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ORIGINAL ARTICLE

Radioactive isotopes theft in Mexico during 2011–2023: a green criminological approach

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Abstract

In the last decade, cases of radioactive isotope theft have been observed more frequently in Mexico, endangering human health, biodiversity, and the environment due to the risks of mishandling radioactive isotopes. The aim of this study was to analyze the theft of radioactive isotopes in Mexico in the period 2011–2023 from the perspective of green criminology through official data and radiological emergency bulletins. The results show that the most frequently stolen isotopes were ^{192}Ir, ^{137}Cs, and ^{131}I in this study period, and it was also identified that the isotopes are stolen unintentionally, since it is the vehicles that transport them that are stolen, most of the time without knowing what they contain. It is concluded that the theft of radioactive isotopes in Mexico is a crime linked to vehicle theft, which in turn stems from the conditions of public insecurity but puts the health, safety and well-being of people, biodiversity, and the country's ecosystems at risk, so that institutional actions must be oriented considering the conditions of public insecurity to improve nuclear safety in the country.

Keywords Crime · Green criminology · Radioactive isotopes · Radioactivity · Vulnerability

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Introduction

Background

Radioactive isotopes (radioisotopes or radionuclides) are chemical elements with unstable atomic nuclei that, in order to achieve stability, tend to emit a particle or radiation, a phenomenon known as radioactivity. Radioisotopes are used in two main ways: (a) by their radiation (irradiation, nuclear batteries) or (b) by the combination of their chemical properties and their radiation (tracers, biopharmaceuticals). Radionuclides can emit radiation, mainly, of three types: emission of alpha particles (α), beta particles (β) or gamma rays (γ) (Centro de Investigaciones Energéticas, Medioambientales and Tecnológicas [CIEMAT], 2022; Di Filippo et al. 2015).

Radioactive isotopes offer effective and sustainable solutions in a wide range of applications in areas such as energy, oil extraction, medicine, food and research (International Atomic Energy Agency [IAEA], 2009). In Mexico, radioisotopes are used mainly in the oil extraction and medical sector and to a lesser extent in the energy sector, and their correct use and application offer important benefits that can hardly be achieved with other methods. However, if the radioactive isotopes are used incorrectly or are handled by people with no experience, this can represent a serious danger to human health, biodiversity and the environment (IAEA, 2009).

Accidents and vulnerability

One of the best-known accidents due to the mishandling of radioactive isotopes in Mexico occurred in 1983 in Ciudad Juárez, Chihuahua, with the unintentional dispersal of six thousand ^{60}Co pellets from a radiotherapy unit illegally purchased in the United States by the Medical Specialties Centre, a private hospital in Ciudad Juárez, which, due to a lack of specialized personnel, was stored and later sold and dismantled to use parts in the sale of scrap. Ignorance and lack of regulation and protocols for handling radioactive material led to the smelting of ^{60}Co with other metals, from which thirty thousand bases for tables and more than six thousand tons of contaminated rod were produced, that were distributed in 15 states of Mexico and other US cities (Comisión Nacional de Seguridad Nuclear y Salvaguardias [CNSNS], 1985). In addition to the case of Ciudad Juárez in Mexico, a similar case has also been documented in Brazil in 1987 in the Goiânia accident with ^{137}Cs (Nazaré, 1987; Miranda et al. 2005; Vieira 2013; Fuini et al. 2013), while other incidents of lesser magnitude have occurred in Latin America (see Carregado and Trujillo-Cerda 2001; Clemens and Casani 2016).

Most accidents with radioactive material that involve effects on human health and the environment are due to portability and vulnerability to loss, misplacement or theft (Swindell 1978; National Academies of Sciences, Engineering, and Medicine [NASEM], 2022). This is aggravated by the context of widespread insecurity in Mexico in recent decades (homicides, robbery, extortion, kidnapping, car theft, drug trafficking, etc.) (Soria-Romo 2018; Salazar-Serna et al. 2021; Aguilar-Rodríguez and Nateras-González 2022) making radioactive material prone to theft, increasing the vulnerability of people's well-being and endangering the safety of the community.

Until now academic research into the Theft of Radioactive Isotopes (TRI) has been virtually non-existent. While there are a few studies that make reference to the theft or mishandling of radioactive isotopes (Fink 2005; Weinberger 2012), and illicit trades in radioactive material (Zaitseva and Steinhausler 2006) never before has the behavior of theft been a spotlight criminological issue. Consequently, this study is the first to conduct in-depth analysis into TRI and does so by highlighting the extent of the issue in the Mexican context. It is worth noting at this point that Ruiz and Garcia (2014) conducted a relevant presentation on this issue at the 25th Sociedad Nuclear Mexicana Annual Congress in Mexico in 2014 and Cateriano and Ruiz (2002) report that radioactive accidents come from three main causes: human error, equipment failure, and theft.

This current study complements this presentation and report and adds more substance to these issues. Furthermore, it is the first research article to understand the TRI from the lens of green criminology that focus on the study of crimes and harms against the biodiversity, ecosystems and life on the planet and to visualize human and non-human victims (see Carpio-Domínguez 2023; Brisman 2014; Hall 2014; Lynch 2019; Nurse 2020), adding to that area of academic research, and advancing government, society, industry and academic understandings about the TRI in Mexico. Therefore, this study aims to analyze the theft of radioactive isotopes in Mexico in the period 2011–2023.

Methodology

The present study is based on mixed-method research with a complementarity approach (Greene et al. 1989; Johnson and Onwuegbuzie 2004). Two sources of information were used to analyze the TRI in Mexico: (1) the official data reported by the Comisión Nacional de Seguridad Nuclear y Salvaguardias (CNSNS) (National Commission for Nuclear Safety and Safeguards) and (2) the radiological alert bulletins issued by the CNSNS and Civil Protection.

