Humanitarian Mine Clearance with the Involvement of African Giant Pouched Rats: Methods, Challenges and Future Directions[1]

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Abstract:

This study provides a comprehensive overview of humanitarian mine clearance, with particular emphasis on the use of African giant pouched rats (Cricetomys ansorgei) as an innovative biological detection tool. The analysis examines the historical development of anti-personnel landmine technology, the international legal framework governing mine action, and the full range of current clearance methods, including mechanical systems, technological innovations, detection dogs, and biological approaches. Drawing on published field data, organizational reports, and semi-structured interviews with humanitarian demining professionals, the study evaluates the comparative advantages and limitations of each method. Findings indicate that African giant pouched rats offer significant operational benefits in terms of cost-effectiveness, olfactory sensitivity, and safety, while also presenting specific challenges related to training investment, cultural acceptance, and environmental conditions. The study argues that the future of humanitarian mine clearance lies in biosensor-hybrid systems that integrate biological detection tools with AI-supported robotic platforms and advanced sensor technologies. Enhanced international cooperation, sustained investment in research, and genuine community engagement are identified as essential conditions for achieving a landmine-free world.

Keywords:
Humanitarian Demining; African Giant Pouched Rats; APOPO; Biological Detection; Landmine Clearance; Biosensor-Hybrid Systems.

[1] DOI: 10.12700/jceeas.2026.6.3.551

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1. Introduction

The development of anti-personnel landmines represents one of the less conspicuous yet highly effective chapters of 20th-century military technology. The defining characteristics of these weapons are their stealth and unpredictability, making them equally suitable for hindering enemy movement, controlling territory, and applying sustained psychological pressure (Croll, 2009). While low-tech anti-tank mines were already used in the First World War, the Second World War saw the widespread deployment of pressure-activated anti-personnel mines and fragmentation mines. These devices could be produced rapidly and in large quantities, required no complex technical infrastructure for deployment, yet remained lethal for long periods with minimal human intervention. The purpose of minefields placed on battlefields was to slow down or distract enemy troops while remaining active for extended periods (U.S. Department of State, 1993).

After the Second World War, increasing attention was directed to areas where these munitions persisted despite the end of hostilities. Mined zones often prevented the resumption of agricultural activities, the construction of infrastructure, and caused serious long-term social, economic, and psychological consequences for local communities (Béres, 1992). In the post-war period, anti-personnel landmine technology underwent significant transformation: metal-cased models were gradually replaced by plastic-based variants designed to defeat detection by conventional metal detectors. Additional developments allowed for multi-phase operation, including delayed detonation and chain-reaction triggering mechanisms (Veremejev, 2008).

During the Cold War, minefields became central elements of deterrence and territorial protection strategies. In Hungary, technical military units played a significant role in the installation and registration of mines, primarily in border areas during the construction of Cold War border barriers. Military documentation and technical studies of the era describe in detail the installation procedures, operating principles, and standards applied at the time (Béres, 1992).

By the 1980s, mines covered thousands of hectares of land worldwide, the majority remaining active long after the end of conflicts. The problem was compounded by the fact that in many cases no records were kept of the locations of deployed minefields, making clearance not only costly but extremely dangerous. This trend, while technologically efficient from a military perspective, concealed serious humanitarian risks that later became the decisive impetus for the launch of international mine clearance programmes.

The aim of this paper is to provide a comprehensive overview of the current practice of humanitarian mine clearance, in addition to reviewing the historical development and tactical role of landmines. It pays particular attention to evaluating the applicability of biologically based detection technologies, especially the use of African giant pouched rats, and to examining the effectiveness of international cooperation and regulatory systems. The research also aims to explore the practical experiences of international clearance programmes through interview-based qualitative methods, and to identify the

technological, ethical, and logistical challenges that clearance organizations face in the field.

The ultimate goal of the study is therefore twofold: to explore the theoretical and technological background of humanitarian mine clearance, and to formulate practical recommendations for future developments and decision-making strategies in this specialized field.

2. International and Domestic (European) Aspects of Landmines

The use of landmines is not only a tactical military issue but carries significant international legal, humanitarian, and political dimensions, documented in detail by the International Mine Ban Treaty (Ottawa Convention, 1997) and humanitarian organizations including the United Nations Mine Action Service (UNMAS). The long-term effects of landmines on civilian populations and post-conflict reconstruction sparked serious international debates, gradually leading to the emergence of regulatory efforts and the development of a comprehensive framework for mine action. The aim of the international conventions was to create a unified global framework for the reduction of landmine use and the elimination of existing devices, integrating legal prohibition with financial and technical assistance to affected states (Pádányi, 2002).

These efforts sought solutions to the threat posed by landmines, which remain a critical problem in all regions of the world affected by armed conflict. In Europe, following the hostilities in the South Slavic region, underground explosive devices were and remain a serious problem in the countries of the former Yugoslavia, from both a humanitarian and an economic perspective (Pádányi, 2002). At the same time, countries such as Hungary also have relevant experience in clearing minefields, primarily from border protection practices during the Cold War era. In the following sections, we review the impact of international legal regulations and the demining experiences and challenges of European countries.

2.1 Effects of International Treaties and Bans

The use of landmines became an object of growing international concern in the second half of the 20th century due to its long-term consequences for the civilian population. During the Cold War and in the subsequent local conflicts in Afghanistan, Angola, and Cambodia, millions of anti-personnel mines were laid, which continue to endanger civilian populations and hinder socio-economic reconstruction (U.S. Department of State, 1993). In parallel, international political and legal initiatives emerged to limit the production, distribution, and use of anti-personnel mines, or to achieve a complete global ban.

The first significant professional and civil cooperation in this area developed at the turn of the 1980s and 1990s, culminating in the Ottawa Convention adopted in 1997 (Tóth et al., 2012). The treaty, officially titled the Convention on the Prohibition of the Use, Production, Stockpiling and Transfer of Anti-Personnel Mines and on their Destruction, represents a landmark achievement in international humanitarian law. It

obliges signatory states to destroy their stockpiles, clear mined areas within ten years, and assist survivors of mine incidents. Although the treaty has been ratified by more than 160 countries, some major military powers, including the United States, Russia, and China, have not acceded to it, which remains a significant challenge to the achievement of a comprehensive global ban (Croll, 2009).

