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European cooperation to tackle the legacies of hexachlorocyclohexane (HCH) and lindane

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A B S T R A C T

Hexachlorocyclohexane (HCH) waste isomers from lindane production are the largest single POPs legacy, with an estimated 4.8 to 7.4 million tonnes of disposed waste. The largest part of this waste – 1.8 to 3 million tonnes – was disposed in Europe, where most producers were located. This paper provides a short overview of projects supported by the European Union (EU) to address this waste legacy and to implement the Stockholm Convention for this group of POPs with associated protection of soil, ecosystems and human health. We report here particularly on the results of a project financed by the EU called the “HCH in EU project”, which aimed to develop a systematic inventory of sites where HCH was handled and potentially resulted in contamination. The compiled information provide guidance for competent authorities to further assess their national HCH inventory and to further develop a strategy to address this large POP legacy in future. The systematic inventory revealed that there were at least 299 sites where HCH was handled. These sites include 54 former production sites, 76 pesticide processing plants that used lindane, 59 uncontrolled HCH waste isomer deposits, 29 landfills with HCH waste, 34 former or current storage sites for stocks of obsolete pesticides including technical HCH or lindane, and 16 HCH treatment or disposal sites. Additionally, at 31 of the sites lindane/technical HCH was used in applications with significant risk of soil pollution, such as wood treatment. The number of sites in this latter category is likely higher and will need further assessment. In addition to this inventory, the “HCH in EU project” produced detailed country reports, a guidance document for how to find potentially HCH-impacted sites, and a strategy document for implementing the sustainable management of these sites EU-wide, with proposed actions at the EU, country, and site level. Furthermore, the project has facilitated information exchange and – together with other related EU projects – has led to sharing information and best practices among member states and to establishing a network of authorities and other stakeholders working on the lindane/HCH waste legacy. This collaboration will facilitate a more systematic and better coordinated process to further assess, secure, and remediate the large HCH waste legacy and reduce and control lindane/HCH releases in the EU and possibly beyond. Such a coordinated effort and exchange of information for inventorying and managing contaminated sites might also be useful for other POPs such as PFOS/PFOA or dioxins.

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1. Introduction

Hexachlorocyclohexane (HCH) was one of the most extensively produced pesticide, industrially manufactured mainly after the Second World War [1]. HCH was available in two formulations: technical HCH and lindane. Generally, technical HCH contains the following percentages of HCH isomers: 55–80% alpha (α), 5–14% beta (β), 8–15% gamma (γ), 2–16% delta (δ), and 3–5% epsilon (ε) [2]. Of these HCH isomers only the γ -isomer has specific insecticidal properties [3,4]. Lindane contains more than 90% γ-HCH produced by separation of the γ-isomer from the technical HCH mixture [1,4].

The production and application of lindane and technical HCH during the last 7 decades have resulted in environmental contamination of global proportions [1,5-7]. For each tonne of lindane, 8–12 tonnes of other HCH isomers were produced as unwanted by-products [1]. Therefore, the production of the approximately 600,000 tonnes of lindane has generated 4.8 to 7.2 million tonnes of HCH waste isomers [1]. This HCH POP-waste was mostly dumped uncontrolled at many sites in the former producing countries around the world [1,6,7] and were partly released into rivers [8]. Some of the large HCH-contaminated sites have been investigated for example in Brazil [9,10], China [11,12], France [13], Germany [14-17], India [18-20], and Spain [21-23]. Therefore in the case of HCH, the major POP contaminated site load and risk is related to the production and related disposal of HCH waste isomers at and around production sites [1]. The disposal of the major POPs share at the production sites of HCH is different from e.g. PCB where most (likely >95%) of the produced 1.5 million tonnes of PCB was sold as product and most PCB-contaminated sites were then generated along the life cycle of PCBs [24,25]. However also contamination legacies exist at the PCB production sites [26-29].

In May 2009, α-HCH, β-HCH, and lindane (industrial γ-HCH) were listed in the Stockholm Convention as persistent organic pollutants (POPs) due to their persistence, toxicity and long-range transport [30–33]. Toxic effects of HCH isomers include neurological disorders [34,35], cancer [36-38], endocrine disruption [36,39,40], and reproductive disorders [36,41,42]. Thus, as listed POPs these HCH isomers need to be addressed globally, including the obsolete stockpiles and large waste volumes remaining as a legacy from the historical production, use and disposal of HCH [1,43].

Most of the production and use of lindane took place from the 1950s to the 1990s in Europe. with minor use of technical HCH in the late 1940s and early 1950s. This resulted in HCH pollution and an estimated 1.8 to 3 million tonnes of deposited HCH waste isomers from the production of 290,000 tonnes of lindane [1,6,7,43]; [44]). In a recent study it was documented for three of the European HCH-contaminated production/disposal sites that the footprint of pollution can increase over time [43]. The study also highlighted the lack of activities on the part of former HCH producing countries to manage their large HCH waste deposits and fulfil their obligations as Parties to the Stockholm Convention, and documented that HCH-contaminated sites were not appropriately addressed in the Stockholm Convention national implementation plans of several European countries [43].

Legacy POP pollution, especially in soils and sediments, is a contemporary issue and human health risk since these POPs can accumulate in free range cattle and chicken, which can lead to human exposure [24,25,45]. For example, the surroundings of an HCH production site in a rural area along the Sacco river (Sacco Valley, Central Italy) were found to be contaminated with HCH (in particular the more persistent waste isomer β-HCH), which has resulted in HCH-contamination of cows and cow's milk as well as human blood in the area [46]. Cow's milk and products from farms located in the area had high β-HCH levels of up to 0.062 mg HCH/kg [46,47]. This was more than 20 times the regulatory limit of 0.003 mg β-HCH/kg for milk, according to European law (European Commission Regulation No 149/2008). Additionally, HCH released from such waste deposits can leach into ground water and surface water [17] and result in contamination of fish. This has been documented in the Elbe river downstream of the former production sites in Bitterfeld [17]. The release of POPs from landfills and other deposits can strongly increase due to flooding events [48-50], resulting in increased HCH (or other POPs) levels in surface water and in fish, as observed in the Elbe river after a flooding event in 2002 downstream of the former HCH production sites in Bitterfeld and Hamburg [17]. Another study reported that 120 kg HCH are released per year from one landfill in Spain into surface water [22].

The remediation or securing of two HCH deposits was recently documented. A first HCH waste deposit in France from the former lindane producer Ugine-Kuhlmann company was excavated together with the contaminated soil and sent for destruction at various waste incinerators in Europe by the current owner of the site. The remediation of that site has now been finalized [51]. An HCH dumpsite in Spain was transferred to a new established landfill [21], with some HCH releases to the environment during the transfer process [52].

The European Union and its Member States are Parties to the Stockholm Convention, which was first implemented in the EU law by Regulation (EC) No 850/2004 to assess, manage, and eliminate POPs [53]. That regulation was recently replaced by the recast Regulation (EU) 2019/1021 on POPs [54]. The EU developed a first 'Community Implementation Plan' (CIP) in 2007 (SEC (2007) 341). The CIP was first updated with a 'Union Implementation Plan' (UIP) in 2014 (COM (2014) 306 final), and further updated in early 2019 (COM(2018)848 final). In addition, the EU countries have individual national implementation plans (NIPs). Within the UIP, the European Union has financed several projects to assess and address the HCH POP legacy in Europe. An inventory of POPs waste and contaminated sites is a prerequisite for the proper management of certain POPs. Furthermore, the responsible authorities need support for managing, regulating, securing, and remediating large contaminated sites and waste deposits. Therefore, the EU financed a project aiming to develop an inventory of HCH production sites, waste deposits, landfills, and treatment centres in the EU, and to assist local, regional, or national public authorities confronted with lindane and HCH-related issues by providing them with support, expertise, advice, and consultancy. Our paper describes the major outcomes of this project and provides an overview of other EU-financed projects aiming to address the HCH/lindane legacy. This is part of the implementation of the Stockholm Convention and contributes to the protection of soils, ecosystems and human health.