In Mexico the CNSNS and the Instituto Nacional de Investigaciones Nucleares (ININ) (National Institute for Nuclear Research) both aim to monitoring the application of nuclear, radiological, and physical safety standards and safeguards so that the operation of nuclear and radioactive facilities is carried out with the maximum security for the inhabitants of the country (CNSNS 2022).

The methodology was applied in two phases: (1) in the first phase, data on the TRI in Mexico during the period 2011–2023 were requested from the CNSNS through the platform of the National Institute of Transparency, Access to Information and Protection of Personal Data (INAI) (Folio: 1810000007221). The requested data were the variables: year, state, municipality, isotopes, cause of loss, sector (medical, research and explorations for oil extraction) and the status of the case (recovered or not recovered) (Table 1).

Table 1 Variables and subvariables analyzed in the theft of radioactive isotopes in Mexico during the period 2011–2020

Variable	Subvariables
Year	2011–2023
State	32 states of Mexico
Municipality	2 471 municipalities in Mexico
Isotopes*	^{137}Cs, ^{241}Am, ^{192}Ir, ^{57}Co, ^{60}Co, ^{99}Mo, ^{99m}Tc, ^{131}I, ^{133}Ba, ^{223}Ra and Be
Sector	Medical, research and explorations for oil extraction
Status	Recovered and not recovered

*The isotopes described correspond to those identified in the data provided by the CNSNS, and their characteristics are described in Appendix 1

The second phase was the analysis of 15 radiological alert bulletins issued by the CNSNS and Civil Protection in Mexico to identify elements of interest for this study such as the possible causes of theft, the modalities of crime (with violence, assault, vehicle theft, etc.), time and location of the theft (parking lot, warehouse, road/highway, etc.), and the type of vehicle. These data made it possible to contextualize the phenomenon with the security conditions in the country and, in turn, offer a criminological profile on the theft of radioactive material and its implications for public safety and human and environmental health.

Results and discussion

Description of stolen radioactive isotopes

The radioactive isotopes identified in the robberies correspond to 10 radioactive isotopes, which were classified in two groups depending on the characteristics of the robbery: (1) those corresponding to a single isotope at the time of the robbery: ^{137}Cs, ^{192}Ir, ^{60}Co, ^{131}I and ^{223}Ra; and (2) those with two or more isotopes stolen in a single event because these isotopes are combined at the time of use: ^{137}Cs, ^{241}Am, Be; ^{99}Mo, ^{99m}Tc and ^{57}Co, ^{137}Cs, ^{133}Ba.

Considering the frequency of thefts, from the first group it was identified that the isotope with the most cases was ^{192}Ir (n = 17) representing 51.5% of the cases identified in the study period which is consistent with what was reported by National Academies of Sciences, Engineering, and Medicine (NASEM) (2022). The second most frequently stolen isotope was ^{131}I with three cases, which represents 9.1% of the cases. While ^{137}Cs represented the third isotope with the highest frequency of theft cases (n = 2, 6.1%), isotopes of ^{60}Co and ^{223}Ra were stolen only once each.

The isotopes stolen by group, were ^{137}Cs, ^{241}Am and Be and had the highest frequency of robberies (n = 6, 18.2%), followed by ^{99}Mo and ^{99m}Tc with two cases (6.1%); finally, the group of ^{57}Co, ^{137}Cs and ^{133}Ba with only one case (3.0%) in the study period (Fig. 1).

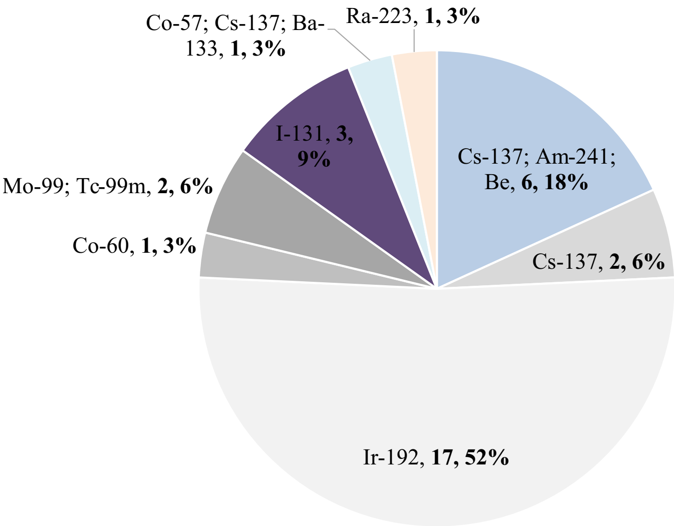

Fig. 1 Frequencies of radioactive isotopes theft in Mexico in the period 2011–2023. *Note* isotopes are shown considering the frequency of theft cases, so those isotopes that were stolen by group (e.g., ^{137}Cs, ^{241}Am and Be) were analyzed as a single theft case

The identified isotopes are mainly used in the medical sector and explorations for oil extraction. The data analyzed show that 75.8% (n = 25) of the stolen isotopes belonged to the explorations for oil extraction: ^{192}Ir (n = 17), ^{137}Cs, ^{241}Am, Be (n = 6) and ^{137}Cs (n = 2), while 24.2% (n = 8) of the isotopes belonged to the medical sector: ^{131}I (n = 3), ^{99}Mo, ^{99m}Tc (n = 2), ^{223}Ra (n = 1, Co^{60} (n = 1) and ^{57}Co, ^{137}Cs, ^{133}Ba (n = 1) (see Appendix 1).