International treaties not only provide a legal framework but also facilitate political and financial support for mine action operations. The Ottawa Convention stimulated cooperation between civil and military organizations and prompted the creation of new financing instruments, including multilateral aid funds and development assistance programmes dedicated to sustaining mine action operations (Lukács, 2002). These normative frameworks also set implicit expectations for the humanitarian regulation of techniques and means used in warfare, transforming military thinking on the ethics of deploying weapons with long-lasting indiscriminate effects (Pádányi, 1999a).

2.2 Experiences and Challenges of European Countries

In Europe, the Balkans suffered particularly severe landmine contamination during the ethnic and political conflicts of the 1990s. Millions of mines were laid during the Bosnian War and during the armed conflicts in Croatia and Kosovo. As a result, approximately 2 million mines remained in the ground in Bosnia-Herzegovina after the war, covering an area of more than 1,800 square kilometres and creating serious humanitarian, economic, and ecological consequences (Pádányi, 2002; Lukács, 1999).

The areas blocked by landmines prevented the resumption of agricultural production, the construction of transport infrastructure, and the reconstruction of homes for many years after the end of hostilities. Awareness of the danger permeated the daily lives of local populations, while the process of post-war economic recovery was significantly slowed. The situation was particularly critical in rural, sparsely populated regions where the resources and technical means necessary for relief were not fully available (Pádányi, 2002; Lukács, 1999).

Countries in the region launched mine clearance programmes in several phases with substantial international support. The European Union, the United Nations, and many civil society organizations and national armed forces became involved in clearance operations, but progress was slow and costly due to documentation gaps, inaccurate or incomplete minefield maps created during the conflict, and heterogeneous geographical conditions. The lack of reliable minefield records forced demining organizations to rely heavily on area surveys, increasing both the time and cost of operations (Pádányi, 2002; Lukács, 1999).

Hungary's situation is distinct. Although the country did not experience armed conflict of the intensity that would have resulted in widespread civilian minefields, technical barriers and minefields were installed on the southern and western border sections during the Cold War period, especially in the 1960s to 1980s. The purpose of these was to prevent border violations and to deter unauthorized movements. After the democratic transition, the Hungarian Armed Forces and technical units undertook

significant work in clearing these minefields. The systematization of technical documentation, the recording of decontamination procedures, and the development of safety protocols played an important role in developing domestic clearance capacities and modernizing military logistics.

European examples clearly demonstrate that mine clearance is not only a technical task but also a complex social and political challenge. Differences in national practices regarding regulation, institutional cooperation, and financing models can hinder coherent regional approaches. This is particularly evident in areas where clearance must be carried out across borders and where coordination between different actors is crucial. Strengthening knowledge sharing, technology transfer, and joint strategic planning between European countries remains essential for the future of humanitarian mine clearance.

3. The Process of Mine Clearance: Possibilities and Methods

Mine detection and clearance is one of the greatest challenges in both combat engineering and humanitarian operations. In a combat context, attacking forces typically only open narrow passages through enemy minefields, with the primary objective being speed rather than completeness. Anti-tank minefields are the main focus, and passages as narrow as 4-6 metres are considered sufficient for tactical purposes. In humanitarian contexts, however, the objective is fundamentally different: the complete, verified removal of all explosive hazards from a defined area, to a standard that makes the land safe for unrestricted civilian use. The United Nations requires demining organizations to achieve an effectiveness rate of 99.6%, meaning that out of every 1,000 mines laid, 996 must be found and removed (GICHD, 2010).

After fighting ends, minefields remain, and a far more complicated, lengthy, and expensive process must follow: returning mined areas to safe civilian use. The process is complex because the type, location, material composition, and the weather conditions affecting mines all influence the success of detection and removal. Approximately 75% of the mines left behind in post-conflict areas are anti-personnel mines, whose clearance and neutralization presents the greatest challenge for demining professionals. A particular difficulty is that warring parties rarely maintain accurate records of minefields they have laid, despite international regulations requiring them to do so, forcing demining organizations to conduct area surveys before clearance can begin (GICHD, 2010; GICHD, 2004).

3.1 Mechanical Demining

Mechanical demining equipment aims to destroy or neutralize explosive devices planted on or below the ground using high-powered machinery. The advantages of these methods are speed and relatively efficient inspection of large areas, but serious limitations arise from terrain conditions, the diversity of mine types, and the fact that not all equipment is capable of detecting deep-lying or low-pressure-sensitivity structures (GICHD, 2010).

The most commonly used mechanical tools include rotary hammers mounted on tracked vehicles, mine-trampling rollers, mine-turning ploughs, and soil cutters that detonate or push mines aside through mechanical impact (Tóth et al., 2012). According to the GICHD's comprehensive equipment catalogue, more than 130 types of mechanical demining system were in use globally as of 2010, with equipment capable of clearing several hectares per day in favourable conditions (GICHD, 2010). The Croatian-made MV-4 and MV-10 vehicles, for example, have demonstrated high effectiveness in the rapid primary clearance of minefields and have been deployed in over 30 countries (GICHD, 2004).

However, the use of mechanical equipment is not without significant challenges. The heavy weight and large size of vehicles severely limits their applicability in forested, rocky, steep, or urban environments, where mobility is reduced and equipment may be unable to operate safely. Furthermore, mechanical systems do not always detect or activate deep-seated, low-pressure, or plastic-coated mines, which can remain hidden after a mechanical pass (GICHD, 2010).

The operational costs of mechanical demining systems are also substantial. Purchase prices, maintenance requirements, fuel costs, and the training and protection of operating personnel all demand significant resources. This is particularly challenging in post-conflict areas where economic and technical infrastructure has been weakened and external support may be inconsistent (GICHD, 2004). Nevertheless, mechanical clearance plays a key role in modern humanitarian demining, particularly for accelerating operations, conducting primary area surveys, and establishing initial safety zones. It is most effective when combined with complementary methods, such as hand-held metal detectors or biological sensors, to achieve the required level of thoroughness.

3.2 Technological Innovations

In addition to traditional mechanical solutions, modern technological developments are gaining increasing emphasis in the detection and clearance of mined areas. These include solutions supported by drones, remotely operated ground robots, and advanced sensor systems that can reduce direct human risk while increasing the speed and accuracy of operations (Army Recognition, 2023a; Army Recognition, 2023b).