2. Methods

2.1. Assessment of the HCH contamination of EU member countries and methodology development

As part of the "HCH in EU project," the European sites were HCH were handled were mapped following a stepwise approach, starting from the list of countries where lindane/HCH was produced [1]. The EU-member states on this list were Austria, Croatia, Czech Republic, France, Germany, Hungary, Italy, Netherlands, Poland, Romania, Slovakia, and Spain. In the second step draft country specific lists of known sites where lindane/HCH was handled where compiled, and these draft country specific lists of sites were shared with all known relevant stakeholders, and the lists were updated based on the feedback received.

Additionally, a literature survey of HCH-contaminated sites in

Europe was conducted and related information, including peer reviewed publications, national implementation plans, national reports, and grey literature screened and relevant information compiled. Further, information was reviewed from the thirteen Forums of the International HCH and Pesticide Association (IHPA 2013), which has been working to address this legacy for the past 30 years and has generated detailed information on HCH sites [55] and pertinent information was extracted.

Also Regional and local authorities and other stakeholders were interviewed and compiled a list of all countries with HCH production with the support of national teams. This outreach campaign ended with two open online workshops used to present the project results and request help with identifying further sites. The country specific lists of sites were again updated based on this information received during the outreach campaign.

Furthermore, different types of sites where HCH/lindane was handled were defined and compiled (see Section 3.2.1). Based on this structured assessment, a methodology was developed that can be utilized by countries to further map and assess HCH-contaminated sites in a systematic manner (Section 3.5). In addition, potential co-pollutants (POPs and other hazardous pollutants) were assessed and compiled for the different site types (see Section 3.3). Specific monitoring or analysis of soils or sediments were not conducted as part of this project since the focus of the project was the compilation of information available in institutions and literature and not to generate monitoring data.

2.2. Compilation of other EU funded projects related to HCH management

Activities of other EU funded projects dealing with the HCH legacies in the European context and supporting the implementation of the Stockholm Convention for this POP group were mapped, assessed, and summarized. For this the respective project documents were evaluated and, for some of the projects, contacts were made stakeholders involved in the current and former project activities to compile additional relevant information and for verification of findings.

3. Results and discussion

3.1. Projects conducted or currently implemented for addressing HCH and lindane contamination in the European context

In addition to our “HCH in EU project” (Section 3.1.1 and Sections 3.2-3.6), we identified five other EU-funded initiatives aiming to address the HCH/lindane legacy in Europe. Below we give an overview on the different scopes, methods, and approaches of these projects and studies and some major outcomes to date.

3.1.1. EU pilot project “HCH in EU project” reviewing the presence of lindane and HCH sites in the EU

The project consortium consisted of TAUW, CDM Smith Europe GmbH from Germany, and Sociedad Aragonesa de Gestión Agroambiental (SARGA) S.L.U from Spain. Because the project spans various international parties and locations, good cooperation and sharing of information was/is essential. To facilitate this, the project uses tailor-made digital environments including a Geographic Information Model (GIM) to collect, organize, store, interpret, assess, and report all inventory data from the different locations. The GIM Viewer is available to the project team members, the European Commission, and project stakeholders, and will be made available to the public.

The project consortium conducted the “HCH in EU project” to evaluate and address the presence of lindane and HCH in the EU. The diffuse pollution from the use of lindane/HCH in agriculture and forestry was not in the scope of the project. This pilot project included the following objectives:

(1) provide an overview of the legacy of the lindane and technical HCH production in Europe (for outcome see Sections 3.2 to 3.3);
(2) to assist EU activities currently developing best practices for the sustainable management of HCH contaminate sites at six HCH contaminated pilot test sites (see Section 3.4);
(3) a report on the use and legacy of HCH in the EU, as a guide to help identify further potentially HCH-impacted sites in addition to the ones already in the inventory (See section 3.5);
(4) a guidance to develop an EU-wide strategy to sustainably manage HCH-impacted sites, to address the legacy of HCH and lindane in the EU (See Section 3.6).

Webinars including a final workshop were conducted within the project to inform policy makers and other stakeholders as well as the interested public (https://lnkd.in/dzbJ_hD).

In total, 299 sites where HCH and lindane were produced or handled and therefore seen as potentially HCH-contaminated sites were identified. The major outcomes of this project are compiled in Sections 3.2 to 3.6 below.

3.1.2. Project LIFE DISCOVERED

The project LIFE12 ENV/ES/000761 with the acronym DISCOVERED LIFE – “Lab to field, soil, remediation demonstrative project: New ISCO application to DNAPL multicomponent environmental problem” (01/2014–06/2017). The project was led by the authorities of Aragon together with the Sociedad Aragonesa de Gestión Agroambiental (SARGA) and the International HCH & Pesticides Association.

This project addressed the contamination at the HCH/lindane megasite in Sabiñanigo south of the Pyrenees, where the company Inquinosa has dumped several hundred thousand tonnes of HCH-waste over decades [22], with large associated practical challenges, health risks and remediation costs. At present, tests are being performed to destroy and eliminate the heavy layers of oily pesticide residues laying on the bottom of the aquifer.

The project dealt with a pilot scale chemical oxidation technique of dense contaminants and pesticides existing in the Bailín aquifer, Sabiñánigo (Huesca). One of the main tasks is the implementation of a pilot test based on an ISCO with activated persulfate technique which addresses the oxidation of the DNAPL with the aim of assessing the risk reduction and evaluating the transferability of the technique from lab to field. The ultimate goal: to clean up the site and reduce the existing pollution load by chemical oxidation of the contaminants and pesticides and their transformation into less harmful compounds, was achieved for all the objectives set out in it: the use of the in situ chemical oxidation (ISCO) technique has demonstrated its feasibility at the site, with successful results in the degradation, greater than 90% on average, of:

- the residues of HCH (Lindane manufacture's residues)
- and of the intermediate metabolites existing in the site (polychlorinated benzenes and phenols), that on average suppose more of the 90% of the organic compounds present in the contaminated water).

The study also assessed the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDFs) as by-products (see Section 3.3.2).

The project produced a movie about this site, since pictures can transmit another part of the story than reports and data. The film won an international award and was shown at the 13th International HCH & Pesticide Forum organized as part of the predecessor project [56]. This forum brings together all stakeholders working on HCH and other pesticide-legacy issues and technical solutions, as well as also politicians that support political solutions [55].

3.1.3. EU project LIFE SURFING

The EU LIFE SURFING 2019–2023 project is led by the authorities of Aragon together with the University of Madrid, the University of Stuttgart, and the International HCH & Pesticides Association. This project deals with the same area and contamination as in the Project LIFE DISCOVERED. The project aim to develop a practicable remediation technique for soils with non-aqueous phase liquids (DNAPL). This technique will be developed in a demonstrative project that will combine the use of chemical oxidation techniques with the action of surfactants. A project website has been established were project background and details can be found and outcomes will be reported (http://www.lifesurfing.eu/en/life-surfing-project)/

This project includes the organisation of the 14th International HCH & Pesticides Forum (the event was originally planned for 2021, but had to be cancelled due to COVID-19 and is currently planned for end 2022 or beginning 2023 depending on the results of the field tests).

3.1.4. EU Interreg Project LINDANET

The EU Interreg LINDANET 2019–2023 project addresses 6 EU regions that are seriously confronted with HCH problems due to the local productions of lindane: Aragon and Galicia (Spain), South Bohemia (Czech Rep), Sachsen-Anhalt (Germany), Lazio (Italy), and Silesia (Poland). These regions are represented by the Government of Aragon, the Government of Galicia (General Directorate of Environmental Quality and Climate Change), the Regional Development Agency of South Bohemia - RERA a.s., the State Office for Contaminated Soils of Sachsen- Anhalt (LAF), the Experimental Zooprofilactic Institute of Lazio and Toscana (IZSLT), and the Central Mining Institute, respectively.