Theft of radioactive isotopes (TRI) in Mexico

The TRI in Mexico during the period 2011–2023 is represented by 33 cases, with an average of 3 cases of theft per year. The year 2017 was the year with the most cases of TRI during this period (n = 8, 24.2%), while in the years 2011, 2012, 2013, 2019 and 2022 only one case was reported per year. The frequency of TRI shows an increasing trend, with a decrease from 2017, but an increase in cases is evident in the last four years of this period (2020–2023) (Fig. 2).

About the status of isotope thefts, it was identified that 72.7% (n = 24) were recovered by government institutions, of the first group (a single stolen isotope) was recovered (Fig. 3): ^{192}Ir (n = 17), ^{60}Co (n = 1) and ^{223}Ra (n = 1); while from the second group (two or more stolen isotopes) were recovered: ^{137}Cs, ^{241}Am, Be (n = 5) and ^{99}Mo, ^{99m}Tc (n = 1).

Due to the high frequency of cases of TRI during transport, the Government of Mexico approved in 2017 a new regulation for transport of radioactive material named Reglamento para el Transporte Seguro de Material Radiactivo (Regulation for the Safe Transport of Radioactive Material) (Gobierno de Mexico 2017), which

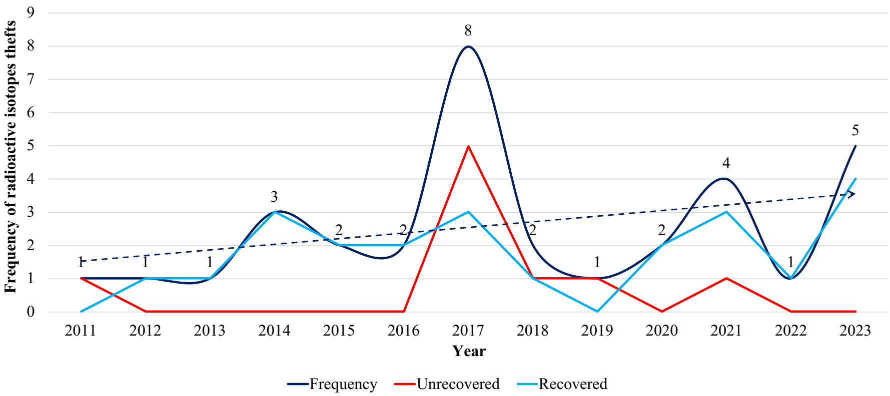

Fig. 2 Frequencies of cases of theft of radioactive isotopes in Mexico per year in the period 2011–2023

Fig. 3 Radioactive source of ^{192}Ir recovered. It was abandoned by thieves in a vacant lot in Estado de Mexico in 2021. *Source*: Uno TV (2021)

states that radioactive isotopes such as ^{192}Ir, ^{60}Co, ^{137}Cs, ^{241}Am, ^{90}Sr and fissile substances must have global positioning systems that include at least a GPS device, tracking service and real-time map location (CNSNS 2017).

Although the government regulation on nuclear matters has 32 Official Mexican Standards (NOM) which establish the procedures for handling, supervision, review, control, safety and transport of radioactive materials (CNSNS 2022), only

NOM-011-NUCL- 2021 establishes the criteria for the transport of radioactive isotopes in the country (Secretaría de Energía [SENER], 2021).

However, as Fig. 2 shows, the frequencies of cases from 2017 decreased, but an increasing trend can be observed in the years 2020 (n = 2), 2021 (n = 4), 2022 (n = 1) and 2023 (n = 5), adding a total of twelve cases, which exceed the ten cases in the 2011–2016 period. However, it should be noted that in the cases of the last four years the number of recovered isotopes increased, which could be due to the implementation of the Regulation for the Safe Transport of Radioactive Material (Gobierno de Mexico 2017).

When analyzing the frequencies by month, the data show that the highest number of robberies occurred during February (n = 6, 18.2%), followed by March (n = 4, 12.1%) and April (n = 4: 12.1%) and the months of June (n = 3, 9.1%), August (n = 3, 9.1%) and December (n = 3, 9.1%) with three cases each month. It should be noted that in November no cases of TRI were reported (Fig. 4).

Based on the foregoing, the months with the highest frequency of cases of TRI are February, March, April, June, August, October and December, so security both in nuclear matters and in public safety must be reinforced in these months with the purpose of implementing supervision and prevention activities.

It has been identified that radioactive isotope thefts occurred in 13 of the 32 states of the country, which represents 40.6% of the states of Mexico. TRI is concentrated in the central and western region of the country, in the states of Guanajuato (n = 7, 21.2%), Estado de Mexico (n = 6, 18.2%), Jalisco (n = 5, 15.2%), Ciudad de Mexico (n = 2, 6.1%) and Hidalgo, Querétaro, Nayarit and Puebla (n = 1, 3.0%, each one). In the northern region of the country cases of TRI were identified in the states of Sonora (n = 3, 9.1%), Nuevo León (n = 2, 6.1%), and Chihuahua and Tamaulipas (n = 1, 3.0%, each one). Finally, in the southern region of the country a case was identified in the state of Tabasco (n = 2, 6.1%) (Fig. 5).