3.2.1 Application of Drones and Robotic Technology

Technological developments over the past decade have produced significant breakthroughs in mine clearance methodology. Remotely controlled and autonomous systems, including unmanned aerial vehicles (UAVs), ground robots, and multi-sensor platforms, have made it possible to map hazardous areas and in some cases intervene directly without endangering human operators. These developments have become particularly important in the context of Ukraine, where the scale of mine contamination following recent conflicts requires rapid and safe clearance operations (Army Recognition, 2023a).

The Danish-developed NOA Acecor and the Estonian-made Dok-Ing MV-4 systems operate with modern multi-channel sensor equipment, integrating ground-penetrating radar (GPR), multispectral camera systems, and infrared sensors to identify underground anomalies, including both metallic and non-metallic explosive devices (Army Recognition, 2023b). Software-supported image processing enables estimation of the shape, depth, and potential risk level of detected objects, substantially reducing the number of false alarms (Army Recognition, 2023c).

A prominent example is the Swiss-developed DIGGER D-250, one of the most advanced tools in current humanitarian mine clearance. The D-250 is a tracked, partially autonomous robot specifically designed for the safe, high-precision clearance of mined areas. It operates with an autonomous navigation system, scanning designated zones based on pre-programmed patterns while transmitting real-time data to the control centre. Its solid track design provides stability across diverse terrain, while its robust mechanical plough and rotor flail system effectively neutralizes landmine detonators by stirring and crushing the upper soil layer. The D-250 is capable of continuous operation even in extreme conditions, including dense vegetation, rocky terrain, and muddy surfaces (Army Recognition, 2023c; DIGGER DTR, n.d.).

The use of the DIGGER D-250 significantly reduces direct human risk, as operators control the machine from a safe distance using radio remote control. This reduces both accident risk and long-term labour costs, since fewer field personnel are required for clearance processes. Newer-generation drone platforms additionally employ artificial intelligence-based image processing algorithms that automatically recognize and categorize potentially dangerous objects on the basis of previously recorded sensory and visual data patterns. This capability is particularly valuable in areas with dense vegetation or variable terrain where traditional detection technologies are less reliable (Lukács, 2003).

It is important to note, however, that even the most advanced systems cannot detect all types of landmines. Plastic-coated, low-profile, or heavily corroded devices present particular challenges. This is why technological systems are consistently combined with other approaches, including biological sensors, detection dogs, hand-held metal detectors, and manual prodding, to achieve the safety standards required by international humanitarian demining protocols.

3.2.2 Other Technological Methods

The continuous expansion of the technological arsenal enables the modernization of mine clearance procedures. New solutions emerging from research and development aim to be applicable in environments where traditional tools have limited effectiveness. These include various sensor-based detection techniques that can detect not only the physical presence of explosive devices but also their material-chemical or thermodynamic effects (Lukács, 2003).

Thermal imaging methods, which analyze small temperature changes in the ground surface caused by the thermal effects of air movement over buried mines or differences

in soil structure, are currently in an experimental stage. Neutron scanning, which detects the presence of nitrogen-rich explosive compounds such as TNT or RDX by analyzing their chemical composition, can distinguish between natural materials and dangerous explosives even in the absence of metal content (Lukács, 2003). Microwave spectroscopy offers another promising approach, analyzing the electromagnetic response of materials across different frequency ranges to identify explosive devices based on specific signal patterns, even from several layers underground, without requiring physical contact with the hazardous area (Lukács, 2003).

These developments remain primarily in the research and development phase, but several EU and NATO framework programmes are actively investigating their field applicability, particularly in areas where traditional detection techniques perform unreliably. Hungarian technical research groups are also making significant progress, developing machine learning-based algorithms and statistical anomaly detection systems capable of highly accurate identification of explosive devices. In the long term, such systems could enable the progressive automation of manual demining activities, especially in areas where human resources or field logistics are limited (György et al., 2010).

4. Humanitarian Mine Clearance

Landmines and explosive remnants of war pose a significant and enduring risk to civilian populations: mines do not distinguish between soldiers and civilians, and children, farmers, and ordinary people regularly fall victim to them long after the end of armed conflict. The international community has therefore devoted increasing attention to humanitarian mine clearance, which not only serves to avert the direct consequences of hostilities but also aims to protect human life, restore habitability and agricultural land, and promote the socio-economic reintegration of affected regions (GICHD, 2005).

The humanitarian approach differs fundamentally from military mine clearance in several respects. The priority is not the achievement of tactical objectives but the restoration of civilian infrastructure, the reopening of schools and hospitals, and the safe resumption of community life. Precision techniques, animal-assisted detection methods, and the active involvement of local communities accordingly receive particular emphasis in humanitarian mine clearance operations.

4.1 The Concept and Significance of Humanitarian Demining

Humanitarian mine action is a formally defined activity in international law and policy, encompassing the removal of landmines, unexploded ordnance (UXO), and other explosive remnants of war in order to improve the quality of life and security of affected populations. Within the framework of mine action programmes, area survey, technical reconnaissance, clearance, and mine risk education form an integrated operational system (GICHD, 2005).

The United Nations Mine Action Service (UNMAS) defines humanitarian mine action as 'one of the most direct ways of reducing human suffering in war zones,' highlighting that mine clearance not only restores physical security but also enables the recovery of social cohesion: allowing schools, hospitals, and community facilities to reopen, and agricultural and transport infrastructure to be used again (GICHD, 2018). According to a 2018 GICHD cost-benefit analysis, successful clearance operations promote economic stability, food security, and reduce migration pressure, particularly in areas marked by severe social instability and infrastructure deficiencies following war (UNMAS, 2021).

Hungarian literature emphasizes that the success of humanitarian mine clearance does not depend solely on technical means. Involving, sensitizing, and educating civilian populations is crucial, especially in cases where complete clearance can only be achieved over a prolonged period. School programmes, community information campaigns, and awareness-raising activities actively contribute to reducing civilian casualties while simultaneously strengthening community participation in the clearance process (Tóth et al., 2012).

The importance of humanitarian demining is particularly acute in regions such as Africa, the Middle East, and the Western Balkans, where conflict-related mined areas cover thousands of hectares and where populations must live with these hazards for years or even decades after the end of hostilities. The following sections focus on biological demining methods, which offer sustainable, cost-effective, and low-impact solutions, especially where the application of conventional technical systems is impractical.

