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MATERIALS USED FOR PERSONAL PROTECTIVE EQUIPMENT FABRICATION: A SHORT REVIEW

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Abstract: *The evolution of industry today has forced occupational health and safety practices to continuously adapt to the new challenges posed by robots and AI-driven processes. Therefore, there is an ongoing need to develop personal protective equipment (PPE) to meet these challenges effectively. This can be achieved by customizing the design or the materials used in PPE manufacturing. The PPEs are categorized based on their protective function and the specific areas they should protect. This study analyzes the current literature regarding the diverse array of materials used in PPE and their ongoing development, which are crucial for improving comfort and safety. Therefore, PPE has become lighter and more durable, fostering greater adoption and use.*

Keywords: *PPE; new materials; body protection; hand protection; foot protection; head protection.*

1. INTRODUCTION

In the modern industrial context, employees continue to be an irreplaceable component of the work system. Automating work processes and using robots in industry do not eliminate the need for humans, but instead change the work skills that the employees must have [1].

The protection of workers thus becomes vital for the whole process. European regulations provide a strategic and political framework for effectively implementing legislation on safety and health at work. Through the framework directive 89/391/EEC, accompanied by other specific directives, the European Commission is an indispensable instrument helping to improve safety and health at work [2, 3].

However, Eurostat statistics at the European Union level show an increase in non-fatal accidents. Table 1 shows the top 5 EU countries by the number of accidents recorded and the total number of fatal accidents recorded in 2022. As can be seen, the number of accidents at work has increased, with 87,139 more accidents recorded in 2022 than in 2021.

Fatal accidents, numbering 3286, registered a slight decrease in 2022 compared to 2021. It is worth noting that approximately 66% of non-fatal work accidents are suffered by men. This is due to the fields in which they work, with more accidents in heavy industries, mining, construction, or manufacturing [4].

Table 1

Number of non-fatal and fatal accidents at work, 2022, and the top five countries in the EU.

Non-fatal accidents at work involving at least four calendar days of absence from work				Fatal
	Total	**Men**	**Women**	**Total**
EU	2,973,646	1,969,779	1,003,046	3,286
Germany	791,319	582,822	208,211	397
France	622,538	381,528	241,009	775
Spain	497,832	340,327	157,504	411
Italy	330,131	209,908	120,223	469
Portugal	125,607	87,708	37,899	141

Another important aspect is that these accidents affected body parts that could have been protected by Personal Protective Equipment (PPE). Therefore, using adequate and sufficiently performing personal protective equipment could significantly reduce the number of accidents at work.

The worker can wear or handle PPE to provide protection against one or more risks. This PPE is mandatory in workplaces where there is a risk of injury. PPE can be classified according to the type of protection provided, the area it protects, and the level of safety it provides. As can be seen in Figure 1, PPE mainly protects the lower limbs, upper limbs, trunk, head, eyes, and face.

Table 2

Part of the body that is affected by work accidents.

Part of the body	Number
Upper extremities	908,711
Lower extremities	640,665
Back, including the spine and vertebrae	210,209
Head	144,426
Torso and organs	83,660
Whole body and multiple sites	70,909
Part of the body injured (not specified)	52,620
Neck, inclusive spine, and vertebrae	41,069
Other injured parts of the body	14,679
Total	2,166,948

They can also provide better visibility to the worker when PPE is in the form of a reflective vest, or they can provide comfort in work environments with extreme temperatures or inclement weather. In addition, safety harnesses or ropes secure the worker when the risk of falling is high [5].

Fig. 1. Types of personal protective equipment.

The requirements imposed on the materials from which PPE can be manufactured refer to the mechanical and physical properties that they must possess. PPE must withstand and provide protection depending on the environment in which they are used. Thus, the standards of this equipment require durable materials that ensure comfort and are economically feasible.

2. MATERIALS USED FOR BODY PROTECTION

Protective clothing is personal equipment designed to protect workers from chemical, mechanical, biological, or physical hazards. It can also come in various forms, from vests, gowns, overalls, and trousers to aprons used by welders [6].

