastomer known for its superior resistance to oils, chemicals, and punctures. It is highly durable and does not trigger allergic reactions, making it a preferred choice in environments with a high risk of exposure to hazardous substances. Vinyl gloves are made from plasticized polyvinyl chloride (PVC). They offer a cost-effective solution for short-term, low-risk tasks. Although less elastic and less form-fitting than nitrile or latex gloves, they provide adequate protection in non-critical settings such as food handling or general hygiene. Latex gloves, made from natural rubber, are highly elastic and provide excellent tactile sensitivity and fit. They are widely used in medical and surgical settings but may cause allergic reactions in some individuals due to natural rubber proteins. These three materials form the basis of modern disposable medical glove production and are selected based on the balance between cost, chemical resistance, barrier performance, and wearer comfort (see Tables 1 and 2, Fig. 2). In the disposable glove market, vinyl

and polyvinyl chloride (PVC) gloves are the most common varieties, with nearly two-thirds of gloves made from vinyl in certain industries.

Taking into account the presence or absence of coating, gloves are powdered and unpowdered. For individuals with latex allergies, nitrile (Patrawoot et al. 2021; Yew et al. 2020; Phalen and Wong 2015; Liu et al. 2024), vinyl are the preferred alternatives (Table 1). High-risk tasks require gloves with superior puncture resistance (e.g., nitrile), while low-risk tasks can use vinyl gloves. Surgical and examination procedures often demand gloves that provide a good fit and high tactile sensitivity, favoring materials like latex and nitrile. While natural latex possesses inherent biodegradability, its disposal in anaerobic landfill conditions prevalent in many countries significantly limits actual degradation rates. In contrast, synthetic polymers such as nitrile and vinyl are not biodegradable and persist in the environment. Consequently, all glove types contribute to environmental burden, underscoring the urgent need for the development of more sustainable end-of-life management solutions, including recycling and advanced disposal technologies.

Chemical additives included in the composition of medical gloves

An integral component of vinyl gloves are plasticizers, which are added for greater elasticity of the main material (Table 3, Fig. 3).

Plasticizers and softeners

The purpose of using plasticizers and softeners in the medical gloves is to improve the flexibility, softness, and overall

Table 3 Composition of polymers and functional additives in medical gloves (European Union Number (EN) International Organization of Standards (ISO) 2016; Norhanifah et al. 2024; Herkins and Cornish 2024; Ogawa et al. 2024; Xu et al. 2008; Restelatto et al. 2024a, b; Claus et al. 2024; Michaels et al. 2024; Nuzaimah et al. 2021; Mahler 2021; Aalto-Korte et al. 2006; De-la-Torre et al. 2022; Luca et al. 2024; Wissen et al. 2025; Celina et al. 1998)

Polymer type	Functional additives	Chemical substances	
Polyvinyl chloride (PVC)	Softeners and Plasticizers	Stearic acid	Acts as both a lubricant and a processing aid, helping the material flow during manufacturing
		Phthalates:	DEHP (di-(2-ethylhexyl) phthalate), DEHT (di-(2-ethylhexyl) terephthalate), DINP (diisononyl phthalate), DIDP (diisodecyl phthalate)
		Naphthalate plasticizers	Diisononyl 1,2-cyclohexanedicarboxylate (DHIN), are used as substitutes for phthalates. The concentrations of phthalates in PVC vary: DEHP—up to 44% by mass, DINP—up to 43% by mass, DIDP—up to 3% by mass
		Stabilizers	Zinc oxide: Also serves as an activator in the vulcanization process Calcium carbonate: Sometimes used as a filler to improve strength and reduce cost
	Antibacterial supplements	Styrene and complex phenols (Kurul et al. 2025; Wojnowski and Pena-Pereira 2020)	
	Colorants	Dyes or pigments to impart desired colors	
	Surfactants and emulsifiers	Used during polymer synthesis to maintain a stable emulsion	
	Defoamers and surfactants	Silicone-based defoamers Nonionic surfactants	
	Common cross-linking agents (Herkins and Cornish 2024)	Peroxides (e.g., benzoyl peroxide)	Commonly employed for initiating free-radical polymerization and cross-linking in acrylic and vinyl gloves (Ogawa et al. 2024; Esmizadeh et al. 2021)
		Acrylates (e.g., ethylene glycol dimethacrylate):	Utilized in forming a three-dimensional polymer network in various synthetic gloves
Zinc oxide and stearic acid		Often act as activators in the cross-linking process, particularly for natural and synthetic rubbers	
Organosilanes		Used for enhancing adhesion and cross-linking in specialized applications	

Table 3 (continued)

Polymer type	Functional additives	Chemical substances	
Nitrile	Antioxidants	Phenolic stabilizers to protect against oxidation (Phenolic acids) (2,4-bis(1,1,3,3-tetramethylbutyl)phenol and 2,6-bis(1,1-dimethylethyl)-4-(1,1,3,3-tetramethylbutyl)phenol) (Claus et al. 2024; Michaels et al. 2024; Nuzaimah et al. 2021; Mahler 2021; Aalto-Korte et al. 2006; De-la-Torre et al. 2022; Luca et al. 2024; Wissen et al. 2025; Celina et al. 1998)	
	Fillers	Carbon black, talc, calcium carbonate (chalk)	
	Typical vulcanization and agents accelerators	Zinc oxide; MBT (mercaptobenzothiazole), CBS (cyclohexylbenzothiazole sulfenamide)	
	Plasticizers	Paraffinic or aromatic oils (e.g., DAE, RAE), phthalates	
	Activators	Zinc oxide (ZnO), zinc stearate (ZnSt)	
	Latex	Accelerators	Thiurams, carbamates, and thiazoles
		Stabilizers	Zinc oxide
		Antioxidants	Phenolic compounds or amines
		Softeners and plasticizers	Glycerol or phthalates
		Proteins	Natural latex contains proteins that can sometimes cause allergic reactions. Manufacturers may add processing agents to reduce these proteins to minimize the risk of latex allergies
Powder	Powder	Comstarch	
	Typical vulcanization agents	Zinc oxide (ZnO) Accelerators: MBT (mercaptobenzothiazole), CBS, TMTD, ZDEC	