23 municipalities reported TRI; of these, Salamanca in the state of Guanajuato (n = 5, 15.2%) and Guadalajara in the state of Jalisco (n = 4, 12.1%) show the highest number of TRI, followed by Ciudad de Mexico (n = 2, 6.1%), Ciudad Obregón in the state of Sonora (n = 2, 6.1%) and Toluca in the Estado de Mexico

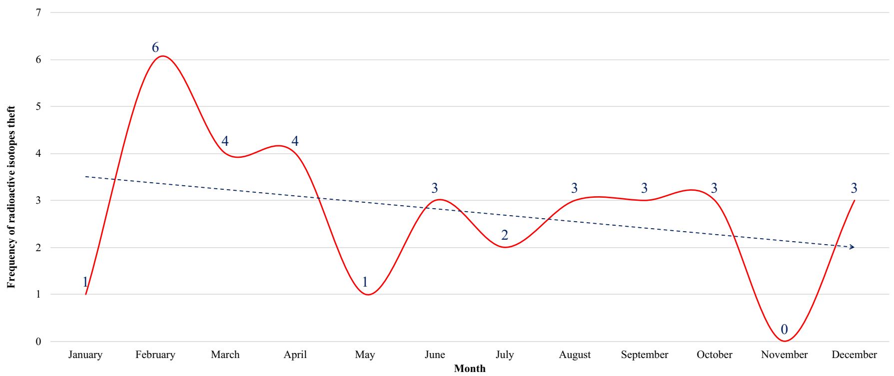

Fig. 4 Frequencies of cases of theft of radioactive isotopes in Mexico per month in the period 2011–2023

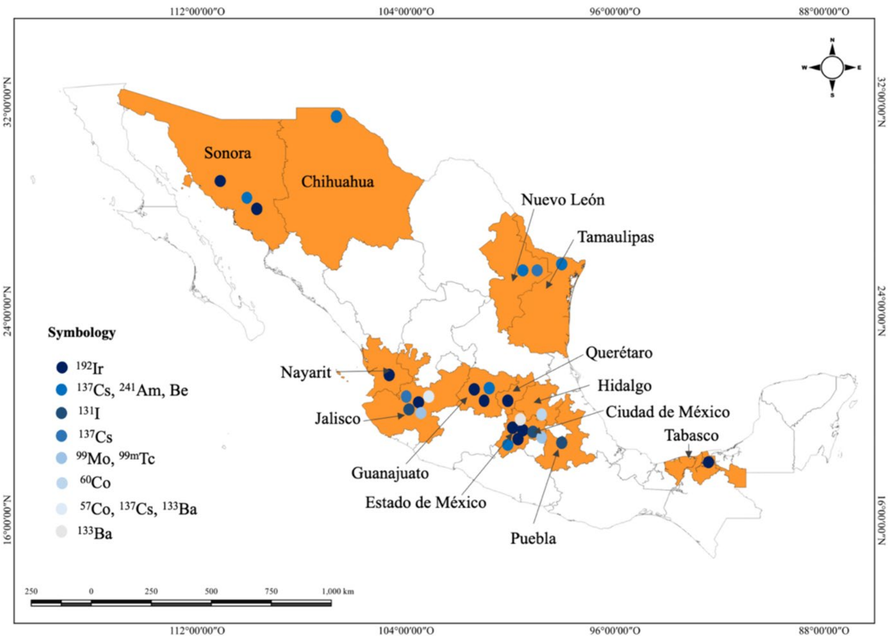

Fig. 5 Geographical distribution of radioactive isotope thefts in Mexico during the period 2011–2023

(n = 2, 6.1%) (see Fig. 5). These municipalities have a population of > 80,000 people, considering that Mexico City has a population concentration of > 9,000,000 people (Instituto Nacional de Estadística y Geografía [INEGI], 2020); therefore, the health risk represented by the TRI in these municipalities increases due to the high population concentration.

Given the increase in the frequency of cases of theft from 2013 onwards regulations were implemented, including NOM-014-NUCL-2017 which regulates and classifies the categories of packages, overpacks and cargo containers that contained radioactive materials: marking and labeling (SENER 2019a), the Regulation for the Safe Transport of Radioactive Material (Gobierno de Mexico 2017) and NOM-009-NUCL-2017 to regulate the transport index for radioactive materials and the safety index with respect to the criticality for the transport of fissile substances (SENER 2019b).

The actions to finding, recovering, investigating, regulating and the final disposal of the stolen radioactive isotopes are responsibility of the Attorney General's Office and the CNSNS; however, it was identified that 27.3% (n = 9) of the stolen isotopes were not recovered, from the first group (a single stolen isotope): ^{131}I (n = 3), ^{137}Cs (n = 2) and ^{192}Ir (n = 1); while from the second group (two or more stolen isotopes): ^{137}Cs, ^{241}Am, Be (n = 1), ^{99}Mo, ^{99m}Tc (n = 1) and ^{57}Co, ^{137}Cs, ^{133}Ba (n = 1) (Fig. 6).

The main radioactive isotope not recovered was ^{131}I (n = 3), belonging to the nuclear medicine sector, which is categorized in Category IV by the IAEA (2003). It is used in radiotherapy because it emits β and γ particles to treat some diseases of