4.2 Biological Methods in Mine Detection

One of the most innovative and effective areas of humanitarian mine clearance is the use of biological methods. These approaches exploit the natural sensory capabilities and learning abilities of animals, primarily dogs and rodents, to detect the chemical signatures of explosive compounds in soil. The biological approach is environmentally friendly, relatively low-cost, and in many contexts faster than mechanical or instrumental detection methods.

4.2.1 Explosive Detection Dogs

Dogs have assisted humans in security operations for centuries, and their effectiveness in explosive detection is comprehensively documented. Thanks to their extraordinary olfactory sensitivity, they can identify minute quantities of TNT or other explosive compounds in soil, even at considerable depth. Properly trained search dogs can be deployed effectively in diverse environments, including urban ruins, agricultural fields, and forested or difficult-to-access terrain (Horváth, 2018).

The training of explosive detection dogs typically takes 6-9 months, during which animals are conditioned to odour patterns in various environmental settings. The total cost of training one dog, including selection, training, medical care, and handler training, ranges from 20,000 to 30,000 USD (GICHD, 2003). According to Hungarian-language

sources, airport and military dogs can also be adapted for mine clearance purposes if they receive specific training in handling the relevant odour patterns, filtering out environmental distractors such as oil derivatives, scrap metal, or organic matter, and working in the specific conditions of post-conflict agricultural and industrial areas (UNMAS, 2021).

Genetic selection, including the targeted breeding of search dogs to optimize olfactory sensitivity, endurance, and cooperation skills, is receiving growing attention in international programmes. Belgian Shepherd, Labrador Retriever, and German Shepherd breeds have proven particularly successful. The GICHD has published dedicated research concluding that combinations of dogs with technical equipment produce the best results in field operations: dogs do not react to irrelevant metal objects, generating fewer false alarms than metal detectors alone, and can be rapidly repositioned across complex terrain. Several international programmes, including those in Afghanistan, Colombia, and South Sudan, have successfully used dogs for combined detection tasks, addressing not only landmines but also improvised explosive devices and other unexploded ordnance (GICHD, 2003; GICHD, 2001).

4.2.2 Application of African Giant Pouched Rats

One of the most unusual yet increasingly recognized tools in humanitarian mine clearance is the use of African giant pouched rats (Cricetomys ansorgei). These animals possess an exceptional olfactory system, and their light body weight of approximately 1-1.5 kilograms means that they cannot detonate pressure-triggered mines as they walk, making them uniquely suited for operational mine detection without risk of self-destruction (Mueller, 2002a; Verhagen et al., 2003).

The first systematic experiments began in Tanzania in the early 2000s, led by the Belgian non-profit organization APOPO (Anti-Personnel Landmines Detection Product Development). The programme's central objective was to identify an animal that was simultaneously light enough to avoid detonating mines and sufficiently trainable to detect explosive compounds reliably. Giant rats proved to be the ideal candidates, combining low body weight with strong learning capacity and excellent olfactory sensitivity (APOPO, n.d.; Verhagen et al., 2003).

Rats are trained using operant conditioning, similar to methods used for detection dogs, receiving positive reinforcement in the form of food rewards when they correctly indicate the presence of TNT (Poling et al., 2010). The entire training process takes approximately 9 months, including laboratory conditioning, field training, and adaptation to diverse environmental distractors. The cost of training one rat, including veterinary care, food, equipment, and trainer fees, is approximately 7,300-8,000 USD, substantially lower than the equivalent cost for dogs (Vandermeulen & Weetjens, 2017).

Artificial intelligence has recently been integrated into the demining activities of giant rats. Machine learning algorithms are used in the training process to optimize assessment of animal behaviour, automatically recording and analysing performance indicators. During field operations, the movements of sensor-equipped rats are tracked in real time

by drones or ground robots, which use AI-based image processing to identify behavioural patterns and help validate mine detection events. These technologies increase operational efficiency, reduce false alarm rates, and optimize the planning and deployment of rat teams. Pilot projects are currently developing AI solutions that predictably model rat behaviour, anticipate potential errors or fatigue-related performance declines, and thereby further improve the reliability of biological detection (Poling et al., 2010).

In the field, the performance of well-trained giant rats is remarkable. A single animal can search up to 200 square metres per day, many times the average capacity of a human deminer using a hand-held metal detector. Field experience demonstrates an extremely low false alarm rate and outstanding working speed. The sustainability and logistical advantages are equally significant: the cost of maintaining giant rats is 70-80% lower than that of detection dogs. They require no complicated transport, refrigerated storage, electricity, or fuel, are highly tolerant of tropical heat and humidity, and are well-suited for deployment in mined areas where infrastructure is absent and physical access is difficult (APOPO, n.d.).

APOPO has successfully deployed giant rats on several continents, with documented contributions to the safe clearance of thousands of mines and unexploded ordnance in Mozambique, Tanzania, Cambodia, Angola, and Laos. In 2020, the rat named Magawa received the British PDSA Gold Medal for exceptional service, having cleared more than 70,000 square metres of Cambodian land over five years of active service. This was the first time the award had been granted to a rat rather than a dog, marking a significant symbolic recognition of the animal's contribution to humanitarian mine action (Richardson, 2015).

According to recent research, giant rats are not only reliable and efficient but also remarkably long-lived as working animals: a single individual can remain in active operational service for up to 7 years, providing an extended return on the substantial initial training investment. Research also indicates that these rodents experience lower stress during detection work than dogs, and their natural curiosity and exploratory behaviour actively support their detection activities (APOPO, n.d.).

However, the use of giant rats is not without challenges. A significant obstacle in some regions is social perception: where rats are culturally associated with disease or agricultural damage, their operational deployment can provoke community distrust or resistance, requiring sustained awareness campaigns and educational engagement before and during clearance operations (Mueller, 2002a; Richardson, 2015). A further regulatory challenge is that giant pouched rats are potentially invasive outside their native Sub-Saharan African habitat, and their import and use in many countries requires strict licensing, including quarantine, health inspections, and breeding controls. In some regions, legal or animal health regulations restrict or prohibit the use of exotic species for operational purposes (Richardson, 2015).

Environmental factors also influence detection effectiveness. Very dense vegetation, extreme weather conditions such as severe heat or heavy rainfall, and rocky terrain can

reduce the usability and accuracy of biological detectors. These limitations reinforce the case for hybrid approaches that combine biological tools with complementary technological systems.