The project has set the following general objectives:

- To create a network of European regions affected by contamination derived from lindane production wastes (HCH and others),
- To establish an Action Plan focused to the solutions to the problems in each region,
- To exchange experiences and knowledge that contribute to addressing the contamination derived from the HCH and lindane production wastes,
- To involve all stakeholder groups in the knowledge generation and the solution to the problem,
- To contribute to the Policy Learning Platform of the Interreg Europe programme,
- To raise public awareness about the HCH pollution and other related contamination problems derived from POPs and Obsolete Pesticides.

As of now, four Interregional Thematic Workshops have been held. The partners have also organized in their regions 18 Stakeholder workshops and meetings, and 2 exchanges with the HCH in EU project. Additionally, 1 Thematic Workshop is taking place by the end of November 2021. All workshops were in webinar format due to COVID-19. After November, the plan is for each partner to implement Action Plans during the following year, after receiving approval from the Project secretariat.

In 2021, the LINDANET project conducted a SWOT analysis that identified the most important elements needed for remediation: long-term funding, partnerships, and political endorsement. The LINDANET project has confirmed the overall benefits of interregional cooperation, forward looking approach, and the need for a permanent platform for sharing knowledge and experiences derived from all aspects of lindane contamination management and remediation. The strategy going forward is also recommending to also include governance, transparency, and awareness raising as important themes in the LINDANET Action Plans now under design and implemented during 2022 and beginning of 2023. But the lack of long-term financing, partnerships, and political endorsement are seemingly insurmountable barriers that need to be tackled to achieve a final solution for the mega-sites in the LINDANET partner regions. Additionally, more R&D projects are needed, to help bring down remediation costs. Additional EU support for the Regions is also needed.

The EU Interreg Project LINDANET has developed a project website where further information can be found and followed (https://www.interregeurope.eu/lindanet/).

3.1.5. EU project LIFE POPWAT

The EU LIFE POPWAT 2020–2024 project is led by the University van Liberec in the Czech Republic in cooperation with the water treatment companies Photon Water (Czech Republic) and SERPOL (France) and the University of Aarhus (Denmark). With the help of so-called "Wetlands + system", Wetland+ is a highly adaptable system that integrates a series of reactive zones along a drainage pathway avoiding the need for pumping. Reactive zones comprise zerovalent iron (reducing environment), a sorbent material zone, a biodegradation zone and a wetland zone, which is principally to polish residual biological oxygen demand from the preceding steps. HCH and lindane-contaminated waters are treated effectively in a very simple way. Two such water treatment plants are under construction at two different locations, one where lindane was produced at the former Azot factory in Jaworzno in Poland, and one in Hajek in the Czech Republic, where 3000 tonnes of HCH-containing waste were dumped. After testing the treatment plants at these two sites, the plan is to construct the same type of treatment plants at five other lindane production or HCH waste dump sites, so that these site owners can take advantage of the experiences gained at the initial two sites. Since the assessment and management of legacies from HCH production sites are complex, there is great need for such cooperation and information exchange that can eventually create synergies.

Also the EU Project LIFE POPWAT has developed a project website where further information can be found and followed (https://cxi.tul.cz/lifepopwat/).

3.1.6. Project Citizens' Rights and Constitutional Affairs

In 2015, a study was commissioned by the European Parliament's Policy Department for Citizens' Rights and Constitutional Affairs at the request of the Committee on Petitions (PETI). The related report, published in 2016, provided an updated mapping of the lindane production plants and HCH waste dumping sites in the EU [57]. Potential remediation techniques, including lessons learned implementing these techniques in the laboratory and field, were also provided together with a selection of best practices for contaminated site restoration and stakeholder engagement. The study also analysed information on lindane from official websites [57]. Therefore, their report served as one of the information sources for the HCH inventory of the "HCH in EU project" described in this publication.

3.1.7. EU legal framework that facilitates monitoring of HCH/POPs

The Water Framework Directive (WFD [58]; includes many POPs and imposes monitoring obligations on Member States to progressively reduce emissions, discharges, and losses of priority substances to waters. The WFD establishes two types of environmental quality standards (EQS) for priority substances: annual average concentrations and maximum allowable concentrations. All HCH isomers are included in the list of priority substances. EQS have been established for lindane as well as for the sum of HCH isomers.

Different monitoring activities for POPs in air, including HCHs, have been conducted or are ongoing in the EU. EMEP (European Monitoring and Evaluation Programme) is the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe. It is a scientifically based and policy driven programme under the UNECE Convention on Long-range Transboundary Air Pollution. EMEP's activities are supported through the work of a number of EMEP centres and task forces (https://www.emep.int/). As of 2016, EMEP operates 12 active sampling sites that have long-term monitoring data for POPs in air and aerosols. Six of these sites have a co-located MONET passive sampler and were therefore selected for a recent study: Birkenes (Norway), Košetice (Czech Republic), Pallas (Finland), Råö (Sweden), Stórhöfði (Iceland) and Zeppelin (Norway/Svalbard). Each of these EMEP active samplers has been monitoring some legacy POPs since at least 2004 [59]. Such monitoring activities can give valuable complementary information on the status of and trends in HCH emissions.

In absence of an EU soil legislation, there are currently no common provisions on the presence of lindane or HCH monitoring and assessment in soil. However, such standards and screening values exist in several national legislations. The EU Soil Strategy for 2030 recently announced that the Commission will table a new legislative proposal by 2023 to achieve good soil health across the EU by 2050. In this context, the Commission will consider proposing legally binding provisions for the identification, registration and remediation of contaminated sites.

3.2. Inventory of HCH sites in EU where HCH was handled (main task 1 of the “HCH in EU project”)

As mentioned above, a major goal of the “HCH in EU project” was the development of an inventory of sites where HCH/lindane was handled and disposed of in the past. The inventory of a POP is the basis for managing that specific POP and prioritizing action. In our earlier review of the lindane production and HCH legacy, we already compiled the major countries that had HCH/lindane production and their estimated amounts of disposed waste isomers [1].

One of the tasks of the “HCH in EU project” was to make an inventory of potentially HCH-impacted sites in Europe. By this