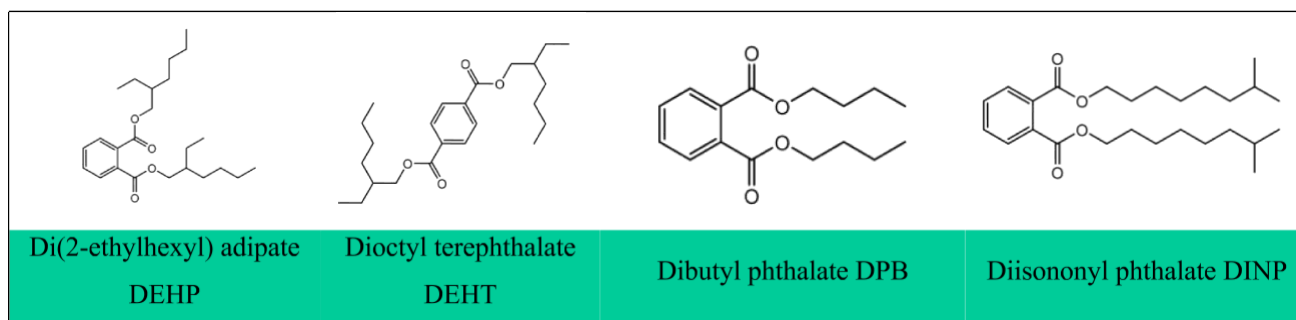


Fig. 3 Chemical structure of the four most common chemical plasticizers for PVC, nitrile, latex and gloves (Skorokhod et al. 2023; Martínez-García et al. 2023; Kochanska et al. 2022; Mylon et al. 2013; Garus-Pakowska et al. 2013; Salmanov et al. 2023; <https://pro-consulting.ua/en/issledovanie-rynka/Analiz-rinku-medichnih-ta-specializovanih-rukavichok-v-Ukrayini-u-2021-roci>; [handling of the gloves without compromising strength. Plasticizers are commonly used to impart elasticity to materials such as polyvinyl chloride \(PVC\) and silicones \(Xu et al. 2008; Restelatto et al. 2024a, b\). Stearic acid is used as a lubricating additive and auxiliary processing agent. It promotes better processing of the polymer mass, reduces friction between particles and molds during casting or extrusion. In some systems, naphthalate plasticizers are used, such as diethylene glycol dibenzoate, triethylene glycol dibenzoate, alkyl sulfonic esters of phenol, and diisononyl adipate \(DINCH\). For example, in a polymer with naphthalate plasticizers, their concentration is 37.5–48.9% by mass. PVC materials can be of different types, from "hard" to "soft" and different concentrations of plasticizers correlate with their flexibility and application. For example, in "hard" PVC, the content of DEHP can be 60.2 mg/g, while in "soft," its concentration can reach up to 301 mg/g.](https://www.alliedmark</p>
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Figure 3 above displays the chemical structures of the four common chemical plasticizers. Phthalates and alternative biocompatible plasticizers can be used. The concentrations of phthalates in PVC vary: DEHP—up to 44% by weight, DINP—up to 43% by weight, DIDP—up to 3% by weight (Fig. 3). Due to toxicological concerns (especially regarding DEHP) in many countries, including the

[etresearch.com/nitrile-medical-gloves-market](https://www.research.com/nitrile-medical-gloves-market); Hashim 2013; Nakamura et al. 2003; Chauhan et al. 2024; Shenoy et al. 2024; Zhao et al. 2023; Wang et al. 2022; Phalen et al. 2014; Gee 2023; Brundage et al. 2018; Moldan et al. 2012; Kurul et al. 2025; Pajula et al. 2017; ISO 2006)

EU and the US, their use in medical devices and gloves is restricted or banned, especially for products that come into contact with skin, blood or food.

Antioxidants and stabilizers

The purpose of antioxidants is prevent the degradation of nitrile rubber when exposed to oxygen, heat, and UV light, extending the gloves' shelf life and durability (Restelatto et al. 2024a, b; Esmizadeh et al. 2021; Yew et al. 2019; Kruželák et al. 2017; Fleischmann et al. 2018; Allergy 2018; Reitzel et al. 2009; Alleged Allergenicity of Latex Gloves 2006). The main additives are phenolic antioxidants (e.g., butylated hydroxytoluene, BHT) and aromatic amine antioxidants. Antioxidants included in medical gloves shield them from oxygen exposure while being stored. Antioxidants that do not leave stains, including phenolic antioxidants such as styrenated and complex phenols, are commonly used in surgical and examination gloves. Occasionally, these antioxidants are coupled with a secondary antioxidant for enhanced stability. Defence against harmful microbes is provided by organic antibacterial compounds, copper, and silver. Protection against

Table 4 Stabilizers of UV radiation (Alleged Allergenicity of Latex Gloves 2006)

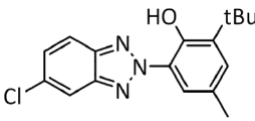
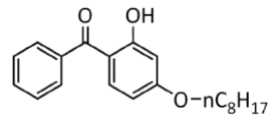
	
2-(5-chloro-2H-benzotriazol-2-yl)-6-tert-butyl-4-methylphenol (Alleged Allergenicity of Latex Gloves 2006)	[2-hydroxy-4-(octyloxy)phenyl](phenyl)methanone
Benzotriazole UVA type Provides absorption at long wavelengths	UVA of the benzophenone type. High absorption in the short-wave range Good compatibility with many polymers

Table 5 Commonly used colorants in disposable polymer gloves (Nambiathodi et al. 2021; Lovato et al. 2023; Martínez-Tadeo and Perez-Rodriguez 2014)