Recent studies have succeeded in developing new materials that can be used to manufacture PPE. Carbon nanomaterials based on graphene, carbon nanotubes (CNT), or fullerene can be integrated into textiles. These are used due to the properties of carbon to form different allotropes, and materials with exceptional properties can be obtained [7, 8]. Composite materials are often used to manufacture body armor. These materials are used in military, medical, and police applications to protect the torso from ballistic and sharp object impacts [9]. In addition to the protective plates that can be integrated into the protective equipment, the protective clothing must also be durable. The fibers used for today's protective clothing fabrics are diverse, affordable, and performant. Woven materials can integrate aramid fibers to improve thermal protection characteristics [10]. Polyetheretherketone (PEEK) fibers are used to manufacture textile membranes due to the balance between good ventilation, chemical protection, and impermeability [11]. Ultra-high molecular weight polyethylene (UHMWPE) fibers are used for protective clothing due to the thermal comfort offered, breathability, and mechanical resistance [12]. Technical textiles are also used to ensure thermophysiological comfort in extreme temperatures. By combining the arrangement of fibers on different layers of insulating material between two layers of protective textile material, technical textiles can be obtained that can provide effective insulation, durability, and comfort [13]. Long polyester fibers can be used for such materials. These ensure the material returns to its original shape after compression or stretching. Shorter, thicker, treated fibers are added under another layer to ensure water resistance [14, 15]. At the same time, protective clothing can provide a barrier against chemicals. Four main types of materials can provide such protection. A representation of the capabilities of these materials can be seen in Figure 2 [16]. Air-permeable materials comprise an outer fabric treated to repel liquids, an absorbent layer, which can be activated carbon or carbon-filled felt, and a lining to ensure comfort. Semi-permeable materials can be porous or non-porous membranes that allow the diffusion of moisture vapor to provide ventilation.

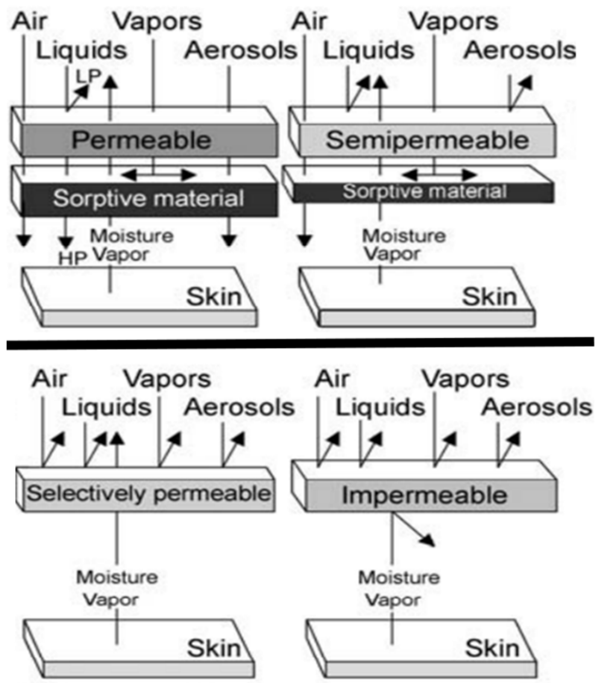

Fig. 2. Types of protective materials [16].

Waterproof materials, usually made of elastomers, provide complete isolation against liquids. Finally, selectively permeable materials (SPMs) combine the properties of waterproof and semi-permeable materials. For the protection of foundry workers, using materials with aluminized basalt fabric has achieved excellent results for radiant heat protection (Figure 3). In the case of protection against molten metal splashes, protective clothing made of aluminized basalt fabric has offered similar results at a lower cost compared to the conventional material usually used, namely aluminized glass fabric [17].

Incorporating nanoparticles, such as silver or zinc oxide, into electrospun nanofibers has allowed the production of textiles with antibacterial and antiviral properties, essential for producing protective clothing. [18].

Other studies have highlighted multifunctional protective clothing for medical use. Graphene modifications of textile materials offer exceptional properties, but low chemical interaction on the textile surface and poor dispersion bring several limitations to the large-scale production of these multifunctional materials [19].

Fig. 3. Anti-heat suit made from aluminized basalt [17].

3. MATERIALS USED FOR HEAD PROTECTION

Even if we are talking about sports activities, outdoor recreation, or work-related tasks, head protection must be ensured [20–22]. There are numerous standards, laws, and recommendations regarding head protection during these activities [23, 24]. A safety helmet provides security against direct hits/mechanical shocks from falling objects, difficult/hard-to-reach working positions, or dangers of slipping, tripping, or falling from a height [25].

The primary role of safety helmets is to prevent concussions or traumatic brain injuries (TBIs) that occur after a harsh blow to the head. They can also provide protection against electrical hazards and molten metal splashes, help the workers stay visible by wearing them, or even maintain their characteristics when exposed to extreme temperatures.

The most essential components of a safety helmet are the outer shell, the shock absorption system, and the inner lining that protects against side impacts, as can be seen in Figure 3 [23, 25].