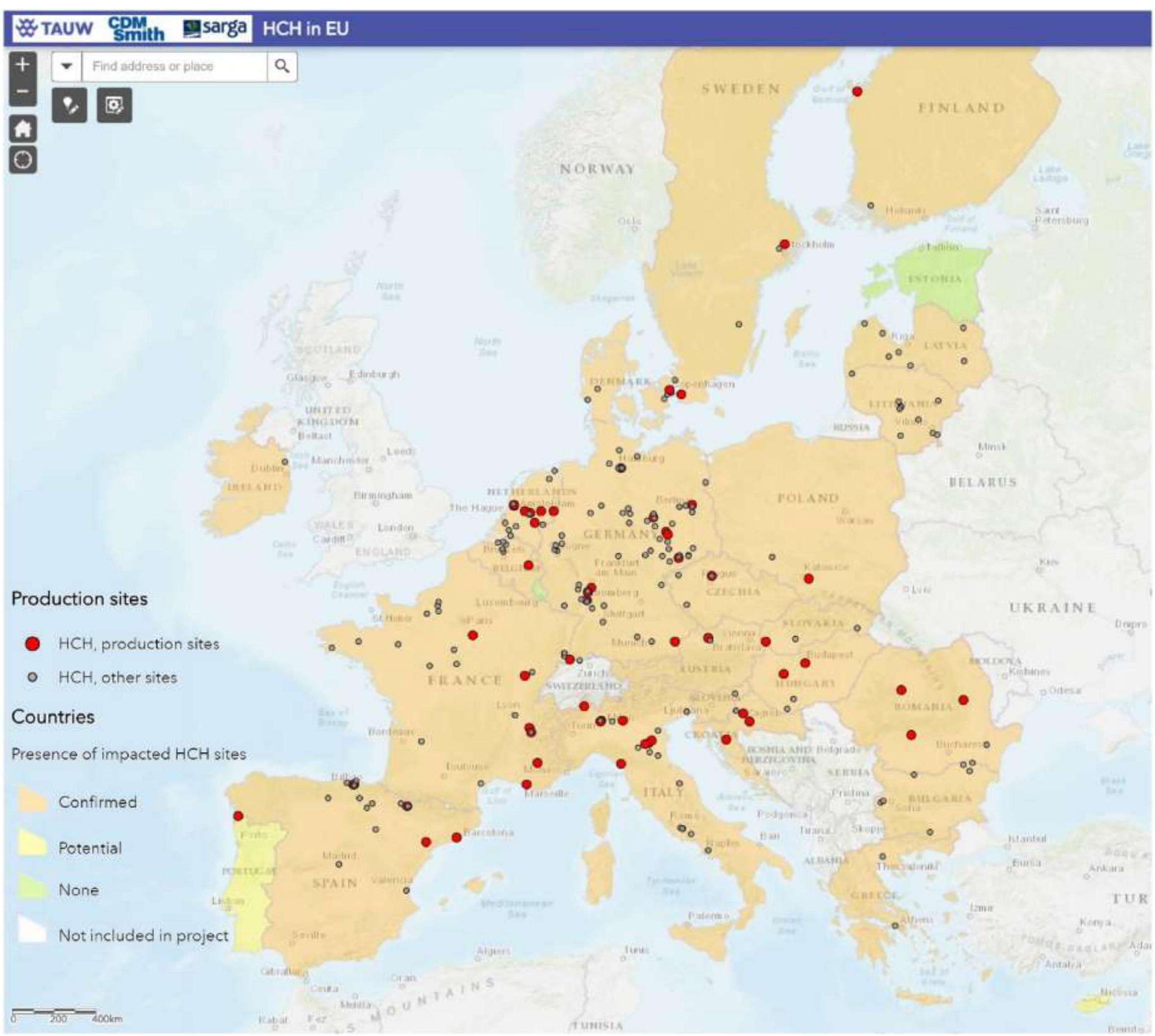

Fig. 1. EU overview map with 299 identified sites where HCHs were handled, including 54 high-risk sites.

Table 1
Summary of the EU-wide inventory of sites where lindane and HCH handling was confirmed developed and compiled within the “HCH in the EU project”.

Category	Description	Number	Remarks
Production sites	Sites where technical HCH and/or lindane were produced	54	When not remediated, these are mostly high-risk sites close to urban settlements, often with HCH-waste deposits.
Processing sites	Sites where technical HCH and/or lindane were processed or formulated into market-ready pesticides	76	This is only the tip of the iceberg, as most pesticide producers between 1950 and 1980 used lindane.
Waste deposits	Sites where lindane production wastes (HCH) were dumped without proper containment	59	Often in the direct vicinity of production sites; when not remediated, these are mostly high-risk sites.
Landfills	Sites where lindane production wastes (HCH) were disposed of with some containment measures	29	These sites are usually connected to large production facilities. The distinction between landfills and waste deposits is vague.
Storage facilities	Storage facilities for obsolete stocks of POP-pesticides, including lindane and HCH	34	Present in former socialist countries, these sites are often large collection points of obsolete pesticides where lindane is only a minor component.
Treatment centres	Incineration facilities, soil treatment centres, and recycling centres	16	These facilities are state of the art and operate in controlled environments. Environmental impacts of HCH released from these locations are unlikely.
Use sites other than agricultural use	Sites that do not fall under the above categories, but lindane/technical HCH was used there for other purposes. Examples include wood treatment/preservation facilities.	31	Alternative uses of lindane in products were found during the inventory project. These are described in a separate project report to help further expand the country specific site inventories.

Table 2
Overview of identified sites where HCH/lindane handling was confirmed developed and compiled within the “HCH in the EU project”.

Country	Total Sites	Production sites	Processing sites	Waste deposits	Landfills	Treatment centres	Storage facilities	Other
Austria (AT)	**2**	1	0	1	0	0	0	0
Belgium (BE)	**6**	1	3	1	0	1	0	0
Bulgaria (BG)	**7**	0	0	0	0	0	7	0
Croatia (HR)	**2**	1	1	0	0	0	0	0
Cyprus (CY)	**0**	0	0	0	0	0	0	0
Czech Republic (CZ)	**4**	1	1	0	1	0	0	1
Denmark (DK)	**8**	1	5	2	0	0	0	0
Estonia (EE)	**0**	0	0	0	0	0	0	0
Finland (FI)	**3**	1	1	1	0	0	0	0
France (FR)	**38**	6	7	13	2	2	0	8
Germany (DE)	**98**	12	32	20	13	11	6	4
Greece (EL)	**2**	0	2	0	0	0	0	0
Hungary (HU)	**5**	1	3	1	0	0	0	0
Ireland (IE)	**1**	0	0	0	0	0	0	1
Italy (IT)	**38**	8	8	6	0	0	0	16
Latvia (LV)	**7**	0	0	0	0	0	7	0
Lithuania (LT)	**10**	0	0	1	0	0	9	0
Luxembourg (LU)	**0**	0	0	0	0	0	0	0
Malta (MT)	**0**	0	0	0	0	0	0	0
Netherlands (NL)	**18**	7	6	0	2	2	1	0
Poland (PL)	**3**	1	0	0	1	0	1	0
Portugal (PT)	**0**	0	0	0	0	0	0	0
Romania (RO)	**12**	3	1	7	0	0	1	0
Slovakia (SK)	**5**	1	1	0	1	0	2	0
Slovenia (SL)	**2**	1	0	0	1	0	0	0
Spain (ES)	**22**	6	2	6	8	0	0	0
Sweden (SE)	**6**	2	3	0	0	0	0	1
Total	**299**	**54**	**76**	**59**	**29**	**16**	**34**	**31**

project now all inventory data for the discovered sites where HCH was handled or disposed in all the EU member states are stored in the Geographic Information Model (GIM). This enables now countries to localize sites where it is confirmed that HCH was handled and therefore could be potentially impacted by contamination (see Fig. 1). For each EU country a report providing a country specific list of such sites was developed (number of sites in Table 2).

The “HCH in EU project” found a total of 299 sites where HCH and lindane have been handled (Tables 1 and 2). These sites were subdivided into 7 categories (see Table 2 and description in section 3.3): Of these, 54 were former production sites which were estimated to be high-risk sites, with potentially significant impact on people and the natural environment. Many of the high-risk sites are mega-sites with large amounts of deposited HCH waste and extensive contamination of soil and groundwater, which is still spreading into the environment. Furthermore, there are 59 uncontrolled HCH waste deposits, 29 landfills with HCH, 76 pesticide formulation plants that used lindane, 34 current or former storage sites for stocks of obsolete pesticides including HCH or lindane, 16 HCH and lindane treatment or disposal sites, and 31 other sites where lindane or technical HCH was used or handled. Lindane was used in a wide variety of formulations, including: wettable powders; emulsion concentrates; suspensions; solutions; dusts and powders; granules and coarse dusts; baits; preparations for fumigations, aerosols, and special formulations such as powder, solutions, and creams for the use in the fields of human and veterinary medicine, wood treatment or use as plastic additive (see 3.2.1.7) in addition to the major use in agriculture [3]. Because of these diverse uses and formulations of lindane and considering the lindane life cycle (see Fig. 2), it is important to further investigate the category of ‘other’ sites which is certainly much larger than the 31 sites compiled in this first inventory also including the