4.2.3 The Use of Bees and Innovative Biological Methods

In recent years, the potential use of honeybees (Apis mellifera) in explosive detection has attracted increasing scientific attention. The method is based on classical conditioning, in which bees are trained to associate the odour of explosive compounds such as TNT with food rewards. Conditioned bees then preferentially forage in areas where explosive scent is present, and their movement patterns, monitored by video camera tracking or RFID-based technology, can identify spatial concentrations that may indicate buried explosive devices (Bromenshenk et al., 2003).

The advantages of the bee-based method include low training costs, environmental friendliness, and the ability to survey large areas without direct human intervention. However, natural environmental factors, including weather conditions, flowering periods, and competing odours in the area, significantly influence bee behaviour and reduce detection accuracy. Controlling bee movement in the field remains technically challenging, and the method is currently regarded as a complementary technology rather than a primary clearance tool (Bromenshenk et al., 2003).

At the frontier of biological research, modified microorganisms, primarily bacteria, have been demonstrated to detect the presence of TNT in soil and produce fluorescent proteins in response. When these bacteria encounter TNT molecules, they emit visible light under UV illumination, providing a precise visual indication of potential mine locations. This approach is particularly promising for rapid pre-screening of large areas without physical intrusion, with basic system implementation costs of approximately 15,000-25,000 euros and single-use sensor costs currently ranging from 10-20 euros per unit (Mueller, 2002b).

Another experimental direction is the use of genetically modified plants whose leaves change colour from green to a reddish or brownish hue when TNT compounds are detected in the surrounding soil. These plants have produced reliable results under controlled conditions, but field deployment is currently limited by legal and ecological concerns regarding the deliberate environmental release of genetically modified organisms (Mueller, 2002b). Both directions, fluorescent bacteria and indicator plants, represent potentially valuable additions to the future mine clearance toolkit, particularly in areas where classical methods cannot be applied due to danger, inaccessibility, or lack of infrastructure.

4.3 Comparative Analysis of Demining Methods

In humanitarian demining, biological and technical methods each present distinct advantages and limitations, and their systematic comparison is essential for informed operational decision-making. Mechanical systems are capable of covering the largest daily area but are expensive, fuel-dependent, and constrained in complex terrain.

Manual demining using hand-held detectors offers high accuracy but is slow and exposes operators to direct risk. Detection dogs provide speed and sensitivity but require intensive maintenance and perform less reliably in extreme climates. Electronic sensor systems can detect a broad range of explosive types but are expensive and sensitive to environmental interference (GICHD, 2010; GICHD, 2004; GICHD, 2003).

The use of African giant pouched rats combines several key advantages: very low operational cost, high olfactory sensitivity, no risk of mine detonation due to minimal body weight, long working life, and strong adaptability through training. The primary limitations are the time and cost of initial training, cultural barriers in some operational contexts, and sensitivity to extreme environmental conditions. In terms of ESG considerations, the use of rats compares favourably to mechanical systems: they require no fuel or energy, do not pollute the environment, and operate with a minimal ecological footprint. Organizations such as APOPO implement transparent ethical standards and animal welfare protocols, including formal retirement of animals at the end of their working lives (Verhagen et al., 2003; Poling et al., 2010; Vandermeulen & Weetjens, 2017; APOPO, n.d.; Richardson, 2015).

Based on the comparative analysis, the most effective approach to humanitarian demining in the contemporary operational environment involves the integration of multiple methods in a context-specific manner. Mechanical systems are most appropriate for primary clearance of open terrain; biological detection tools, especially rats and dogs, excel in area reduction and verification tasks; and advanced sensor platforms provide documentation and quality assurance capabilities. The future of the field lies in the intelligent combination of these approaches within biosensor-hybrid operational systems.

5. Interviews with International Mine Action Programme Participants

The practical implementation of humanitarian demining is not only a technological and organizational matter but is closely intertwined with the experiences, cultural contexts, and personal commitments of the professionals who carry out this work. Primary qualitative research in the form of semi-structured interviews was conducted with staff from international humanitarian mine action organizations, including demining technicians, programme coordinators, animal trainers, and community liaison officers with operational experience spanning Africa, Asia, and the Balkans.

Since the full primary research programme of semi-structured interviews was not completed within the timeframe of the present study due to logistical and time constraints, the analysis draws on directly conducted interviews supplemented by secondary sources, including published testimonies, APOPO annual reports, GICHD field studies, and validated practitioner accounts available in the peer-reviewed literature (FHI 360, 2005).

5.1 Purpose, Significance, and Methodological Background

The aim of the interviews was to explore the effectiveness of methods employed in practice, operational obstacles in the field, the reliability of biological and technical tools, and the social acceptance of demining activities by affected communities. The semi-structured format was selected for its flexibility: while maintaining the logical structure of predefined thematic questions, it allows respondents to elaborate freely on their own experiences, professional reflections, and specific challenges from their operational contexts.

The interview questions covered five main thematic areas: (1) the purpose and operating structure of the programme; (2) technological and methodological experiences in the field; (3) the practical side of working with animals, including training, performance, and limitations; (4) relationships with local communities, including trust-building, social impact, and community involvement; and (5) personal motivations, field experiences, and psychological challenges. Full ethical principles were observed throughout the research, including informed consent, guaranteed anonymity, confidential data handling, and the right of participants to decline any question (FHI 360, 2005).

Responses were processed through thematic content analysis using qualitative research methods, structured around a coding system aligned with the five thematic question areas. Emotional tone, both positive and negative, was documented alongside thematic content to enable a nuanced interpretation of the human dimensions of mine action work. The method follows the recommendations of the FHI 360 Qualitative Research Methods Guide, a widely used standard in international humanitarian and health research (FHI 360, 2005).

5.2 Summary of Key Findings from the Interviews

Several consistent patterns and key lessons emerged across the interview material, reflecting the specific characteristics and demands of humanitarian mine action:

Motivations and personal commitment: The vast majority of respondents identified humanitarian motivation as their primary driver. Many reported that while initial career interest may have been driven by adventure or professional challenge, over time a deepening sense of community responsibility and a commitment to protecting human life became the dominant force in their professional identity. Personal experience of the consequences of mine accidents, either directly or through sustained contact with affected communities, was frequently cited as a transformative influence.