Colorant	Chemical identity/CI number	Type	Color appearance	Typical application and notes
Titanium dioxide	TiO ₂ –	Inorganic pigment	White	Widely used for white or opaque gloves; provides high coverage and UV resistance; FDA-approved
Carbon black (Jędruchiewicz et al. 2021)	Amorphous carbon/pigment Black 7	Inorganic pigment	Black	Common in industrial gloves; provides antistatic properties and UV protection
Iron oxide red (Zhu et al. 2022)	Fe ₂ O ₃ /CI Pigment Red 101	Inorganic pigment	Red-brown	Used for beige or skin-tone gloves; chemically stable and non-toxic
Iron oxide yellow (Zhu et al. 2022)	FeOOH/CI Pigment Yellow 42	Inorganic pigment	Yellow ochre	Imparts natural tone; often used in examination gloves
Chromium oxide green (Zhu et al. 2022)	Cr ₂ O ₃ /CI Pigment Green 17	Inorganic pigment	Green	High thermal and chemical resistance; limited use due to chromium content
Phthalocyanine blue (Purnomo et al. 2021)	Cu-phthalocyanine/CI Pigment Blue 15	Organic pigment	Blue	Common in medical-grade gloves; offers high color strength and stability
Phthalocyanine green	CI pigment green 7	Organic pigment	Green–blue	Lightfast and weather-resistant; may be used in industrial or color-coded gloves
Solvent Red 24	CI 26105	Organic dye	Bright red	Used for vivid coloration; may present migration risk, limiting use in food or medical gloves
Solvent Yellow 93	CI 18785	Organic dye	Yellow-orange	Provides bright colors; less stable than pigments, typically avoided in critical applications

the destructive effects of ultraviolet light is particularly important for devices sterilized by UV (Patrawoot et al. 2021; Yew et al. 2020).

Vulcanization agents and accelerators

Latex gloves rely primarily on sulfur-based vulcanization systems, which are essential for developing their characteristic elasticity and strength. The vulcanization process typically includes the use of accelerators, which not only reduce the amount of sulfur required but also lower the vulcanization temperature, thereby enhancing production efficiency and improving the mechanical properties of the final product. Common accelerators used in latex formulations include zinc diethyldithiocarbamate (ZDEC), zinc dibutyldithiocarbamate (ZDBC), and tetramethylthiuram disulfide (TMTD) (Phalen and Wong 2015; Liu et al. 2024; Herkins et al. 2024). These compounds promote faster cross-linking of rubber chains but may also pose allergenic risks, particularly in sensitive individuals, due to the presence of thiurams and carbamates. To address this, manufacturers may adopt alternative low-allergen formulations. Nitrile gloves, synthesized from acrylonitrile-butadiene rubber (NBR), often utilize a dual curing system that includes both sulfur and organic peroxides, selected

according to the desired performance attributes such as chemical resistance and elasticity. Like latex, the inclusion of accelerators enhances the efficiency and quality of vulcanization, though peroxide curing may be preferred in applications requiring reduced sulfur content. In contrast, vinyl gloves made from polyvinyl chloride (PVC) do not undergo vulcanization. As a thermoplastic material, PVC relies instead on heat stabilization and the addition of plasticizers to achieve the necessary flexibility and durability. Stabilizers, such as metal soaps or organotin compounds, are used to prevent thermal degradation during processing (Aalto-Korte et al. 2006). In Table 3 summarizes the typical curing and stabilization strategies used for latex, nitrile, and vinyl glove materials, along with common vulcanization accelerators and associated allergenic risks.

Stabilizers of UV radiation

HALS (Hindered Amine Light Stabilizers) work by scavenging free radicals generated by UV radiation (Table 3). UV Absorbers, such as benzophenones and benzotriazoles, absorb harmful UV radiation and dissipate it as harmless heat. In PVC, stabilizers often serve dual roles: thermal stabilization during processing and UV protection during use. The choice and concentration of UV stabilizers depend on

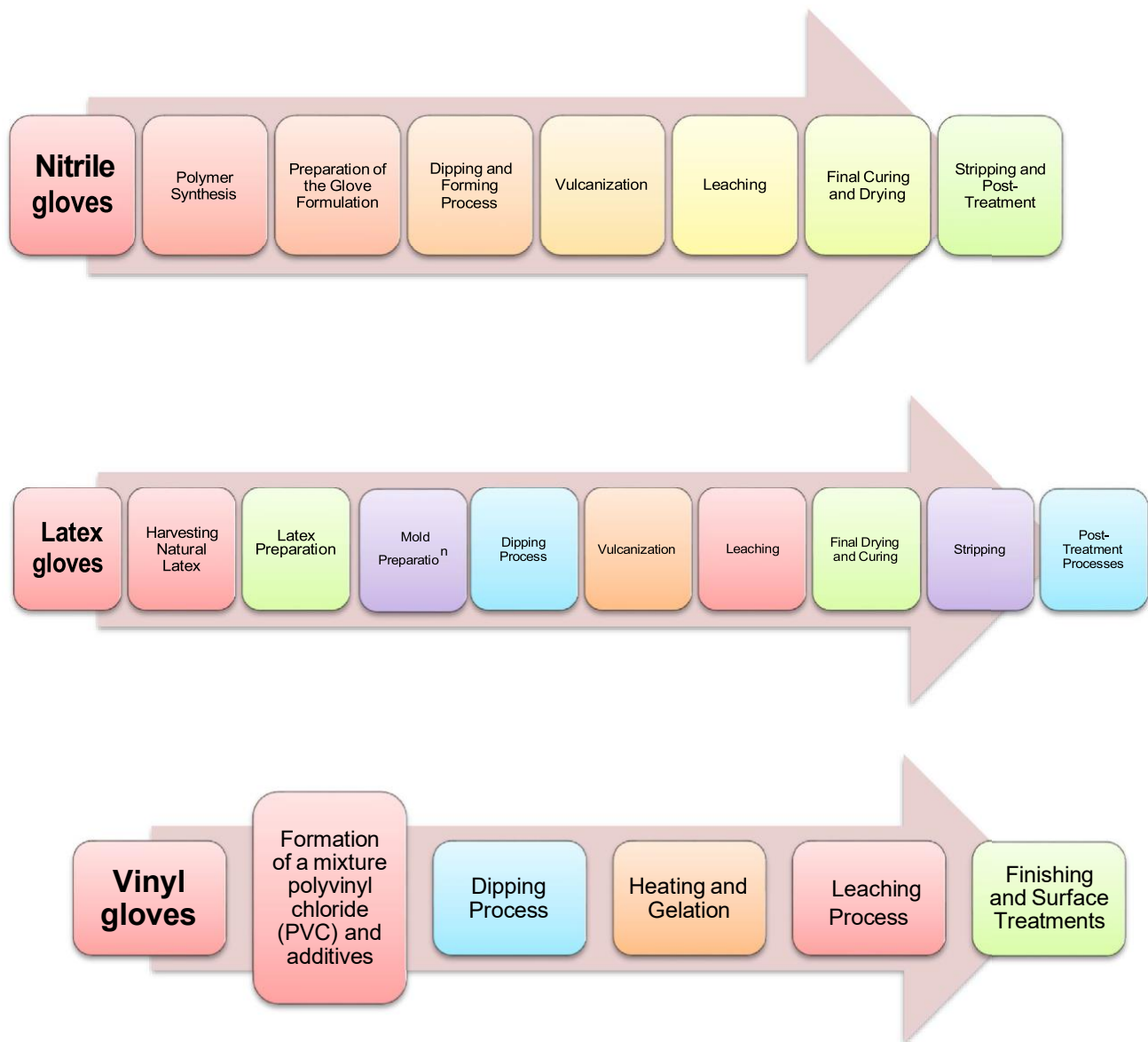


Fig. 4 Steps of the manufacturing process of nitrile, latex and vinyl gloves

the intended use duration, exposure level, and regulatory considerations (e.g., for medical applications). The structural formulas of the main ones are presented in Table 4.