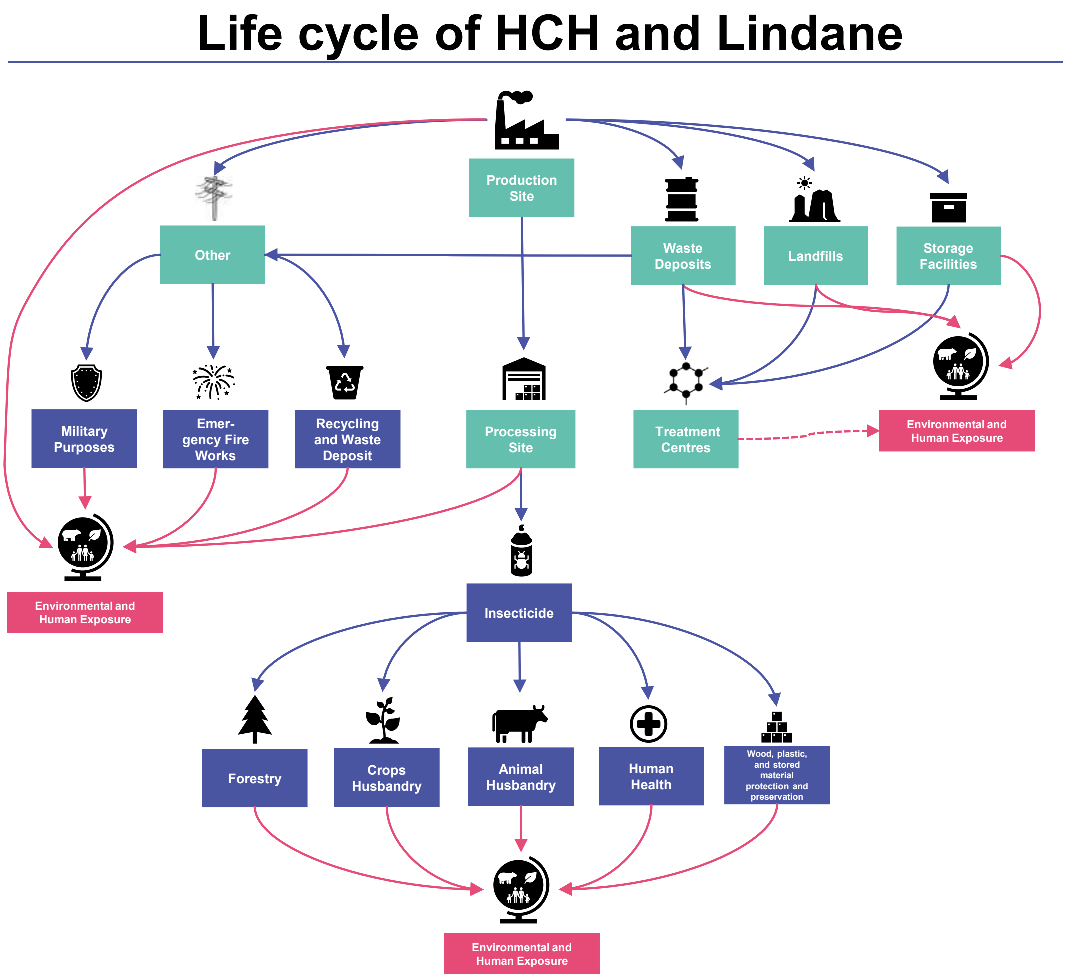

Fig. 2. Lifecycle of former HCH production and use and contemporary impact on the environment and humans.

application sites (see 3.2.1.7). This to alert authorities and owners of such sites where the onsite use of lindane might have resulted in soil contamination.

3.2.1. Categories of sites where HCH was handled

In the first phase of the project, the different categories of sites were HCH was handled were defined to develop a systematic approach for inventory development for the pilot countries. This provides a methodology for other countries to develop HCH inventories through a systematic assessment of the different site types.

Tables 1 and 2 provide an overview of the site types and the number of sites where HCH is/was handled for each of the 27 EU countries. As mentioned, a total of 299 sites have been identified in the EU where lindane or HCH were handled (Tables 1 and 2). Many other sites are suspected to have handled HCH/lindane in particular the application sites other than agricultural use (e.g. wood treatment sites, military uses or cable production), however the evidence uncovered as part of this project was insufficient to confirm more of these sites, therefore they were not added to the inventory.

3.2.1.1. Production sites. Within the entire EU, a total of **54 former production sites** were identified. The size of these production sites varies from massive production facilities such as the Inquinosa site in Spain, with up to 1000 tons/year of lindane production capacity, to small factories such as the one in Valentuna, Sweden, with 500 kg/year production capacity.

3.2.1.2. Formulation sites. A total of **76 processing sites** were identified, however this is likely only the tip of the iceberg. Lindane/HCH was a commonly available product between 1950 and 1980 and was an active ingredient in a variety of pesticides. Most pesticide production companies that operated between 1950 and 1980 have likely used lindane at some point during their existence. The exact impact of lindane/HCH use at these sites is difficult to estimate and will depend on the scale of their activities in relation to the use of lindane/HCH and the respective waste management and the sites.

3.2.1.3. Waste deposits. **59 waste deposits** were identified across the EU. Often these waste deposits received wastes from multiple sites over prolonged periods of time. HCH wastes were often mixed with other (household) wastes. This is a problem particularly common in Germany, and to a lesser extent in France.

3.2.1.4. Landfill sites. **29 landfills** were identified across the EU. Most of these landfill sites were dedicated to the receival of HCH wastes and are connected to large production facilities. The distinction between landfill and waste dump is often vague as quite a few landfills lacked/are lacking appropriate containment measures.

3.2.1.5. Treatment centres. In total, **16 treatment centres** were identified. These include incineration facilities, soil treatment centres, and recycling centres. Most of these facilities are state of the art, highly controlled environments, and adverse impacts of HCH released from these locations are unlikely.

3.2.1.6. (Former) storage facilities. **34 current and former storage facilities of (obsolete) pesticides** are still present, mainly in former Eastern bloc countries. Most of these storage facilities are large collection points of different obsolete pesticides, of which lindane is only a minor component. The largest storage facility identified, in Bulgaria, contains approximately 2000 kg of lindane. Most storage facilities contain less than 200 kg of lindane or have already been cleared but contamination of soils at or around these sites are likely.

3.2.1.7. Major historical uses of technical HCH/lindane and related potentially contaminated sits. As mentioned in the introduction, 290,000 t of lindane were used in Europe for different purposes with some use of technical HCH in the late 1940s and early 1950s [1]. mainly for agricultural use on a large share of Europeans agricultural fields for many crops (Table 3) with major uses in Czechoslovakia, Germany, Italy, France, Hungary, Spain, Russia, Ukraine, Yugoslavia and Greece [6,7]. Some HCH contamination can be found in these areas where lindane or technical HCH was used in the past 70 years, such as in agricultural areas or where veterinary applications like sheep dips were performed [12,60-63]. Due to the moderate persistence of gamma-HCH in soil of approximately 2 years [64] and the moderate volatility, the agricultural soils treated in the 1950s–1990s with mainly lindane contain now HCH concentrations below levels considered polluted [12] and are not considered contaminated sites. However, former mixing areas and storing areas for agricultural and other uses might be contaminated at higher level (Toichuev et al., 2016). Furthermore for some uses of HCH containing pesticides, larger amounts were applied on small space which have likely resulted in elevated contamination of soils (e.g. wood treatment sites) and might possibly still be contaminated sites/hot spots. We identified five different types of such historical uses of technical HCH/lindane (see below). The inventory project identified **31 such "other" sites**, including wood treatment/preservation facilities.

3.2.1.7.1. Use site type 1: agricultural areas

3.2.1.7.1.1. Crops

HCH and lindane were used as a broad-spectrum insecticide for a wide variety of fruit and vegetable crops (including seed treatment), tobacco, (greenhouse) vegetables, and ornamentals. HCH and lindane are applied to crops through a variety of different methods, depending on the desired pest control. Elevated concentrations of HCH are expected in areas where the insecticide was applied. Hotspots are also expected in areas where technical HCH/lindane was stored, mixed, or otherwise handled prior to application. Table 3 provides an overview of the areas of use, plant types, treatment application methods, and potential legacy.