Field experience and challenges: Most respondents had between 5 and 12 years of professional field experience and had worked in multiple countries across different continents. Field operations are consistently influenced by weather conditions, geographical characteristics, and the political environment of the host country. Extreme heat, flash floods, dense jungle terrain, and desert conditions were identified as the most challenging environmental factors. Improvised explosive devices of unknown composition and inaccurate or missing minefield maps compound the operational risks.

Methods and technologies used: According to the interviews, most field projects employ a combination of methods, integrating hand-held metal detectors, drone pre-surveys, and biological detection tools including detection dogs and rats. Giant rats were found to be particularly effective in flat, sparsely vegetated terrain. Their fast movement and sensitive olfactory capability significantly increase detection efficiency, though performance may decrease in rocky or dense jungle environments. Respondents emphasized that while technological innovations are increasingly important, human observation and on-site decision-making remain essential and irreplaceable in complex field situations.

Community relations: The success of demining operations depends heavily on effective cooperation with local communities. Gaining the trust of the population is essential, as dangerous areas are frequently identified on the basis of community knowledge. Respondents stressed that sensitization training, public information campaigns, and joint fieldwork serve not only operational purposes but also contribute to making deminers trusted members of the communities they serve. However, in some regions, foreign experts were received with initial scepticism or political distrust, requiring sustained relationship-building before effective collaboration could be established.

Psychological effects and coping strategies: Respondents almost unanimously reported significant psychological stress associated with their work. The constant proximity to explosive hazards, encounters with civilian casualties, and extended periods of isolation in remote field locations generated chronic stress, anxiety, and in some cases PTSD-like symptoms. Team cohesion, regular psychological consultations, and rotational shift arrangements were identified as the most important protective and coping mechanisms. Several respondents explicitly noted that maintaining mental health is at least as important as ensuring physical safety.

Future outlook: Participants expressed cautious optimism about the future of humanitarian mine action. Increasing international political attention and more predictable long-term funding were seen as creating opportunities for methodological improvement and scaling up of operations. The integration of AI, drone technology, robotics, and advanced biological detection tools was identified as the most promising direction for increasing operational effectiveness in the coming decade.

5.3 Quantitative Summary and Professional Archetypes

Based on the quantitative analysis of completed interviews, 60% of respondents carried out mine clearance work primarily in Africa, 30% in Southeast Asia, and 10% in Europe. Regarding detection tools, 50% cited giant rats as their primary biological detection tool, 40% mentioned detection dogs, and 10% relied primarily on technological solutions such as metal detectors or drones. More than 70% of respondents reported that active and sustained involvement of local communities was essential to successful outcomes.

The average field experience of respondents exceeded 8 years, with individuals having worked in an average of 3-4 different countries. The most frequently cited field challenges included dense and difficult vegetation, inaccurate or entirely absent minefield documentation, and adverse weather conditions.

Qualitative analysis revealed two dominant professional archetypes within the humanitarian demining sector. The first is the 'young field operator', typically aged 25-30, with a military, technical, or engineering background, motivated primarily by humanitarian values and open to technological innovation. These professionals are particularly receptive to new biological and digital tools and are often active participants in community education and awareness programmes. The second archetype is the 'experienced security leader', typically in their 40s or 50s, characterized by decades of field experience in dangerous environments, a strong emphasis on strict protocol adherence and team management, and a pragmatic, strategically oriented approach to complex operational challenges.

Both archetypes play complementary and essential roles in the success of humanitarian demining programmes. The dynamism and technological openness of younger operators provides impetus for innovation, while the disciplined experience and crisis management capabilities of senior leaders ensure operational stability and long-term effectiveness. The synergy between these profiles, with the younger generation learning from experienced mentors while contributing fresh approaches and technological literacy, is a consistent feature of the most effective international mine action teams.

5.4 Thematic Deepening: Stress and Local Community Relations

The interviews revealed that psychological stress is an unavoidable dimension of humanitarian demining. All respondents reported that the constant proximity to explosive hazards, working under time pressure, and direct exposure to civilian casualties create a heavy and sustained psychological burden. Field conditions including extreme terrain, weather limitations, and technological constraints further compound this stress.

The most acutely stressful experiences cited were prolonged spatial isolation in remote field assignments and the direct witnessing of mine explosion accidents involving children or families, which led to PTSD-like symptoms in some respondents. Among effective coping strategies, respondents most frequently identified the strengthening of team cohesion, regular access to mental health support, and the use of rotational shift assignments that prevent burnout through structured recovery periods.

Engagement with local communities emerged as a central determinant of operational success. In projects where local people were consciously and continuously involved in the clearance process, for example through information gathering, community outreach, or logistical support, both the speed and quality of clearance operations improved significantly. One respondent recalled a particularly poignant illustration of this principle:

"When an old man showed me where his son had died on a mine and gave me the location of all the known minefields in the village, that's when I understood what it means to truly do humanitarian work."

Such personal connections represent a powerful driving force for field professionals and strengthen the long-term commitment that sustained humanitarian mine action demands. They also illustrate the irreplaceable role of the human factor: despite technological advances, the courage, empathy, and perseverance of demining professionals remain at least as important as the quality of the tools available to them.

6. Risks and Challenges

Field experience and the literature consistently confirm that humanitarian demining involves significant and irreducible operational risks. Field demining is one of the most dangerous peacetime engineering activities, and despite the development of modern methods and protective equipment, fatal and serious accidents continue to occur in even well-resourced programmes. A 2023 incident in Croatia, in which two experienced deminers were killed in an explosion, illustrates the ongoing severity of these risks and underscores the importance of protective equipment, careful prior site survey, and strict adherence to safety protocols (168.hu, 2023).

According to the interviews and literature, the majority of accidents arise from a combination of human inattention, time pressure, home-made explosive devices of unknown construction, and inadequate minefield documentation. Dense vegetation, proximity to ruined structures, and poorly documented urban and rural minefields create particularly high-risk operational environments. Historical records indicate that significant numbers of demining personnel lost their lives during post-conflict reconstruction periods in various countries, including Hungary, emphasizing the importance of continuous training and psychological preparation (Kenyeres, 2002).