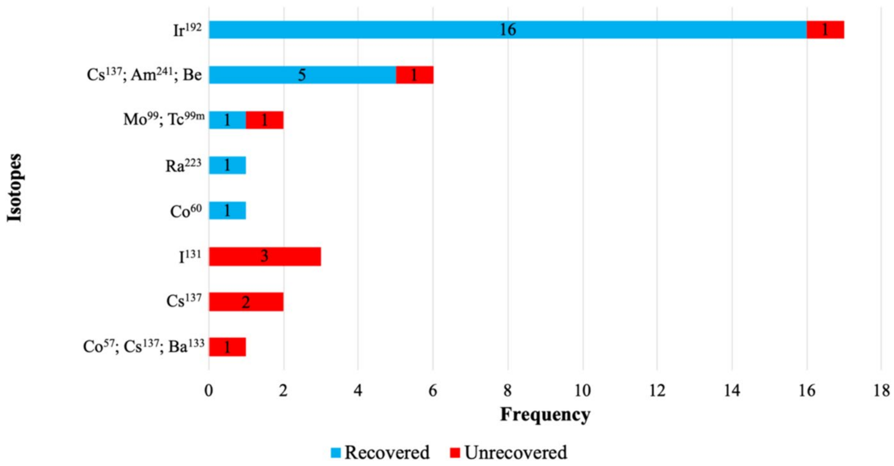

Fig. 6 Frequencies of stolen radioactive isotopes recovered and not recovered in Mexico during the period 2011–2023

the thyroid gland such as hyperthyroidism and cancer (González-Rivero et al. 2012; Zimmerman and Bergeron 2016).

It is noteworthy that isotopes such as ^{137}Cs occupy the second place of unrecovered isotopes, and they are in Category I of danger of the IAEA (2003) which emits gamma radiation (γ) with a half-life of 30 years (see Appendix 1). Although it is mainly used in the oil extraction to determine the density, porosity and moisture or hydrocarbon content of geological structures for well logging of oil and gas wells, it is also used in the medical sector (Bergman and Pettersson 1994; Torres-Carranza and Ortiz-Oliveros 2019).

An important aspect that stands out when analyzing the location of the stolen radioactive isotopes is that it coincides with the location of oil and gas extraction activities in the country (Fig. 7), which also coincides with the high frequency of TRI from the industrial sector (n = 25, 75.8%). Among the main stolen radioactive isotopes that are used in oil and gas extraction processes are: ^{192}Ir (n = 17), ^{137}Cs, ^{241}Am, Be (n = 6) and ^{137}Cs (n = 2).

These isotopes are used for the profiling of oil wells and the losses or misplacement of these isotopes are common in the oil industry; according to the data provided by the CNSNS in the period 2011–2023, 24.4% (n = 12) of the loss of radioactive isotopes in Mexico is due to incidents in oil wells in which the radioactive material must be confined inside the well.

The correct processing and confinement of these isotopes within the wells do not represent a danger to people or the environment, because the radioactive material is confined (covered and sealed with concrete) and later another space is sought to drill. The importance lies in the fact that the radioactive material must be transported to the location of each well and back to the warehouses of

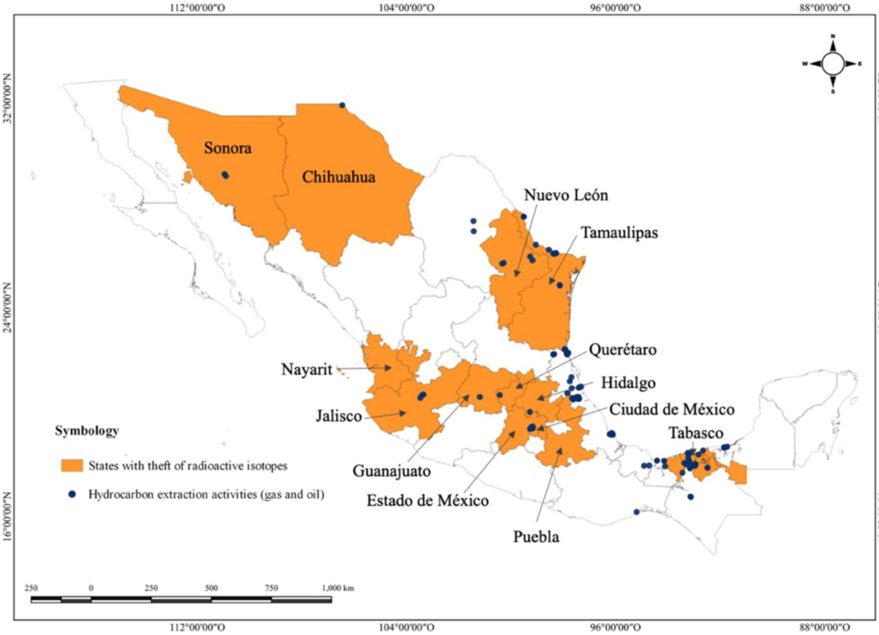

Fig. 7 Gas and oil extraction activities and cases of theft of radioactive isotopes in Mexico during the period 2011–2023. *Note* Sites of hydrocarbon extraction activities were obtained from INEGI (2022)

each company or institution, which makes these radioactive isotopes available to the population, and consequently prone to being stolen.

Criminologically relevant data on the theft of radioactive isotopes

From a legal perspective, the TRI is typified as a crime in chapter 1 of “crimes against people and their property” of the Mexican Federal Penal Code, so their prosecution and enforcement correspond to federal jurisdiction. This legal framework establishes that whoever commits the crime of theft of radioactive material, nuclear material, nuclear fuel, radioactive mineral or radiation source will be imposed twelve to twenty years in prison and a fine established in the Mexican Federal Penal Code (Article 368 Quinquies from Código Penal Federal 2024).

It is highlighted that, regarding the modality of thefts, the TRI was carried out mainly in the legal classification of "simple theft" which is defined as the act of seizing another’s movable property, without right and without consent of the person who can dispose of it according to the law (Article 367 from Código Penal Federal 2024). In addition, the crime of simple theft is equated to the intentional seizure or destruction of one’s own movable property, if it is in the possession of another person by any lawful title and there is no consent (Article 368 from Código Penal Federal 2024).