Colorants

Colorants used in disposable gloves are selected based on their chemical compatibility with the glove polymer (nitrile, latex, or vinyl), compliance with regulatory frameworks such as FDA and REACH, and the intended application (medical, food handling, or industrial use) (Table 5) (Nambiathodi et al. 2021; Lovato et al. 2023; Martínez-Tadeo and Perez-Rodríguez 2014). Pigments are generally preferred over dyes due to their lower migration potential and greater chemical

stability. These pigments can be either inorganic (e.g., titanium dioxide, carbon black, iron oxides) or organic (e.g., phthalocyanines), depending on the desired color and regulatory requirements. Dyes are less commonly used because of their higher tendency to migrate but are valued for their ability to produce bright, vivid colors. The primary function of colorants in gloves is to provide visual differentiation (e.g., blue for medical use, black for industrial settings, purple for latex-free alternatives), aiding in safety, compliance, and usability.

Technology of obtaining gloves

Nitrile gloves

Nitrile gloves are manufactured from synthetic rubber based on acrylonitrile and butadiene monomers (Patrawoot et al. 2021; Yew et al. 2020; Phalen and Wong 2015; Liu et al. 2024). The production process comprises several stages designed to ensure high tensile strength, elasticity, and resistance to chemicals and punctures (Fig. 4). The key material, nitrile butadiene rubber (NBR), is synthesized through emulsion polymerization of acrylonitrile and butadiene. This process is initiated by free-radical initiators, while emulsifiers and surfactants are incorporated to stabilize the emulsion and promote uniform polymer growth.

The proportion of acrylonitrile in nitrile butadiene rubber (NBR) determines the glove's chemical resistance, while butadiene contributes to its elasticity. Typically, a higher acrylonitrile content enhances oil and chemical resistance but reduces flexibility. The raw NBR latex is blended with various chemical additives to improve the physical and mechanical properties of the gloves. These additives include sulfur and vulcanization accelerators, antioxidants, plasticizers, stabilizers, and softeners. An important stage in glove manufacturing is the dipping and forming process. It begins with mold preparation, during which ceramic or metal hand molds (formers) are thoroughly cleaned and coated with a coagulant solution—typically a mixture of calcium nitrate and water—to promote latex adhesion. The prepared formers are then dipped into the NBR latex compound, forming a thin film over each mold. A bead is rolled at the open end of the glove to reinforce the cuff and facilitate easier removal. The next phase involves drying and pre-vulcanization. The latex-coated molds pass through drying ovens, which remove moisture and partially cure the gloves. This is followed by vulcanization (Kruželák et al. 2017), a critical step that cross-links rubber molecules to enhance elasticity, strength, and heat resistance. Vulcanization typically occurs at temperatures ranging from 100 to 130 °C, using sulfur and accelerators to form cross-linked bonds. After vulcanization, the gloves undergo a leaching process, where they are immersed in hot water baths to remove residual proteins,

unreacted chemicals, and impurities that could cause skin irritation or allergic reactions. This is followed by multiple washing cycles, a vital step for ensuring compliance with safety standards and minimizing sensitization risks. The gloves then undergo final curing and drying, completing the vulcanization process and ensuring optimal mechanical properties. Remaining moisture is removed through drying. Finally, the gloves are stripped and post-treated (Michaels et al. 2024). They are removed from the molds either manually or using automated systems. To reduce tackiness and improve donning, gloves may be chlorinated or coated with a thin polymer layer as an alternative to chlorination.

Latex gloves

Latex gloves are made from natural rubber latex (NRL), which is derived from the sap of rubber trees (*Hevea brasiliensis*) (Fig. 4). The production process involves multiple steps to transform raw latex into durable, flexible gloves suitable for medical and industrial use (Xu et al. 2008). The main stages of the production technology are described below.

The first stage is the harvesting of natural latex. Natural rubber latex is collected by tapping rubber trees and gathering the sap in containers. To prevent coagulation during storage and transport, the raw latex is stabilized using ammonia or other preservatives. The next step is latex preparation. The latex is concentrated through processes such as centrifugation to increase the rubber content, typically to around 60%. At this stage, various chemical additives are blended into the latex to tailor its properties for glove manufacturing. These include: Vulcanization agents for cross-linking, Antioxidants to prevent degradation, Stabilizers such as zinc oxide to maintain latex stability, Softeners and plasticizers for improved flexibility, and Colorants where applicable.

The following stages—mold preparation and dipping—are similar to those used in the production of nitrile gloves. Molds (formers) are cleaned and coated with a coagulant (usually calcium nitrate), then dipped into the compounded latex solution. A thin, uniform film of latex forms over the surface of each former. Next, the coated formers pass through drying ovens to remove moisture and partially cure the latex, stabilizing the glove shape.

Table 6 Comparison and classification (Yew et al. 2019; Patrawoot et al. 2021; Aalto-Korte et al. 2006)

Glove material	Renewable/non-renewable	Biodegradability	Chemical use and exposure risks	Greenness score
Latex	Renewable	Biodegradable	Moderate (due to additives)	Moderate
Nitrile	Non-renewable	Non-biodegradable	High (due to synthetic additives)	Significant
Vinyl	Non-renewable	Non-biodegradable	High (plasticizers, PVC)	High

A critical subsequent step is vulcanization. The partially cured gloves are further heated in chambers at temperatures typically ranging from 100 to 130 °C to complete the vulcanization process, forming the final elastic structure of the glove. After vulcanization, the remaining stages—including leaching, final drying, stripping, and post-treatment—follow the same sequence as described for nitrile glove production. These steps ensure glove safety, cleanliness, and user comfort.