International literature confirms that both technical equipment failure and human error contribute substantially to incident risk during mine clearance operations. Older minefields present particular challenges, as the physical and chemical state of explosive compounds changes over time due to moisture and soil interaction, which can reduce the sensitivity of electronic detection equipment and alter the odour signatures detectable by trained animals (Fernandez et al., 2024; GICHD, 2017).

Not only human operators but also biological detection tools including trained dogs and rats are exposed to field risks. Research by Morrison et al. (2014) demonstrates that the performance of these animals is highly dependent on environmental factors such as wind direction, temperature fluctuations, and soil moisture (Morrison et al., 2014). While rats rarely detonate mines due to their low body weight, injuries and false-alarm scenarios can pose risks to both the animals and their handlers. These examples reinforce that in humanitarian demining, human experience, strict safety protocols, continuous training, and responsible treatment of working animals are at least as important as the availability of advanced technology (Morrison et al., 2014).

6.1 Technological and Environmental Challenges

Despite technological advances, humanitarian demining continues to face substantial challenges from environmental factors. The performance of new-generation sensors, robotic systems, and automated platforms is often significantly affected by extreme temperatures, high humidity, dust, and the electromagnetic interference present in complex terrain. Maintaining the olfactory performance of biological detection tools in fluctuating weather conditions is a particular operational challenge (Fernandez et al., 2024).

A further persistent problem is the degradation of explosive compounds over time. As mines age, the chemical structure of their explosive filling changes due to moisture absorption and soil interaction, altering or reducing the scent signatures detectable by trained animals and decreasing the response of some sensor-based systems. The GICHD study on Explosives Weapon Effects documents that the diffusion properties of landmine explosives can differ substantially from original specifications after prolonged burial, complicating both chemical detection and risk assessment (GICHD, 2017).

In order to address these challenges, experts and practitioners consistently identify hybrid systems combining biological sensors with advanced sensor technologies as the most promising near-term development direction. Integrating the olfactory capabilities of rats and dogs with ground-penetrating radar, infrared scanning, and AI-supported real-time data analysis is expected to substantially increase both detection accuracy and operational safety in complex environments.

6.2 The Unique Challenges of Using Giant Rats

The growing deployment of African giant pouched rats has opened new perspectives in humanitarian mine clearance, but introduces specific challenges that must be addressed for the method to realize its full potential. A particularly critical issue is performance in extreme environmental conditions: in very hot, dry, or cold weather, olfactory sensitivity may be significantly reduced, necessitating adapted working schedules and more frequent rest periods (Richardson, 2015; Fernandez et al., 2024).

The social and legal dimensions of deploying giant rats in new operational contexts remain significant obstacles in some regions. In countries where rats are culturally associated with disease or treated as invasive alien species, operational deployment requires careful preparatory community engagement and may require the navigation of complex import regulations and biosecurity requirements. In some jurisdictions, the use of exotic animal species is restricted or prohibited, necessitating advance regulatory assessment before any operational deployment can be planned (Mueller, 2002a; Richardson, 2015).

From an ESG perspective, however, the use of giant rats presents several advantages compared to mechanical alternatives. Environmentally, they require no fuel, generate no pollution, and operate with a minimal ecological footprint. Socially, their operational deployment contributes to faster restoration of safe access to agricultural land, schools, transportation routes, and other civilian infrastructure. From a

governance perspective, organizations such as APOPO implement transparent ethical standards and comprehensive animal welfare protocols, including the formal retirement of animals upon completion of their working lives. These characteristics position the giant rat as not only an innovative but also a sustainable and ethically responsible element of the contemporary mine action toolkit (APOPO, n.d.; Richardson, 2015).

7. Future Opportunities and Developments

International and domestic experience in humanitarian mine clearance has made clear that while current methods are increasingly effective, further technological development, biological innovation, and enhanced international coordination are essential to address the global scale of landmine contamination within the timeframes set by international commitments. Precision technology, automation, and the intelligent combination of biological and digital tools will be the defining areas of progress in the coming years.

7.1 New Technological and Biological Approaches

A defining recent trend is the growing role of robotic systems and digital technology in mine clearance operations. AI-based area mapping, drone reconnaissance, and semi-automated ground systems are generating significant efficiency gains, especially in large or difficult-to-access areas. Ukraine's domestic development of demining vehicles since 2023, including models compatible with the DOK-ING MV-10 system, illustrates the potential for national self-sufficiency in mine action technology over the longer term (Army Recognition, 2023d). Such vehicles can clear large areas rapidly without personnel losses, requiring only minimal human presence at the operational interface.

Hungarian researchers have also contributed to this field: László Lukács has consistently emphasized the need for robotics applications in military and technical mine detection, drawing attention to sensor-assisted explosive detection systems, automated reconnaissance units, and armoured vehicles equipped with combined instrument arrays as key directions for future development in the Technical Military Gazette and at international symposia (Lukács, 2006).

In the biological domain, the integration of the DIGGER D-250 and NOA Acecor drone systems with biological detection tools represents a converging development frontier (Army Recognition, 2023a). International research confirms this trajectory: Gustafsson and Mahoney (2022) demonstrate that the coordinated deployment of biological and mechanical sensors can substantially improve field results, particularly in unmapped or incompletely documented mined areas (Gustafsson & Mahoney, 2022).

7.2 The Role of Giant Rats in Future Technologies

The use of African giant pouched rats has significant future potential. Combining the animals' natural olfactory capabilities with GPS-based tracking, real-time data transmission, and AI-supported behavioural analysis creates the foundation for hybrid

detection systems that simultaneously ensure rapid information collection, real-time evaluation of detection events, and compliance with international documentation requirements.

The APOPO research team is currently developing systems for the direct monitoring of rat-indicated mine locations by drones or ground robots, minimizing the need for human presence in the most dangerous phase of the clearance process (APOPO, n.d.). From a sustainability perspective, giant rats also have the advantage of a minimal ecological footprint when trained and deployed, significantly reducing dependence on expensive mechanical devices or energy-intensive robotic platforms.

The most promising future direction is accordingly what practitioners and researchers are calling 'biosensor-hybrid decontamination': an integrated operational system in which trained rats, surveillance drones, robotic clearance platforms, and AI-supported analytical systems work together to identify, confirm, and safely remove explosive hazards. Each element of this system compensates for the limitations of the others: the rat provides olfactory sensitivity that no current electronic sensor can replicate; the drone and robot enable physical clearance and documentation without exposing human operators or animals to direct risk; and AI provides the analytical integration layer that optimizes the operation of the whole system in real time (Gustafsson & Mahoney, 2022).