While to a lesser extent the TRI that were carried out with violence, that is, violence was used in the form of threats and feints to commit the theft; Mexican legislation establishes that, if the theft is carried out with violence, six months to five years in prison will be added to the corresponding penalty for simple theft. If the violence constitutes another crime (e.g., injuries, homicides, etc.), the rules of accumulation will apply (Article 372 from Código Penal Federal 2024).

Radioactive isotope thefts occurred in cities, outlying areas, and on highways during transportation. Public parking lots were mainly the places with the highest frequencies, followed by thefts on roads and highways and, lastly, thefts directly from the warehouses of the owner companies. An important aspect is that the thefts with violence were carried out on roads and highways while the thefts in public parking lots were simple thefts, that is, without violence.

The TRI in Mexico has no other purpose than to steal the vehicle that transports them, so the thieves most of the time did not know what the vehicles were carrying or because those who stole them mistakenly considered that the stolen radioactive isotopes could have some economic value. Even so, during this study any case of sale of radioactive isotopes was identified, all those stolen radioactive isotopes were thrown away or abandoned by the thieves.

This aspect is important because the stolen isotopes were not used, this means that the documented thefts were not intended to be used for any purpose, even though it has been documented that, for example, ^{192}Ir can be used in the production of bombs (Dirty Bomb or Radiological Dispersal Device [RDD]), whether for terrorist purposes or not (Centers for Disease Control and Prevention [CDC] 2018a). Another important aspect identified is that the radioactive isotopes were stolen mainly from pick-up truck type vehicles and less frequently from transport vans; this means that pickup trucks are more useful for the purposes of those who steal them.

In addition, it was identified that the TRI in the country is carried out at two specific times: during the night (0:00–8:00 h) and during the midday (13:00–15:00 h) (Fig. 8), this coincides with the circumstances in which most thefts occur, when those who transport radioactive isotopes stop to rest or sleep and when they stop to eat; therefore, at these times they are vulnerable to theft, which is consistent with what was reported by Swindell (1978) and National Academies of Sciences, Engineering, and Medicine (NASEM) (2022) that establishes that the transport of dangerous substances by land (highways) has led to an increase in thefts of radioactive isotopes.

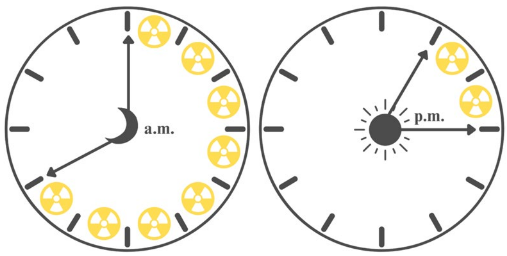

Fig. 8 Hours with the highest potential for theft of radioactive isotopes in Mexico during 2011–2023. *Note* These data were obtained from the review of 15 radiological emergency bulletins

Another important factor identified in cases of theft is the size of the containers in which the radioactive isotopes are transported, since it facilitates their theft, so that it is easy for thieves to take and handling the containers from the vehicles (Campos-Garza 2017). Although different security strategies have been implemented, among which the strengthening of the signaling of the type of (radioactive) material that is transported and the implementation of GPS devices for tracking and location on a map in real time to radioactive isotopes (CNSNS 2017) it is important to highlight that, even with these security measures, the trend of TRI in Mexico is increasing and in many cases due to the ease of holding and moving the containers that contain radioactive isotopes.

Considering the most frequent hours of theft of vehicles transporting radioactive isotopes, it is necessary to implement systems for remote shutdown of the mechanical or electrical operation of the vehicle to prevent their displacement and to recover them in the shortest possible time. This could strengthen the strategy of attaching GPS devices to radioactive isotope containers, which is already being implemented by official order (CNSNS 2017).

Therefore, this vulnerability to theft is aggravated by the context of generalized insecurity in Mexico in recent decades (Soria-Romo 2018; Salazar-Serna et al. 2021; Aguilar-Rodríguez and Nateras-González 2022) since most of the crime figures are represented by the theft of vehicles and according to the CNSNS (2013) one of the main causes of loss or misplacement of radioactive material in Mexico originates from the theft of the vehicle in which they were transported.

Public security conditions in Mexico in recent decades have caused high levels of crime, including vehicle theft and is considered a "crime of high social impact," this means that along with homicide, femicide, kidnapping, extortion, drug dealing, among others are latent risks that cause a feeling of social vulnerability and perception of insecurity due to their high incidence (Observatorio Nacional Ciudadano [ONC] 2021).

When the TRI originates from public insecurity conditions, the challenge of prevention is greater, because prevention strategies must focus on the larger scale on which the TRI occurs. This means that even if nuclear security processes are well implemented, the transport of isotopes depends on the security conditions in the state or region. This represents a situation of social and environmental vulnerability that must be addressed through government action, from the sectors that use them (medical and industrial sectors) and social awareness about the risks of stealing radioactive isotopes without training and care in their handling. Despite the IAEA establishes that not all radioactive isotopes represent a danger to the environment or people, the importance lies in the fact that in the TRI analyzed, in many of them the content of the stolen vehicles was not known, so the risk is present.

Green criminological approach

From a green criminological perspective, the TRI represents a crime that can be classified as a secondary green crime. These are crimes in which waste or substances dangerous to people and the environment are illegally operated (Carrabine et al. 2020; Potter 2017) and its importance lies in the fact that government entities regulate them through legislation and the response of government institutions, but crime does not decrease, endangering people, biodiversity and ecosystems.