3.2.1.7.1.2. Animal husbandry

Lindane was also used against ectoparasites in veterinary applications and in the treatment of domestic animals and fish (Table 4; [3], leading to increased incidence of certain cancers in farmers [61,62]. The current inventory assessment in Croatia (HR-PL-01) lists a product named Gamacid® T-50, which was produced until 2005 by the pharmaceutical company Pliva Ltd., later Veterina Ltd. The preparation was registered for the treatment of sheep, by dipping them in medicinal bath containing lindane in concentration of 0.03–0.06% for pest control against ectoparasites.

For the external treatment of mange, mites, ticks, fleas etc., dips, sprays, washes, and dustings are used. To ensure optimal contact, such as for mange or lice, animals (such as sheep and other livestock; Table 4) are dipped in baths with various concentrations of pesticides. Sometimes animals are submerged two or three times, and the process can be repeated. In New Zealand assessment of the environmental contamination from sheep dips with POP pesticides have been conducted and a guideline for local authorities were developed/published for systematic assessment and risk management of such sites (Ministry for the Environment New Zealand 2006). Therefore, dipping, mixing and pesticide storage areas at farms having used cattle dipping can be considered contamination hotspots.

3.2.1.7.2. Use site type 2: health care. Lindane was also used in human health care for treatment against ectoparasites. For example, to treat lice or scabies on the head or elsewhere on the body, a lotion or shampoo with a concentration of 0.5–1% of lindane was used. The second line treatment for head lice and scabies was originally exempted under the Stockholm Convention [33], but this exemption was revoked in 2019 by Stockholm Convention decision SC-9/1 [66].

Lindane was also applied in closed rooms, by spraying,

Table 3
Principal areas of major lindane agricultural use (adapted from [3]).

Areas of use	Plant types	Application methods	Potential legacy
Field crops	Peanut, sugar beets, sugar cane, cereals (oats, wheat, barley, rye), cotton, flax, abaca, jute, kenaf, ramie, sisal, maize (American corn), sorghum, millet, oil crops (rape, mustard, castor, sunflower, safflower, sesame, oil poppy, oil palm), potatoes, rice (paddy), soya, tobacco	Bran bait, drenching, dust, fumigation, irrigation water, seed, spray, storage, soil	Hotspot areas: sites with storage, mixing, or washing of pesticides (tanks and land/spray machines) Diffuse areas: elevated concentrations in the topsoil, sediments, and drainage systems
Vegetable crops	Garlic, onions, leeks, shallots, asparagus, artichokes, chicory, okra, sweet potatoes, manioc (cassava), celery, carrots, fennel, cruciferous plants (cabbage, cauliflower, brussels sprouts, broccoli, radish), cucurbits, beans, peas, lettuce, spinach, tomatoes, aubergines, peppers, chillies, mushrooms	Casing, compost, drench, dust, foliage, root, packaging and transport materials, fumigation, spray, soil	
Fruit crops	Citrus, cacao, coffee, tea, tropical fruits (avocado, banana, date, fig, guava, lychee, mango, papaw, pomegranate, pineapple), nut fruits (walnut, hazel, Brazil nut, kola nut, pecan), olive, stone fruits (peach, plums, prunes, apricot, almond, sweet and sour cherries), small fruits (gooseberry, currants, raspberry, strawberry), pome fruits (apple, pear, quince)	Aerial treatment, drench, dust, spray, storage, soil	
Viticulture	Vine grapes	Bran bait, drench, foliage, spray	
Ornamentals	Various	Bran baits, bulb, dip, drench, soil	
Pasture and forage crops	Lucerne (alfalfa), clovers, pastures (grasses and other low plants)	Bran baits, dust, spray, soil	

Table 4
Principal areas of use for veterinary applications and treatment of domestic animals (adapted from [3,65]).

Areas of use	Animal type	Treatment type	Potential legacy
Veterinary and domestic animals	Dog	Powder	Hotspot areas: sites with pesticide storage, mixing, and dipping, and where the basin was drained Diffuse areas: elevated concentrations in the topsoil, sediments, and drainage systems
	Cattle	Spray, spot treatment, dip, powder	
	Goats, sheep	Dip, spray, spot, soil	
	Pig	Dip, spray	
	Poultry	Spot, spray houses	
	Rabbit	Not registered	
	Fish (carp)	Spray or solution	

fumigating, or dusting against for example the common house fly, mosquitoes, bugs, etc. It was also used via spraying or dusting in open spaces, such as for combating mosquitos breeding sites.

An example of indoor pest control applications is for example the patented Vulcan-O fumigator bulb, which contains a heating resistor (Fig. 3). Tablets containing lindane could be inserted through holes in the outer glass, and when the lamp was switched on the tablets melted and gave off fumes. Past indoor applications of lindane have resulted in reported deaths, particularly for babies [36].

The potential legacy of these treatments is expected to be minimal due to the local application for indoor pest control, clothes, and body treatment. However, if done on larger scale and extended time, these types of applications could have led to hotspots and contamination inside houses.

3.2.1.7.3. Use site type 3: forestry. Lindane was used in forestry for pest control (Fig. 4). Different application methods were used to protect individual, rows, and groups of trees. Depending on the tree type, application methods performed included soil, spray, fogging, dust, bran baits, lure trees, and aerial foliar applications. Therefore, pesticide storing and mixing areas on forestry sites are potential contamination hotspots. In areas where aerial foliar application was used, the spraying plane, washing stations and the mixing tanks on airstrips are additional hotspots (Toichuev et al., 2016). The topsoil, sediments, and drainage systems where forestry took place are areas where diffuse contamination could have occurred.

3.2.1.7.4. Use site type 4: treatment of wood, plastic, and stored material protection and preservation. **Wood treatment.** Many types of industrial materials manufactured from wood and cellulose derivatives and are subject to attack by insects, especially termites, wood wasps, and beetles (woodworm). To control these pests, insecticides such as lindane were applied by dipping, immersion, painting, smoking/fumigation, spraying, and mixing paints (see Table 5). Wood protection is achieved mainly through fumigation or deep impregnation [67].

From the 1960s to the 1980s, in Germany, as well as in other countries, wood preservatives containing lindane, DDT and PCP were used on non-load-bearing components, which were often used by end consumers as well as by professional builders. Such treated wood was widely used and did not need a test mark or inspectorate approval. The EC Biocide Directive of 1998 (replaced by Regulation 528/2012) was transposed into German law by the Biocide Act of 2002. Biocidal products are since then authorised only if it can be proven that they have no unacceptable effects on humans, animals, or the environment.

A wide range of former wood treatment sites exist in the EU [68]. These sites where lindane solutions were used as wood preservatives have normally multiple contaminants, since different cocktails of fungicides and insecticides were used for the wood treatment (see below Section 3.3.4).

The “HCH in EU project” identified a site of a company formerly known to manufacture products for interior decoration, paints, and varnishes, and which used to be the market leader in wood preservatives. It was revealed that this company was also a formulator of HCH/lindane preparations in different products.

In addition to the wood treatment sites, many older buildings containing wood structures are contaminated with lindane and other former wood treatment of lindane (and other pesticides) in Application which was for example detected in German historical buildings, such as churches [69].

Plastic additive: Lindane was use as pesticide in PVC plastic cabling in the outer sheath of the cable while it is being extruded. It was used in high tension cables, to protect against termites at levels of 0.02% [70]. The controlled release of these active ingredients from the plastic where considered to provide long-term protection.

Areas where plastic cables were produced are suspected HCH contamination sites, and areas where the wood and timber industry stored, mixed, or applied insecticides are considered contamination hotspots.

Fig. 3. Vulcan-O lamp used in combination with lindane tablets for pest control (website of lampes-et-tubes http://lampes-et-tubes.info/sp/sp028.php?l=d).