Vinyl (PVC) gloves

The technology for obtaining vinyl gloves differs significantly from the production of latex and nitrile gloves due to the use of polyvinyl chloride (PVC) as the base material, which is a synthetic plastic polymer (Fig. 4). The main stages of production and the key differences of vinyl glove manufacturing are described below. Vinyl gloves are made from polyvinyl chloride (PVC), which is derived from the polymerization of vinyl chloride monomers. This results in a product that is synthetic, unlike latex gloves (natural rubber) and nitrile gloves (synthetic rubber). Latex and Nitrile Gloves: Made from natural rubber or synthetic nitrile butadiene rubber (NBR), both of which require different types of processing, including vulcanization for improved elasticity and durability. The formulation includes PVC resin mixed with plasticizers to impart flexibility, as PVC alone is rigid. Common plasticizers include phthalates (e.g., DEHP, DINP) or non-phthalate alternatives for health safety. In the technology of obtaining vinyl gloves, the molds are dipped into a liquid PVC

paste, which is a mixture of PVC resin and plasticizers. The paste evenly coats the formers and forms a layer. In the technology of obtaining latex and nitrile gloves, formers are dipped into liquid latex or nitrile compounds, and the coagulant (e.g., calcium nitrate) is used to help the material adhere to the mold uniformly. After dipping, the PVC-coated formers are heated to cause gelation. This process sets the PVC paste, turning it from a liquid to a solid state. Vinyl gloves generally undergo less extensive leaching because they do not contain natural proteins or the same type of accelerators found in latex or nitrile gloves. This reduces the risk of allergic reactions but means fewer purification steps.

The evaluation the greenness of polymer synthesis of medical disposable gloves by uses analytical tool AGREEMIP

The assessment can be performed using user-friendly open-source software, freely downloadable from mostwiedzy.pl/agreemip (Marć et al. 2024; Phalen et al. 2020).

Criterion 1: Removal of Polymerization Inhibitors

In the manufacture of latex, nitrile, acrylic and vinyl gloves, polymerization inhibitors are not usually completely removed, but may be partially removed during washing and processing of the finished products (Phalen et al. 2020; Ogawa et al. 2024; Alleged Allergenicity of Latex Gloves 2006). The main goal of such stages is to reduce the level of residual chemicals, including inhibitors. Polymerization inhibitors (e.g., hydroquinone or methyl methacrylate) are

Fig. 5 Hazard statements for functional monomers used in the production of nitrile (Allergy 2018), acrylic, latex and vinyl gloves (Nuzaimah et al. 2021; Mahler 2021; Celina et al. 1998; Cunha et al. 2024)

Hazard statements for monomer of acrylonitrile	H225: Flammable liquid and vapor	Hazard statements for monomer of Vinyl chloride	H220: Extremely flammable gas.
	H301: Toxic if swallowed.		H350: May cause cancer.
	H311: Toxic in contact with skin.		H372: Causes damage to organs through prolonged or repeated exposure.
	H351: Suspected of causing cancer.		
	H373: May cause damage to organs through prolonged.		
Hazard statements for monomer of methyl methacrylate	H220: Extremely flammable gas.	Natural rubber latex	H317: May cause an allergic skin reaction
	H350: May cause cancer.		H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled
	H372: Causes damage to organs through prolonged or repeated exposure.		H315: Causes skin irritation
			H319: Causes serious eye irritation

Fig. 6 Hazard statements for template used in the production of nitrile, acrylic, latex and vinyl gloves (Kurul et al. 2025; Allergy 2018)

Other components (e.g., butadiene)	H220: Extremely flammable gas H340: May cause genetic defects H350: May cause cancer	Other components	Crosslinkers Varying hazard levels depending on the specific chemical, including irritation and sensitization risks
Plasticizers and Additives	Some may have hazard statements like H361 (Suspected of damaging fertility or the unborn child) depending on their chemical nature.	Other components	H412: Harmful to aquatic life with long-lasting effects H242: Heating may cause a fire H319: Causes serious eye irritation

Fig. 7 Hazard statements for cross-linking agents used in the production of nitrile, acrylic, latex and vinyl gloves (ISO 2006; Norhanifah et al. 2024; Herkins and Cornish 2024; Ogawa et al. 2024)

Hazard statements of cross-linking agents for acrylonitrile (Sulfur-based cross-linkers or peroxide-based cross-linkers)	H315: Causes skin irritation H319: Causes serious eye irritation H335: May cause respiratory irritation. H242: Heating may cause a fire. H317: May cause an allergic skin reaction.	Hazard statements of cross-linking agents for glycidyl methacrylate, divinylbenzene, or other multifunctional acrylates:	H317: May cause an allergic skin reaction. H319: Causes serious eye irritation H335: May cause respiratory irritation. H411: Toxic to aquatic life with long-lasting effects (for certain multifunctional acrylates).
Hazard statements of cross-linking agents for Vinyl diisocyanates organotin compounds.	H220: Extremely flammable gas. H350: May cause cancer. H372: Causes damage to organs through prolonged or repeated exposure.	Hazard statements of cross-linking agents for natural rubber latex (Sulfur-based cross-linkers)	H315: Causes skin irritation H319: Causes serious eye irritation H302: Harmful if swallowed

commonly used in the monomer preparation step to prevent premature polymerization (Table 6).

After polymerization, their residues may partially remain in the polymer material. Purification and treatment processes (such as washing and extraction) are carried out to minimize these residues, but they may be present in small amounts. Comparing the environmental friendliness of obtaining different materials for the manufacture of disposable medical gloves requires the analysis of several key aspects: the use of resources, the impact on the environment during production, biodegradability and recycling possibilities impact (Table 6). As a result of analytical calculations, latex is the most environmentally friendly material of all studied, as it is biodegradable and made from renewable resources, although it can cause allergic reactions and potentially affects biodiversity. Nitrile is less environmentally friendly due to its

synthetic nature, but has advantages in chemical resistance. Vinyl and polyethylene have the worst environmental performance due to long decomposition time and difficulty in disposal. Vinyl gloves use high amounts of plasticizers, while latex and nitrile require vulcanization agents and accelerators. Polyurethane is also not environmentally friendly due to the use of synthetic materials and the difficulty of recycling. Latex gloves have the greatest potential for sustainability if the rubber tree is grown properly, while synthetic materials require new approaches to reduce their environmental impact. Generally, vinyl and polyethylene gloves are the least expensive, making them popular for low-risk, short-term use. Latex and nitrile gloves fall into the mid-range, offering a balance between performance and price. Polyurethane gloves are typically the most expensive due to their more complex manufacturing process and material costs. In

addition to environmental and performance considerations, the economic aspect of glove materials was also analyzed. The cost of disposable gloves varies significantly depending on the material, manufacturing complexity, and intended use. Polyethylene gloves are the most cost-effective option, typically priced at \$2–4 per 100 pieces, but offer minimal protection and are mainly used for food handling. Vinyl gloves are slightly more expensive (\$4–6 per 100 pieces) and are also widely used in the food industry and low-risk environments due to their affordability.