7.3 Enhancing International Cooperation

The effectiveness of humanitarian mine action depends fundamentally on international cooperation in knowledge sharing, technology transfer, and financial support. In February 2024, twenty-four countries announced a joint mine action support programme for Ukraine, encompassing financial, technological, and expert assistance, and providing a clear example of how coordinated regional and international action can address large-scale contamination crises (Infostart.hu, 2024).

New action plans developed by the United Nations, NATO, and the GICHD aim to improve the quality, transparency, and sustainability of mine action operations through common data standards, shared reporting frameworks, and enhanced interoperability between national mine action authorities (UNMAS, 2021; GICHD, 2022). Cooperation is particularly important for local capacity building and long-term sustainability: effective humanitarian demining ultimately requires the development of national expertise and institutions in affected states, rather than indefinite reliance on external technical assistance (GICHD, 2005).

Future challenges, including the growing threat of urban minefields, the proliferation of improvised explosive devices, and the impact of climate change on soil conditions and detection performance, can only be addressed effectively through sustained and enhanced international cooperation. The development of new types of partnerships, for example with technology startups, robotics developers, and biotechnology research centres, will be essential to maintaining the pace of innovation required to match the evolving character of the mine contamination problem. Future humanitarian mine

action programmes will require an increasingly multidisciplinary approach, combining technical development, biological innovation, community engagement, and sustainability principles to achieve lasting results in war-torn areas (GICHD, 2017; GICHD, 2002).

7.4 Future Trends in Humanitarian Demining

The future of humanitarian demining is closely linked to the dynamics of technological development, the scaling of biological methods, and the deepening of international cooperation. In the coming decades, speed, sustainability, and the minimization of risk to human life will be the defining operational priorities. Based on GICHD analyses, the principal development directions and expected innovations include: autonomous AI-guided robotic clearance systems capable of full operational cycles without human field presence; advanced biosensor-hybrid systems integrating rats, dogs, drones, and real-time AI analytics; next-generation sensor platforms capable of detecting all types of explosive devices regardless of material composition or depth; scaled-up international funding mechanisms that ensure predictable and sustainable support for national mine action authorities; and strengthened community engagement frameworks that make affected populations active participants in the clearance and rehabilitation process (GICHD, 2005; GICHD, 2022; GICHD, 2002).

Future mine clearance efforts will increasingly be based on the synergy of technological and biological innovations, operating within frameworks of international cooperation and community partnership. Biological solutions such as the use of giant rats provide a model for how mine action methods can be simultaneously cost-effective, environmentally responsible, and socially acceptable. The development of more effective, safer, and more sustainable clearance practices is not only a technological imperative but a global humanitarian priority for the coming decade.

8. Summary

Humanitarian mine clearance is not merely a technical operation but a fundamental humanitarian and security policy challenge with profound implications for post-conflict recovery, human security, and sustainable development. The presence of landmines in post-conflict areas poses long-term risks to human lives and constitutes a persistent obstacle to economic development and community rehabilitation. Clearance activities therefore create the basic conditions for agricultural recovery, infrastructure reconstruction, and social stability (GICHD, 2005).

Significant progress has been made in the field of mine clearance in recent decades, encompassing robotic developments, the use of biological detection tools, and the strengthening of international cooperation. The elimination of landmines is a cornerstone of post-conflict peacebuilding: explosive devices left behind can prevent the reconstruction and social reintegration of affected areas for decades. Technical analyses confirm that clearance is a prerequisite for creating safe living conditions and that the economic returns on successful demining investments are substantial (Lukács, 2006).

According to the GICHD's authoritative study Mine Action: Lessons and Challenges, humanitarian demining plays a key role in achieving international development goals, contributing to reduced mortality rates and stimulating economic development in previously inaccessible areas (GICHD, 2005). Despite these achievements, the field continues to face serious challenges: funding remains insufficient and unpredictable in many regions, technological capabilities are unevenly distributed globally, and the scale of contamination continues to grow in new conflict zones. The GICHD Annual Report 2022 emphasizes that it is not sufficient to develop innovations; they must also be made widely and affordably available to all affected communities (GICHD, 2022). The study Mine Action Equipment: Study of Goal Operational Needs further underlines that integrated systems, intelligent data management, and the active involvement of communities in clearance projects are necessary conditions for future success (GICHD, 2002).

The African giant pouched rat, systematically developed and operationally deployed by APOPO since the early 2000s, exemplifies how a biological innovation can complement and in certain contexts outperform conventional technical and manual methods, particularly in terms of cost-effectiveness, operational safety, and long-term sustainability (APOPO, n.d.; Verhagen et al., 2003; Poling et al., 2010; Vandermeulen & Weetjens, 2017). The future of the field lies in biosensor-hybrid systems that integrate the olfactory capabilities of trained animals with the analytical power of AI and the physical clearance capacity of autonomous robotic platforms, embedded within frameworks of sustained international cooperation and genuine community partnership.

Overall, humanitarian demining is not only the elimination of the legacies of past conflicts but also a commitment to safe and sustainable development for the future: one in which technological innovation, biological methods, international solidarity, and respect for affected communities together create the conditions for a world free of the long shadow of landmines.

Conflict of Interest

The authors hereby declare that no competing financial interest exists for this manuscript.

Notes on Contributor

Timea Hillender is a Hungarian professional with a diverse background in education and humanitarian work. She graduated from the University of Szeged with a degree in Hungarian and German teaching and later obtained a master's degree in German translation from the University of Miskolc. Seeking to broaden her expertise, she completed a second master's degree in Humanitarian Response Management at Bánki Donát Faculty of Mechanical and Safety Engineering, Óbuda University, where her thesis focused on the innovative use of giant pouched rats in landmine detection. She is the founder and president of Afrika Sztorik Afrika Vadvilágáért Egyesület, an association active in Kenya and Tanzania. Through the organization's programs, she supports

women's training and education, including ranger courses and tour guide certification, with the aim of strengthening communities and promoting sustainable development. Since 2023, she has also been working with APOPO, an international NGO renowned for its mine-detection rats. Her current work focuses on empowering women to participate in the breeding and training of these animals, thereby promoting greater female involvement in humanitarian demining efforts.

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