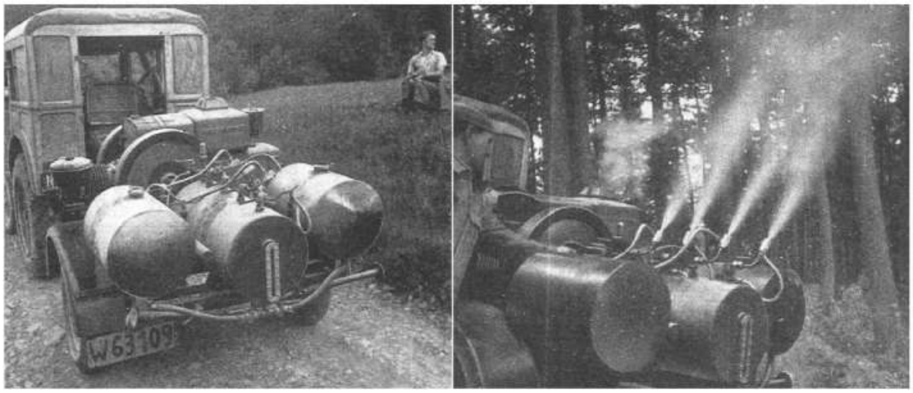

Fig. 4. Borchers' fumigation tanks used in forestry (Sinreich, A., 1952, über die Wirkung neuzeitlicher Insektizide auf die Gliedertier bei Forstschädlingsbekämpfungen 153–165, Mitteilungen der forstlichen Bundes-Versuchsanstalt Wien, Volume 48 1952).

Table 5
Principal areas of use and treatment type per parasite (adjusted from [3]).

Areas of use	Parasite type	Treatment type	Potential legacy
Timber and plywood	Ants, termites, wood wasps, beetles	Dip, painting, smoke/fumigation, spray, mixing in glue (plywood),	Hotspot areas: sites where production, storage, application, mixing and washing of pesticides occurred
Plastics	Termites	Mixing	Diffuse areas: elevated concentrations in the topsoil, sediments, and drainage systems
Storage of goods and industrial or agricultural materials	Termites, moths, silverfish, cricket, bugs, beetles	Fumigation, immersion, spray	

Storage areas. Prior to storage of goods and industrial and agricultural materials in warehouses, ships, silos, etc. prophylactic treatment could have been applied to the walls, floors, ceilings, etc. (see Table 5). The rooms were mainly disinfected using fumigation, since certain areas were difficult to reach by direct treatment. Specially constructed atomising or fumigation equipment was used, or a simple container or bucket that was gently warmed on a heater to produce smoke. Storage sites for industrial materials are also suspected contamination sites and could even be potential hotspots, since stored products needed to be protected from possible pests.

3.2.1.7.5. Use site type 5: use of HCH isomers for military purposes. A special application of HCH isomers is reported by Heinisch [71]. Until 1977, in the former German Democratic Republic (GDR), Falima in Magdeburg delivered annually 120 tonnes HCH isomers for “final products” to the VEB Pyrotechnik, Silberhütte in Freiberg. Here, the HCH isomers were mixed with 10% Aluminium powder to produce smoke generating devices (“Nebelkörper”), including smoke grenades for the National People's Army (Volksarmee). These products were also supplied to the Soviet Army. VEB Pyrotechnik also produced smoldering fog tools called “Hexaschwelkörpern” for mills and ship fumigation, as well as frost protection smoke creators. The related contaminated sites are mainly military training areas.

3.3. Co-pollutants at sites contaminated with HCH

Co-pollutants generated from the production or recycling process are important information for polluted site assessment and remediation. Also co-pollutants used in application sites are relevant in the same sense. This section briefly summarized information on co-pollutants considered relevant for selected HCH-contaminated sites.

3.3.1. Chlorobenzene and chlorophenol and derivatives

HCH waste isomers at some lindane production sites were recycled into chlorobenzenes (Fig. 5; [14,72,73]. These chlorobenzenes were partly sold as commercial products or used as intermediates for the production of other organochlorines, such as chlorophenols, and pesticides, such as 2,4,5-T and bromophos [14]. At one of these production sites high amounts of chlorobenzene have been discovered in soil and groundwater. It was estimated based on comprehensive monitoring that 550 tonnes of chlorobenzene are still in the soil from the recycling activities, exceeding even the amount of HCH in soil (260 tonnes) [15]. The other pesticide products, such as 2,4,5-T and bromophos and their degradation products, might also be present in soils and groundwater at these sites. There is continuous pumping at the site and the pumped residues are incinerated [15].

Additionally, high levels of chlorobenzene and chlorophenols were reported in the dense nonaqueous phase liquid (DNAPL) phase in an HCH landfill from a lindane production site in Spain [22,74].

3.3.2. Polychlorinated dibenzo-p-dioxin and dibenzofurans (PCDD/PCDFs)

PCDD/PCDFs were formed during HCH production, in particular in the recycling of HCH waste isomers for the production of chlorobenzenes and other pesticides, including 2,4,5-T (see Fig. 5). The α-, β- and δ-HCH waste isomers contained dioxin levels ranging from 0.8 to 300 μg toxic equivalents (TEQ)/kg [75]. Three types of waste were generated in this recycling of HCH and the related 2,4,5-T production (Fig. 5). The thermal decomposition of HCH to trichlorobenzene produced the so-called decomposer residue, with levels of PCDD/PCDFs in the percent range (1.4%–2.7%) and TEQ in the high parts per million range (90–230 mg/kg) [14,72]. The TEQ of the “Anisol” waste factions was around and below 1 mg/kg [14]. The acidic waste fraction (so-called R-acid) formed in the production of 2,4,5-T contained 1–330 mg 2,3,7,8-TCDD (TEQ) [76]. The

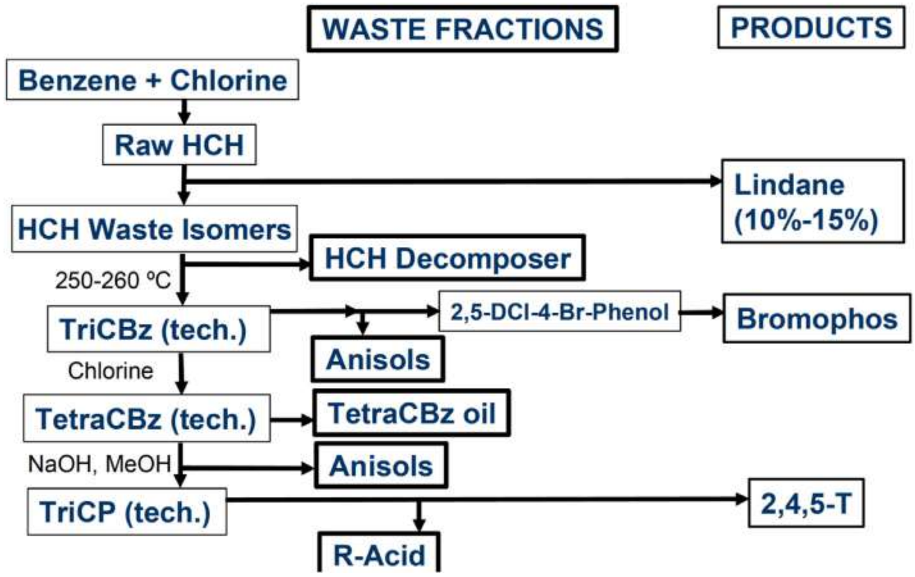

Fig. 5. Production scheme of the former pesticide factory in Hamburg, Germany, showing the major waste fractions and products [14].

final PCDD/PCDF quantity in disposed waste for two factories that were part of inventory were on the order of tonnes and the TEQ on the order of 100 kg [77]; Götz et al., 2015; [76,78]. At a German production site where a detailed inventory is available, 53–102 tonnes total sum of PCDD/PCDFs, including 333–854 kg of PCDD/PCDF TEQ, were disposed of in at least seven landfills [14]. The related production site has documented large-scale PCDD/PCDF contamination, with approximately 6 kg TEQ in the soil [15]. Such "recycling" of HCH waste isomers also occurred in the Czech Republic, France, Spain, Russia, and India [6].