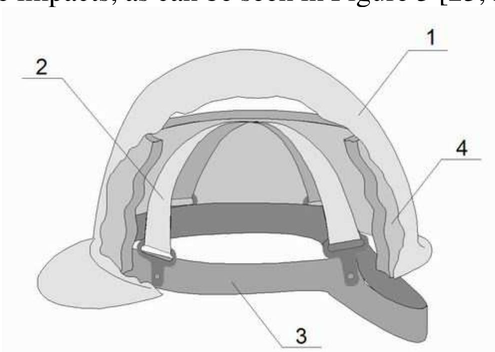

Fig. 3. The components of a high-performance industrial safety helmet: 1- outer shell, 2- headgear, 3- headband (including sweatband), 4- protective liner [25].

Polymers such as “acrylonitrile butadiene styrene (ABS), polycarbonate (PC), high-density polyethylene (HDPE), polyamide 4,6 (PA), or polypropylene (PP) are conventionally used to manufacture the outer shell of safety helmets.” [26, 27]. Polycarbonate is used due to its good impact resistance, transparency, and lightweight. ABS offers good durability and scratch resistance and is easy to process. [28]. HDPE is frequently used to manufacture safety helmets with good durability, good impact resistance, and low weight. [29]. Comparing the mechanical performance of these materials, ABS has excellent impact resistance, but Nylon 4-6 and polycarbonate have better resistance for such applications [30, 31].

To the detriment of plastics, composite materials offer better performance, are environmentally friendly, and can combine the qualities of several materials. By using a composite material with a polymer matrix reinforced with basalt fibers and glass fibers (BF/GFRP), an impact energy absorption of up to 6 times greater than that of polyethylene terephthalate (PET) plastic used to manufacture safety helmets can be achieved. BF/GFRP also has a heat resistance of up to 13 times higher than that of PET [32]. The outer shell of a safety helmet was obtained using the vacuum-assisted resin infusion technique. The material was based on three layers of interwoven carbon fibers, and a thermoplastic resin (ELIUM® 150) was used as a mold. After mechanical tests, the composite material obtained better results than the polycarbonate safety helmet shell [33].

Table 3 presents conventional and composite materials used to manufacture safety helmets. S-Glass reinforced epoxy composites achieved better stress absorption results than ABS and PP in simulations performed in SolidWorks [34].

Carbon fiber reinforced composites (CFRP) perform up to 6 times better than ABS in shock absorption tests. Therefore, using cross-ply reinforcement in composites helps achieve much better shock absorption and interlaminar shear strength. Thus, by using layers of carbon fiber crossed with p-aramid fibers (Kevlar) in the composite material (CF/AFRP), a material is obtained that can successfully replace ABS helmets. CF/AFRP is highly expensive but has much better mechanical properties and resists much higher temperatures than conventionally used materials. Last but not least, by adding granite particles and natural fibers from cotton stalk to the composite material, “the test results of dynamic mechanical analysis (DMA) and thermogravimetric analysis (TGA) showed an improvement in stability” [35–37].

Table 3

The primary materials used to manufacture the shell of safety helmets.

Type	Material	Advantages	Disadvantages	Ref.
PLASTIC	PC	Lightweight. Transparency	Affected by UV exposure	[28]
	ABS	Durability. Impact resistance. Easy to process.	Poor performance at high temperatures	[38]

Type	Material	Advantages	Disadvantages	Ref.
	HDPE	Excellent chemical resistance. Low cost.	Sensitivity to high temperatures	[32]
COMPOSITE	GFRER	High mechanical and thermal resistance. Dimensional stability.	Poor mechanical strength compared to other composites	[34]
	CFRP	Excellent tensile strength. Stiffness.	High cost. Susceptible to delamination.	[36]
	KFRP	Excellent impact resistance. Lightweight. Abrasion resistance	Difficulties in the recycling process. High cost	[37]

In general, research has shown that natural and synthetic fibers can be successfully used in thermoplastic or thermoset matrices to create composite materials with exceptional properties that can be used in a wide range of applications, including safety helmet shells.

4. MATERIALS USED FOR FOOT PROTECTION

Another category of equipment needed to ensure worker’s safety is safety footwear. Safety footwear provides safety to the wearer's feet and ankles. They provide security against contact with sharp objects, stability on slippery surfaces, and even toe protection if objects fall on the worker's foot. [39, 40]. Protective footwear can also provide electrical or foot-transmitted vibration (FTV) protection. This latter risk category can cause toe symptoms and lead to cold-induced vasospastic diseases [41]. Therefore, protective footwear must have characteristics related to other risk categories, not just mechanical ones that can cause trauma or wounds. Structurally, protective boots are generally composed of a sole made of a resistant material that contains an insert that does not allow sharp objects to pass through it and withstand high temperatures. The upper part is made of materials resistant to wear and tear or contact with hot bodies (sparks or molten metal splashes).