Criteria 2–7: Functional Monomer, Template, Cross-Linking Agent, Porogen/Solvent, Other Reagents/Adjuvants/Carriers, Core/Particle Preparation, and Surface Modification

Evaluating these criteria in the context of rubber gloves highlights the complex nature of their production, where the interplay of monomers, cross-linkers, solvents, and other reagents significantly affects the final properties and sustainability of the product. Nitrile gloves tend to be more environmentally friendly due to better durability and longer use cycles, while latex gloves provide excellent biodegradability. Vinyl gloves, though cost-effective, are less durable and often not eco-friendly due to their synthetic PVC base (Figs. 5, 6 and 7) (Alleged Allergenicity of Latex Gloves 2006).

Criteria 2: Functional monomers

Functional monomers used in the production of nitrile, acrylic and vinyl gloves can have various hazardous properties and have relevant hazard statements, which are determined according to the CLP (Classification, Labeling and Packaging) Regulation in the European Union or similar standards in other countries. For the considered technologies for obtaining gloves from acrylonitrile, this monomer is characterized by the following statements (Fig. 5) (Allergy 2018). These warning phrases are

important for risk assessment during the production and use of polymeric materials. Manufacturers must consider these hazardous properties when handling monomers and follow safety measures to minimize risks to workers and end users.

Criteria 3: Template

When assessing the risk associated with the template components of the polymerization mixture for manufacturing nitrile, acrylic, and vinyl gloves, it is important to consider the key monomers used and their associated hazards. Below are the main components and relevant hazard statements for these types of gloves (Fig. 6) (Kurul et al. 2025; Allergy 2018).

Criteria 4: Cross-linking agents

Cross-linking agents are essential in polymerization to enhance the structural integrity and mechanical properties of the final material (Fig. 7). However, these agents can pose specific health and safety risks. Below is an assessment of common cross-linking agents used in the production of nitrile, acrylic, and vinyl gloves, along with their relevant hazard statements (Adawy et al. 2024; Norhanifah et al. 2024; Herkins and Cornish 2024; Ogawa et al. 2024).

Criteria 5: Porogen/solvent

Porogen solvents are used in the polymerization process to create a porous structure in the final polymer (Liu et al. 2024). While they are essential for achieving the desired properties in nitrile, acrylic, and vinyl gloves, they can present certain risks. Below is an assessment of common porogen solvents and relevant hazard statements associated with their use in glove production (Table 1S). For latex gloves, porogen solvents are not commonly associated as they are more relevant to synthetic polymers like nitrile, acrylic, and vinyl. However, during the production of latex gloves, various chemical additives and coagulants are used, which may pose hazards.

Criteria 6: Other reagents adjuvants or carriers in the component in the polymerization mixture

In the production of nitrile, acrylic, and vinyl gloves, various reagents, adjuvants, and carriers are used alongside the main monomers and cross-linking agents. These substances can include stabilizers, accelerators, plasticizers, surfactants, and other processing aids. Each of these components may present specific hazards, which are identified by hazard statements according to safety regulations (Table 2S). Below

Table 7 Polymerization comparison

Glove type	Polymerization method	Greenness score
Latex	Emulsion polymerization	Moderate (Score: 0.6–1)
Vinyl	Suspension polymerization	Low (Score: 0.3–0.5)
Nitrile	Solution/emulsion polymerization	Moderate to low (Score: 0.5–0.7)

Table 8 Comparison and greenness evaluation

Glove type	Material	Key hazardous solvents/additives	Environmental impact	Greenness score
Latex	Natural rubber	Ammonia, chlorine, formaldehyde	Biodegradable, but toxic additives	Moderate
Nitrile	Synthetic (acrylonitrile + butadiene)	Acrylonitrile, plasticizers, initiators	Non-biodegradable, petroleum-based	Low to moderate
Vinyl	Synthetic (PVC)	Phthalates, stabilizers, plasticizers	Non-biodegradable, hazardous chemicals	Low

is an assessment of common adjuvants or carriers and their associated risks.

Criteria 7: Core particle preparation and surface modification

During the production of nitrile, acrylic, and vinyl gloves, the processes of core particle preparation and surface modification play a significant role in enhancing the properties of the gloves, such as strength, elasticity, and chemical resistance. These processes involve various chemical treatments that may pose certain risks (Table 3S).

Criterion 8: Polymerization Initiation

This criterion is fundamentally different for gloves made of different materials. In the production of gloves, particularly nitrile and vinyl gloves, polymerization initiators are essential for synthesizing the raw materials. These initiators are chemical compounds that start the polymerization process by generating free radicals or other reactive species that trigger the chain reaction for forming long polymer chains. In the case of obtaining vinyl and nitrile gloves as initiation of polymerization uses peroxides like dibenzoyl peroxide and tert-butyl peroxide are used in the free-radical polymerization. Just for vinyl gloves can be used UV Initiators. Ultraviolet (UV) light can activate certain photo initiators to begin the polymerization of PVC, though this is less common for large-scale production of glove materials. Natural rubber latex is collected as a liquid and does not require synthetic polymerization. However, synthetic rubber gloves (e.g., synthetic latex from styrene-butadiene rubber or chloroprene) do involve polymerization steps.)

Criterion 9: The size of the polymer particles

The types of polymerization used to produce latex, vinyl, and nitrile gloves differ based on the material and its specific properties (Table 7).