The TRI and their propensity to contaminate may be referred to as a brown issue of green criminology (White 2008) due to the environmental and human health risks represented by the mishandling of radioactive isotopes by those who steal them. Radioactive contamination and radiation exposure could occur if radioactive isotopes are released into the environment as a result of dumping the containers holding the stolen radioactive isotopes or that can be used for malicious purposes (CDC 2018b).

From a green criminological perspective, it was identified that TRI is a crime that originates from the context of public insecurity in the country and that puts health and well-being of people, biodiversity and ecosystems at risk. In Mexico, green criminological studies have made visible this type of green criminal phenomenon, that is, crimes that are properly considered public security problems but endanger humans, biodiversity and ecosystems safety (e.g., Carpio-Domínguez 2021; Martínez-Gallegos et al. 2023).

Ultimately, from a green victimological perspective, victims may include people, non-human animals and ecosystems (Hall 2014) impacted by the exposure to radioactive isotopes; and depending on the isotope, half-life and particles emitted (see Appendix 1), can result in death, species decline, habitat fragmentation, or radioactive sources contaminating food chains. Ultimately, such a green criminological and victimological gaze shines a light on the importance of successfully combating the theft of radioactive isotopes.

Crimes such as TRI and the theft of the vehicles that transport them endanger community safety because it represents a potential risk of social (human health) and environmental (ecosystem and biodiversity) harm. The propensity of isotopes to contaminate threatens the human and biodiversity living environment because its impact can be long-term and large-scale and remediation of the damage can involve the use of human resources at risk and high economic costs (see CNSNS 1985; Nazaré, 1987; Carregado and Trujillo-Cerda 2001; Miranda et al. 2005; Vieira 2013; Fuini et al. 2013; Clemens and Casani 2016); in addition, the potential environmental harm that may result in non-human victims (flora and fauna) and long-term environmental harm must also be considered. However, the impact of mishandling radioactive isotopes as a crime or environmental harm has not been documented in the green criminological literature.

Gaps for future research

Studies are needed to forecast (model) or estimate the social and environmental impact of radioactive contamination (e.g., Reshetin 2005; Evseeva et al. 2009; Andersson et al. 2021) considering the most frequently stolen radioactive isotopes in the country and consequently generate special contingency plans for these isotopes to safeguard the human population and establish institutional strategies (governmental and private) for actions to repair the environmental harm.

Furthermore, although it may seem exaggerated, the potential of the isotopes stolen in Mexico to create weapons of mass destruction or to be used as weapons remains to be analyzed; although several of the isotopes identified in this study have a half-life of a few hours (e.g., ^{99}Mo, ^{99m}Tc, ^{131}I, ^{223}Ra), others can emit radiation for days or years (e.g., ^{192}Ir, ^{60}Co, ^{137}Cs, ^{241}Am, ^{133}Ba) (see Appendix 1), considering that isotopes such as ^{192}Ir can be used in the production of bombs (RDD's).

Although this study did not identify cases of theft of radioactive isotopes for terrorist purposes, it is true that the context of public insecurity in Mexico has led to specialized weaponry and innovation for combat among criminal groups, for example, the modification of conventional drones to bomb rural communities, to perform remote surveillance monitoring of state security forces, to transport drugs across borders, and to coordinate armed attacks (see Bunker and Sullivan 2021; Krame et al. 2023); thus, it cannot be dismissed that radioactive isotopes "potentially" can be used as weapons in Mexico's security context, and criminal groups have not "yet" found the illegal trafficking of radioactive isotopes to be a profitable source of income.

Government efforts should be focused considering public security conditions, strengthening real-time surveillance strategies for containers containing radioactive isotopes during transport. In addition, the national registry of radioactive isotopes should be promoted through inventories and audits to achieve more control over radioactive isotopes and orphan sources. The TRI is relevant and requires future studies from green criminology because it is a crime that puts the health of people, biodiversity and ecosystems at risk, and it is also a crime that is interrelated to the context of generalized crime in Mexico.

A strategy to strengthen community safety is to improve inter-institutional cooperation and promote social participation by raising awareness of the dangers of mishandling radioactive isotopes, as well as to (continue to) strengthen the relationship and trust of society with both public security and nuclear safety authorities.

Conclusions

The theft of radioactive isotopes (TRI) in Mexico is a growing phenomenon in which four factors of social and environmental importance converge: public security, public health, environmental protection and community safety. This crime originates from the theft of the vehicles that transport them, which derives from the conditions of public insecurity in the country. The theft of the vehicles that transport them is increasing despite the security strategies implemented by governmental institutions, and although the number of radioactive isotopes recovered has increased, it represents a potentially harmful security problem that endangers environmental and community safety. Although radioactive isotopes play an important role in human activities, the mishandling of isotopes represents a social and environmental problem of regulatory relevance for security and community safety. The TRI in Mexico is a crime that must be approached in a multidisciplinary way in order to promote governance, communication and collaboration between the different government, private sector and society to reduce the risks of theft, as well as to reduce the human and environmental vulnerability present in the theft of radioactive isotopes.