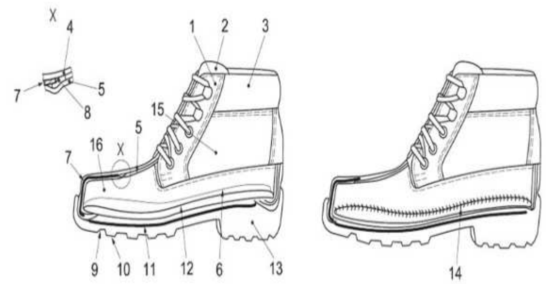

Fig. 4. Elements components of the footwear: 1-facing, 2-tongue, 3-collar, 4-upper, 5-vamp lining, 6-insock, 7-toecap, 8-edge covering, 9-outsole, 10-cleat, 11-penetration-resistant insert, 12-insole, 13-heel, 14-Strobel stitching, 15-quarter, 16-vamp [42].

Usually, natural leather is used, and in the top area, there is a protective toe cap to protect the extremities. Some safety shoes have an integrated plate or can additionally have a plate to protect the metatarsal bones of the foot. All component elements complying with European standards can be seen in Figure 4 [42].

To improve the grip on icy surfaces, studies have shown promising results with composite materials based on rubber and glass fibers. This grip is attributed to the stiffness of the glass fibers. The authors aimed to improve the grip of ski boots, but highlighted that the material and method can also be used for other types of boots [43].

The outer material of safety boots is usually made of natural leather. Natural leather is hydrophobic, flame retardant, abrasion resistant, and waterproof. Technical fabrics such as Gore-Tex© and eVent© are good alternatives for the outer shell of safety boots. These fabrics are made of expanded polytetrafluoroethylene (EPT), which is durable and waterproof while providing good ventilation. [44, 45]. Polyamide fabrics, under the trade name Cordura®, are also used for protective footwear. Initially used in the military, these fabrics also have applications for protective footwear for farmers. Cordura® material is lightweight, waterproof, and has a high resistance to wear [46]. Laminated textile fabrics, Sympatex®, can be used as membranes to provide waterproofing, good ventilation, and comfort when used for protective footwear. In Figure 5, an example of Sympatex® membranes and their main properties is provided [47].

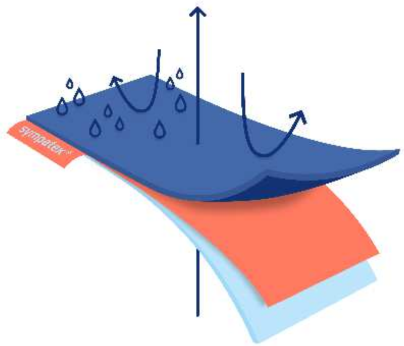

Fig. 5. Sympatex® laminated fabrics, the inner lining absorbs moisture from the foot and evaporates, and the outer waterproof lining [47].

For the protective tip, shapes made of steel, aluminum, composite materials with glass fibers, carbon, or even Kevlar are used [48, 49]. Typically integrated inside safety boots, the toe cap can be designed to be detachable from safety footwear.

Composite materials reinforced with layers of E-Glass, carbon, and aramid fabrics in different configurations can be used to manufacture the toe cap, which can be detached. This material reduces the mass of the safety boots, offers the possibility of mounting and dismounting on the footwear, is resistant to corrosion, and does not conduct electricity. In addition, the use of these types of materials reduces the transfer of extreme temperatures to the worker's foot, whereas a metal toe cap would not be able to do this [50].

Protective footwear is a set of well-defined parts with a well-defined role that can have different characteristics depending on the environment in which they are used and the risks present.

5. MATERIALS USED FOR HANDS PROTECTION

Hand protection is mandatory and must be provided when employees are exposed to workplace hazards such as cuts, severe abrasions, stings, cutaneous absorption of harmful substances, chemical or thermal burns, vibrations, or even electrical hazards [51, 52].