The assessment of polymer sorbent production methods emphasizes the importance of particle size in determining the "greenness" of the system. In situ polymerization emerges as the most sustainable option, maximizing material use and minimizing waste and exposure risks. Bulk polymerization carries moderate sustainability due to necessary additional steps that generate waste and pose exposure risks. Emulsion polymerization is typically employed for natural rubber latex production. It involves the polymerization of isoprene monomers in an aqueous emulsion, usually initiated by free radical initiators. This process is relatively greener compared to others because it uses a water-based system and does not produce hazardous solvents or emissions. The process can generate waste (e.g., washing, leaching), and chemical additives may be used in the process, which can slightly impact its environmental footprint.

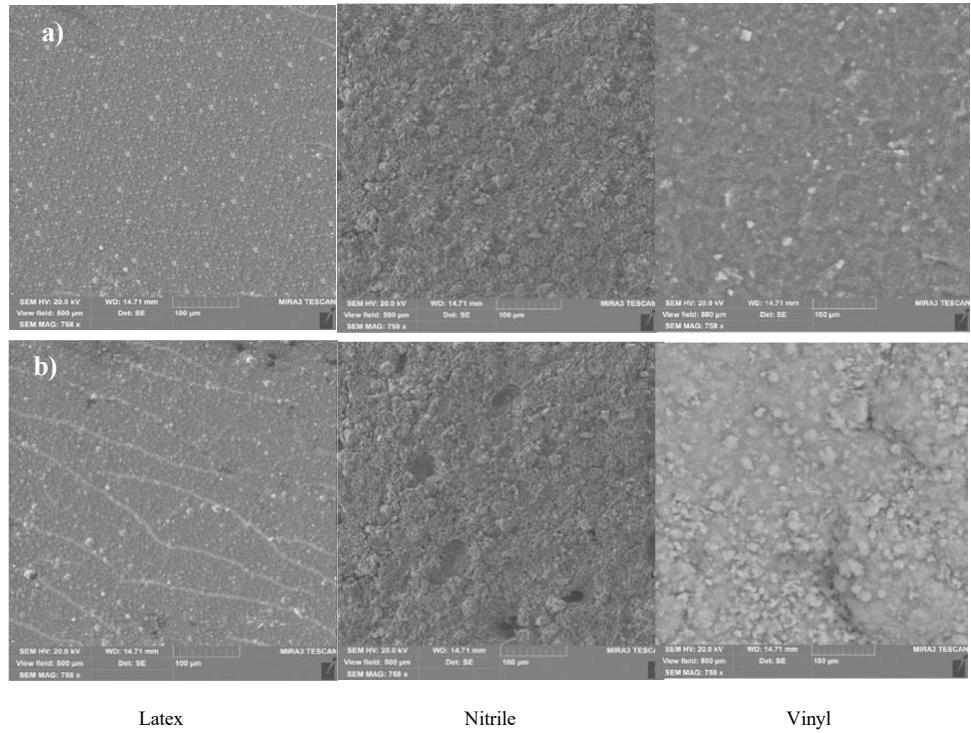
Criterion 10: Template elution solvent

PVC gloves are typically produced via suspension polymerization, where vinyl chloride monomers are polymerized in water using free radical initiators (Luo et al. 2022). The resulting PVC resin is mixed with plasticizers to achieve the desired flexibility (Table 8). However, PVC is non-biodegradable, and plasticizers may be toxic, with the process potentially generating hazardous by-products—leading to a lower environmental rating. Nitrile gloves are made by solution or emulsion polymerization of acrylonitrile and butadiene. Solution polymerization yields more consistent, high-quality material. Although nitrile is also non-biodegradable and its production involves petrochemical-based monomers and solvents, it offers key advantages: greater durability and hypoallergenic properties. Nonetheless, its environmental impact remains a concern.

Table 9 Summarizing the additives used in degradable nitrile gloves

Additive type	Function	Examples
Enzyme-based additives	Break down polymer chains of nitrile, facilitating faster degradation through microbial activity (Phalen et al. 2014)	Lipases, proteases, amylases
Bio-based plasticizers	Improve the flexibility of the material and assist in biodegradation	Plant oils (soybean, castor oil), organic acids
Pro-oxidant additives	Initiate or accelerate the oxidation of the polymer, speeding up degradation under light or heat exposure (Zhao et al. 2023; Aalto-Korte et al. 2006)	Metal salts, such as cobalt salts
UV-activated additives	Enhance degradation of nitrile when exposed to UV light, speeding up biodegradation in outdoor environments (Cunha et al. 2024)	Benzoin or other photodegradable agents
Biodegradable fillers	React with the polymer to create weaker points for faster breakdown (Zhao et al. 2023; Wissen et al. 2025; Luo et al. 2022)	Starch, cellulose, chitosan
Compostable additives	Make the gloves suitable for composting in industrial composting facilities, enhancing degradation (De-la-Torre et al. 2022)	Biodegradable resins, copolymers that mimic natural degradation processes in compost
Antibacterial and antifungal agents (optional)	Prevent bacterial and fungal growth on the gloves during storage and use (Akhtar et al. 2023)	Zinc oxide, silver ions

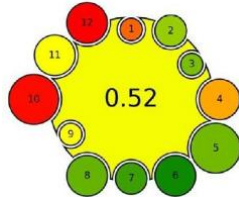
Fig. 8 SEM images for the disposable gloves before (a) and after exposition on model solution after 30 days (b). Model solution Phosphate Buffered Saline (PBS): NaCl (137 mM), KCl (2.7 mM), Na₂HPO₄ (10 mM), KH₂PO₄ (1.8 mM) (pH: 7.4)



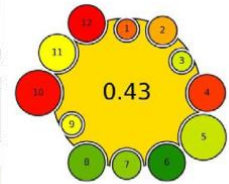
Latex

Vinyl (PVC)

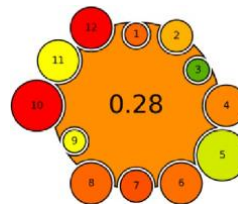
Ecological production	• Latex is obtained from the natural sap of the rubber tree. This process is relatively environmentally friendly, reducing the overall carbon footprint.
Biodegradability	• Latex is biodegradable, making it more environmentally friendly compared to synthetic materials.
Recycling	• Recycling of latex is limited due to contamination from the use of gloves in medical practice, but throwing them into the environment does not create a sustainable plastic.