Appendix 1

Description of radioactive isotopes theft in Mexico during 2011–2023

Isotopes	Particles	Category*	Half-life	Main uses	Hazard
^{137}Cs	γ	I	30 years	Used to determine the density, porosity, and moisture or hydrocarbon content of geological structures for well logging of oil and gas wells. It is also used in teletherapy in the medical sector (Bergman and Pettersson 1994)	In the air, cesium can travel long distances before being deposited on the ground or in water. Most cesium compounds dissolve in water. In moist soils, most cesium compounds are highly soluble. Cesium adheres strongly to most soils and does not burrow below the soil surface (CDC 2016)

Isotopes	Particles	Category*	Half-life	Main uses	Hazard
^{60}Co	β, γ	I	5.7 years	Used to sterilize medical equipment and consumables, in plastics manufacturing and food irradiation, as well as for radiation therapy for cancer treatment (CDC, 2016)	Exposure to radioactive cobalt can be very dangerous to health. Depending on how close one is to the source of radioactive cobalt, cells in the body can be damaged by gamma rays that can pass through the body, even without touching the ^{60}Co. The radiation emitted by ^{60}Co can also damage cells of the body if eaten, drunk, breathed, or touched by anything that contains ^{60}Co. The extent of the damage depends on the amount of radiation, which in turn depends on the activity of the radioactive material and the duration of exposure. Most of the information about the effects of radiation exposure come from brief exposures. The effects of exposure to very low levels of radiation for long periods of time are not known. If a person is exposed to enough radiation, they may experience a reduction in the number of white blood cells, which can lower resistance against infection. The person may also experience blistering and burning of the skin and hair loss from the exposed area (CDC 2016)

Isotopes	Particles	Category*	Half-life	Main uses	Hazard
^{241}Am	α	II	433 years	A compound of americium (Am) and beryllium (Be) is used as the neutron emitter in a neutron probe, which is used to measure the amount of water in soil and log wells	Americium released into the air (from nuclear weapons tests) sticks to particles that rain and snow which will eventually deposit on soil and water. Small airborne particles can travel far from the release site. Americium released into water attaches to particles in the water or to sediment at the bottom. Americium adheres firmly to particles in soil and does not go very deep into the soil. Plants can take up small amounts of americium from soil and fish can take up americium, but little accumulates in their tissues. In shellfish, americium is attached to the shell and not to the parts that are eaten (CDC 2016)
^{192}Ir	γ	II	74.2 days	Used in industrial radiography applications ^{192}Ir is installed in movable instruments and frequently transported, requiring regular replacement due to a shorter half-life (NASEM, 2022). It is also used in the treatment of cancer through brachytherapy due to the emission of gamma rays	^{192}Ir is dangerous just like any other radioactive isotope. The only reports related to iridium lesions concern accidental exposure to ^{192}Ir used in brachytherapy. High energy gamma ray radiation from ^{192}Ir may increase cancer risk (Secretaría de Economía, 2020). External exposure can cause burns, radiation poisoning, and death. Ingestion of ^{192}Ir can burn the lining of the stomach and intestines. ^{192}Ir, ^{192m}Ir, and ^{194m}Ir tend to be deposited in the liver, and can pose health risks from both gamma and beta radiation (IAEA 2013)

Isotopes	Particles	Category*	Half-life	Main uses	Hazard
^{99}Mo	β	III	66 h	^{99}Mo is the parent isotope of ^{99m}Tc, the most widely used radionuclide in medical imaging. Because ^{99m}Tc is unstable and decays rapidly, it is its more stable parent isotope, ^{99}Mo, that is produced and transported to hospitals (Li 2017)	It does not represent a danger to people and the environment due to its very short half-life (Monroy-Guzmán and Alanís-Morales 2010)
^{131}I	β, γ	IV	8 days	Used as a form of radiotherapy for many years to treat some diseases of the thyroid gland, such as hyperthyroidism and cancer (González-Rivero et al. 2012; Zimmerman and Bergeron 2016)	Tumors derived from ionizing radiation emitted by ^{129}I and ^{131}I can form. A major route of exposure is ingestion of milk from cows that graze on iodine-contaminated crops. Other routes are the ingestion of fruits and vegetables and inhalation. Thyroid cancer is the main risk associated with radioactive iodine. Iodine is essential for the growth and development of children. However, children are more sensitive to the harmful effects of excessive amounts of radioactive and non-radioactive iodine because their thyroid glands are still developing (CDC 2016; Navarro and Astorga 2000)
^{223}Ra	α	IV	11.4 days	Used for medical purposes as a treatment for adult patients with castration-resistant prostate cancer with symptomatic bone metastases and no known visceral metastases (National Cancer Institute 2022)	**

Isotopes	Particles	Category*	Half-life	Main uses	Hazard
^{57}Co	γ	V	272 days	Used in clinical and scientific research, ^{57}Co is a radioactive metal used as a radiomarker for the absorption of vitamin B12 in the Schilling test	Regarding health damage from ^{57}Co, it has been documented that exposure to high levels of cobalt radiation can cause alterations in the genetic material inside cells, which can lead to the development of certain types of cancer. It may also affect the lungs and heart and cause dermatitis. Effects on the liver and lungs have also been observed in animals exposed to high levels of cobalt (CDC 2016)
^{99m}Tc	γ	**	6 h	^{99m}Tc is currently the most widely used radionuclide in the field of nuclear medicine (Radiodiagnostics). It has ideal characteristics for obtaining images in a gamma camera, has a short half-life, and is able to bind multiple compounds (Rodríguez-López et al. 2017)	It does not represent a danger to people and the environment due to its very short half-life (Monroy-Guzmán and Alanís-Morales 2010)
^{133}Ba	γ, Ξ − ραψ	**	10.5 years	Used for a variety of purposes, including as an X-ray radiocontrast agent and a gamma source in multiphase flow meters used in the oil and gas industry (National Isotope Development Center 2019; Stanford Environmental, Health and Safety 2020)	**

*This categorization provides a relative ranking of radioactive sources in terms of their potential to cause immediate harmful health effects if the source is not safely managed or securely protected. Sources are classified into five categories: Category I sources are potentially the most dangerous and Category V sources are not dangerous (IAEA, 2003, p. 27; 2009)

**Data not found

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