Dexterity, mobility, and thermal comfort are crucial when choosing the right type of protective gloves. Also, some equipment used generates vibrations that can harm the body, and the use of protective gloves can reduce this danger [53]. Polyester and cotton para-aramid fiber fabrics have good permeability and cut resistance performance. The layer in contact with the skin of the hand can create discomfort, as observed when testing the material with para-aramid fiber fabric woven with polyester fibers with cross-section. In contrast, the use of channel polyester fibers provides increased comfort and knitting with para-aramid outer fibers provides cut resistance [54]. Protective gloves for handling cold objects use various materials that combine synthetic and natural fibers. Fabrics based on polyester and elastomer fibers provide comfort and flexibility, and the addition of natural wool offers thermal insulation. Fibers made of polyurethane, polyester, or polyacrylonitrile are used to achieve good moisture resistance and durability [55, 56]. Conventional fighter pilot gloves can cause the pilot's palm to lose grip due to perspiration. Protex® modacrylic fibers and Lenzing® cellulose fibers, with a blend composition in the knitted fabric of 70% Protex® and 30% Lenzing®, provide high thermophysiological comfort. The material provides good air permeability, flame resistance and reasonable control of indoor humidity [57].

Other studies have shown that ideal materials for protective gloves resistant to oils and chemicals can be obtained by improving the matrix of nitrile butadiene rubber (NBR) with cellulose nanocrystals (NCC). The addition of NCC brings a series of chemical, thermal, and mechanical resistance benefits. In terms of material sustainability, NCC is biodegradable; it is derived from natural and renewable sources and becomes a good alternative to synthetic additives [58, 59]. SuperFabric® materials are becoming a perfect choice for protection against punctures. They are composed of ceramic-polymer plates superimposed on different layers embedded on the outer surface of the protective glove, as can be seen in Figure 6 [60, 61].

Also, functionalized polymer coatings deposited on textile fabrics made of aramid fibers improve the cut resistance of the material. The acrylic-styrene-based polymer paste was doped with particles of different sizes.

Fig. 6. Puncture-resistant SuperFabric® material [61].

The best results were observed when Al_2O_3, SiO_2, CaO, SiO and SiC particles were used in the polymer paste. In addition, it was found that the particle sizes influence the microstructure of the polymer paste. Finally, it was observed that smaller additive particles penetrate more easily into the fibers of the supporting textile, thus achieving better adhesion to the layer and high mechanical resistance of the gloves [62].

The variety of materials that can be used to manufacture protective gloves is beneficial for the safety of workers' hands. Combining natural and synthetic fibers in polymer matrices produces good mechanical, thermal and structural properties.

5. CONCLUSION

With industry development, using the latest technologies and high-performance materials to manufacture personal protective equipment is imperative. Personal protective equipment has the purpose, by definition, of ensuring the protection of the wearer against risks. They are divided into several categories depending on their role and the area they must protect. Although a variety of materials are conventionally used to manufacture PPE, the need for innovation in this area remains essential. The use of aluminized basalt fibers to manufacture thermal protective clothing is highlighted, and polyetheretherketone (PEEK) fibers used to manufacture textile membranes offer good ventilation, chemical protection, and impermeability.

For head protection, composite materials reinforced with carbon and aramid fibers stand out against all conventional materials used to manufacture protective helmets.

Technical fabrics such as Gore-Tex©, eVent©, or Sympatex® can be used as membranes to provide waterproofing, good ventilation, and comfort for protective footwear.

Materials that can replace synthetic substances are increasingly used to manufacture chemical-resistant protective gloves. The use of cellulose nanocrystals as a replacement for synthetic additives in manufacturing nitrile butadiene rubber gloves. Also, textile fabrics coated with functionalized polymer deposits provide mechanical resistance to protective gloves.

Therefore, the variety of materials used for PPE and their continuous development are essential to ensure comfort and, most importantly, safety. Through their constant development, PPE has become lighter and more durable, encouraging its use.

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Materialele utilizate pentru fabricarea echipamentelor individuale de protecție: scurt review

Evoluția industriei a forțat domeniul sănătății și securității în muncă să se adapteze continuu la noile provocări reprezentate de roboți și de procesele bazate pe inteligența artificială. Prin urmare, există o nevoie continuă de a dezvolta echipamente individuale de protecție (EIP) pentru a face față acestor provocări în mod eficient. Acest lucru poate fi realizat prin personalizarea designului sau a materialelor utilizate în fabricarea acestora. EIP-urile sunt clasificate în funcție de rolul lor de protecție și de zonele specifice pe care trebuie să le protejeze. Acest studiu analizează literatura de specialitate cu privire la diversitatea de materiale utilizate în fabricarea EIP-urilor, îmbunătățirea confortului și a siguranței, precum și dezvoltarea continua a echipamentelor individuale de protecție. Prin urmare, EIP-urile au devenit mai ușoare și mai durabile, favorizând adoptarea și utilizarea acestora.

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