Ecological production	• The production of vinyl gloves involves the use of polyvinyl chloride, which is accompanied by emissions of harmful substances, such as dioxins, which can have a negative impact on human health and the environment.
Biodegradability	• PVC is not biodegradable and gloves made of this material can remain in the environment for decades.
Recycling	• Vinyl is difficult to recycle, and recycling PVC is energy-intensive and releases toxic compounds.



Ecological production	• Nitrile is made from synthetic polymers, which requires significant energy resources and petroleum products. This increases the carbon footprint compared to latex.
Biodegradability	• Nitrile gloves do not biodegrade, which contributes to their accumulation in the environment.
Recycling	• Recycling is possible but rarely done due to difficulties in collecting and sorting used gloves.



Nitrile

Fig. 9 Results of AGREEMIP assessment of greenness of polymer disposable gloves

Criterion 11: Template elution technique

In the context of rubber gloves production (specifically latex, nitrile, and vinyl gloves), the template elution process mentioned—typically used in molecularly imprinted polymers (MIPs)—does not directly correlate with the production of gloves. However, if we draw parallels to the production of gloves and focus on removal of residues, chemicals, or unwanted substances used during the manufacturing process (such as the removal of chemical accelerators, plasticizers, or additives), the concept of template elution can be evaluated as follows:

In the context of green glove manufacturing: For latex, nitrile, or vinyl gloves, cleaning and removing residual chemicals after production is an important consideration for improving the greenness of the process. Soxhlet extraction is not ideal due to its high energy consumption and solvent waste (Jędruchiewicz et al. 2021; Zhu et al. 2022). Shaking/mixing with solvents could be a more sustainable option compared to Soxhlet extraction, though still not the most efficient. Supercritical fluid extraction (SFE), while a green technique, is too complex and costly for large-scale glove production. The greener approach would likely be ultrasonic or microwave stimulation, which offers a low-energy, low-solvent alternative for cleaning gloves, aligning with the best practices in sustainable production (Norhanifah et al. 2024).

Criterion 12: Final product reusability and degradability of the final polymer product

While single-use remains the prevailing model for rubber gloves—particularly latex, nitrile, and vinyl—resulting in a low reusability score (0) (Table 4S), some gloves used in industrial or repetitive environments may allow limited reuse, especially if designed for enhanced durability and proper cleaning. In such scenarios, a reusability score of 0.5 or 1 may be applied to reflect their sustainability potential. However, this consideration aligns more with a theoretical "what if" scenario rather than a reflection of current widespread practices. Even if glove materials are redesigned for reusability, significant operational and infrastructural challenges remain. Facilities that rely heavily on disposable gloves—such as hospitals, laboratories, and food production sites—often lack the specialized equipment or protocols necessary to safely clean, disinfect, and validate reused gloves. Implementing such systems would require investment in sterilization infrastructure, staff training, and updated regulatory frameworks to manage hygiene and safety risks. These factors must be addressed before the reusability of gloves can be realized on a meaningful scale.

This increased durability is explained by the strong structure of the nitrile polymer, which is less prone to hydrolysis and oxidation, and which as a result will be more harmful to the environment in the long term. In contrast, latex gloves degrade faster, releasing microparticles and additives into the environment, which is more harmful in the short term,

but safer from the point of view of preventing the accumulation of waste in the environment (Cunha et al. 2024; Zhu et al. 2022). Today, the industry is actively exploring biopolymer-based formulations to produce disposable gloves with reduced environmental impact (Fig. 7). Among the most promising are biodegradable nitrile gloves, which maintain the protective properties of conventional nitrile while degrading more rapidly after disposal due to the incorporation of specific additives. These gloves are already commercially available and decompose faster under environmental conditions such as moisture, heat, UV exposure, or microbial activity. In contrast, fully biopolymer-based alternatives such as those made from PHA, PLA, TPS, or PBAT are still at early stages of industrial application (Luo et al. 2022; Yip and Cacioli 2002; Kadhom et al. 2024; Li et al. 2020). The additives used in biodegradable nitrile gloves are summarized in Table 9.

According to Criterion 12 of the AGREEMIP framework (Final Product Reusability and Degradability of the Final Polymer Product), the scanning electron microscopy (SEM) results demonstrated clear signs of degradation in the single-use gloves (Fig. 8) (Luo et al. 2022; Yip and Cacioli 2002; Kadhom et al. 2024; Li et al. 2020; Nambiathodi et al. 2021). SEM analysis was employed to observe the surface morphology and microstructural changes of the polymer samples (e.g., disposable gloves) before and after exposure to the model degradation solution (PBS, pH 7.4). The technique provides high-resolution imaging for assessing surface roughness, crack formation, degradation features, and particle formation. A description of the rationale is presented in the supplementary materials. The results of the assessment of the environmental friendliness of polymer disposable gloves using the AGREEMIP instrument are presented in Fig. 9.

Conclusions

This analysis underscores the critical need to balance functionality and safety with environmental sustainability in the production of disposable medical gloves. The evaluation of various glove types against the AGREEMIP criteria reveals significant environmental concerns linked to their life cycle—from manufacturing to disposal. Nitrile gloves, while offering excellent barrier properties, exhibit low biodegradability and potential for toxic waste generation. Latex gloves, though more biodegradable, pose risks due to allergenic proteins and chemical additives. Our experimental findings support these observations, confirming that both latex and nitrile gloves undergo notable degradation in weakly acidic aqueous environments simulating soil conditions. Microscopic analysis revealed surface cracking in latex gloves and increased roughness and texture

degradation in nitrile gloves. Additionally, latex gloves were shown to release significant amounts of microplastics and some nanoplastics, raising further concerns about their environmental footprint. These results emphasize the urgent need for the development of safer, more sustainable alternatives such as gloves made from biopolymers or produced using green solvents. Advancing manufacturing practices toward eco-friendly technologies will be essential for reducing the environmental and health impacts of disposable gloves in both medical and emergency response contexts.

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Author contributions DP contributed to conceptualization, formal analysis, writing—original draft, and project administration. VV contributed to methodology, software, formal analysis, writing—review and editing, and resources.

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Data availability No datasets were generated or analyzed during the current study.

Data available with the paper or supplementary information The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Declarations

Conflict of interest The authors declare no competing interests.

Informed consent Not applicable.

Ethics approval (include appropriate approvals or waivers) Ethics approval (include appropriate approvals or waivers) Authors agree with ethical standards.

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