At a Spanish landfill site with more than 100,000 tonnes of HCH waste disposed of, environmental monitored for PCDD/PCDFs was conducted to evaluate remediation risk [23]. Some of the disposed waste samples had up to 79 μg TEQ/kg PCDD/PCDFs, which exceeds the Basel Convention low POP content for waste (15 μg TEQ/kg). However, an initial assessment of PCDD/PCDF pollution in the vicinity of the landfills that measured soils and free range eggs as pollution indicators [79]: [24,25,45] found low PCDD/PCDF levels, suggesting no widespread PCDD/PCDF pollution at the site [23].

Furthermore, the destruction of HCH waste can lead to formation of PCDD/PCDFs, in particular when using certain non-combustion technologies (Weber 2007). A PCDD/PCDF contaminated site was generated in Brazil by the in situ "remediation" of HCH contaminated soils with calcium oxide [80]. Destruction experiments using leachates from the Spanish site mentioned above found that PCDD/PCDF contamination increased when using Fenton Oxidation but decreased with electrochemical oxidation [81]. Also bioremediation can also result in some formation of PCDD/PCDF when precursors such as chlorophenols or chlorobenzenes are present [82]; Weber 2007). Therefore, PCDD/PCDFs can be found as major contaminants at certain HCH-production sites and disposal sites and sites where certain remediation technologies were used.

3.3.3. Pollutants at lindane production and landfill sites unrelated to HCH production

Many factories that produced HCH also had other organochlorine products in their production portfolio, which caused pollution at the same production site and the related landfills. For instance, some lindane factories also produced DDT, and therefore the related landfills contain HCH and waste DDT. This was documented for instance for one major HCH landfill in East Germany, which contains 60,000 tonnes HCH waste isomers and also 48,000 tonnes DDT waste [17].

Another prime example are chlorinated solvents (tetrachloromethane, trichloromethane, and tetrachloroethene), which were produced at several organochlorine production sites where also lindane was produced. A detailed assessment of the 60 km^2 of groundwater pollution at the Bitterfeld site concluded that, despite the high HCH contamination, the individual HCH isomer ranked number 8, 9, 15 and 18 on a scale indicating groundwater pollution risk, while numbers 1 through 7 were monochlorobenzene, tetrachloroethene, trichloroethene, 1,2-dichloroethene, trichloromethane, 1,1,2,2-tetrachloroethane and vinylchloride, respectively [17] generated mainly from the chlorinated solvent production. Therefore, proper risk assessment of HCH production sites and related chemical landfills must also asses the total former production portfolio of those companies and the related contamination risk.

3.3.4. Co-contaminants at technical HCH/lindane use sites

In addition to technical HCH/lindane, wood treatment used a wide range of pesticides such as pentachlorophenol (PCP), DDT, dieldrin, mirex, endosulfan, and polychlorinated naphthalenes (PCNs) [83]. Furthermore, creosote was used at many wood treatment sites, leading to contamination with polycyclic aromatic hydrocarbons (PAHs) [84]. Heavy metals, such as arsenic in the form of chromated copper arsenate, are frequently detected as major contaminants at such sites [85]. Wood treatment sites are also frequently contaminated with PCDD/PCDF, if PCP was used for some time [24,25,85].

For sheep dips, in addition to lindane/HCH, dieldrin, DDT, endrin, aldrin, and arsenic were also used as sheep dipping chemicals to treat sheep ectoparasites [86]; New Zealand Environmental Ministry 2006; Table 6). This depends however on the country. For instance, while in Iceland only lindane was used [61,62]), all these POP pesticides. The compilation of all pesticides and chemical treatments used in sheep dips in New Zealand by the government in the related guidelines can be seen as a best practice case and basis for the assessment of a contaminated site type (New

Table 6
Past and present use of pesticides and other chemicals in sheep dips [87].

Chemical[a]	Period of usage**
Arsenic	1840s - 1980
Nicotine	1840s - mid 1900s
Carbolic acid and potash	1880s
Derris	1910–1952
Lime sulphur	1849–1891
Copper	1950s - present
Zinc	1950s - present
Organochlorines/POPs[a]:	
• **DDT**	1945–1961
• **lindane**	1947–1961
• **dieldrin**	1955–1961
• **aldrin**	1955–1961
Organophosphates	1960s - present
Synthetic pyrethroids	1970s - present
Insect growth regulators	Present

[a] Persistent chemicals of principal concern are highlighted.

Zealand Environmental Ministry [87]: Table 6).

For cable production also PCNs, PCBs and short-chain chlorinated paraffins (SCCPs) and polybrominated diphenyl ether (PBDEs) were used as additives in cables and other plastics [88-91]. Furthermore different phthalates, lead and cadmium all restricted today have been used as additives in PVC cables [88]. Therefore at cable production sites a range of POPs and other contamination might be present from the different historic use.

At military training sites, in addition to HCH also hexachlorobenzene (HCB) and PCNs were used in fog ammunition [91]. Furthermore, PCBs and PFOS are frequent POPs contaminants at military sites [92,93,25].

These examples demonstrate that when investigating suspected lindane/HCH contamination sites, co-pollutants should also be considered depending on the site type. This requires appropriate preparation and planning for sampling and laboratory analysis.

3.4. Assisting site owners with best practice (task 2 of the “HCH in EU project”)

Task 2 of the “HCH in EU project” was to assist site-owners with best practices on sustainable contaminant site management at seven HCH-contaminated pilot sites (see Table 7). The resources provided to these pilot sites are available as reference to those involved in the remediation of similar sites. The consultancy included developing a site road map depicting how to manage the site in a sustain manner and an action plan of consultancy work that could be carried within the scope of the “HCH in EU project.” All activities were reported, and these reports are available for consultation.

3.5. Guidance for countries to identify sites potentially impacted by HCH

In addition to the two above-mentioned project tasks, the “HCH in EU project” team produced a report with guidance for identifying other sites potentially impacted by HCH contamination [94]. This document provides insight for authorities regarding sites where HCH might be a (co)contaminant of concern, in addition to other contaminants of concern at such sites. The document aims to direct stakeholders tasked with the management of contaminated sites to identify other sites potentially contaminated with HCH, in addition to the sites already identified in the “HCH in EU project”, which will be listed on the EU website.

The following activities were taken to provide information on the former use of lindane in this report.

1. Review the Legacy of Lindane HCH Isomer Production published on January 2006, and update the existing information.
2. Study literature on potential HCH-contaminated sites other than production sites, waste deposits, landfills, treatment centres, storage facility, processing facilities from the “HCH in EU project” inventory.
3. Select and present several examples from the current inventory
4. Compile a comprehensive report discussing the whole spectrum of lindane production and use in the EU.

3.6. Guidance to develop an EU-wide strategy to sustainably manage HCH-impacted sites

The “HCH in EU project” provided added value by delivering guidance to develop an EU-wide strategy to sustainably manage HCH-impacted sites and provide a permanent solution to the legacy of HCH and lindane in the EU. This guidance document [95] proposes an outline for a strategy to finally address the legacy of lindane production in the EU Fig. 6. This guidance is meant to inform the development of an EU-wide strategy to manage the 299 or more sites potentially impacted by HCH and lindane. The main target audience are policy makers, who can continue supporting the sustainable management of these POPs contaminated sites. Several steps are recommended to be taken at the country, regional, or site level to, once and for all, solve the problems around the legacy of past lindane production in the entire EU.

The strategy highlights that in order to solve these environmental problems, decision makers on the different levels must realize that this is an environmental legacy that needs to be solved and that the installation of one or more financial instruments (supplementing the Member States’ own investments) to pay for the long-term, expensive, and complex EU-wide clean-up

Table 7
The HCH-contaminated sites provided with assistance by the “HCH in EU project”.

Site location/name	Country	Site specific issue
Wintzenheim	France	Contaminant migration from gravel pit filled with HCH from the PCUK (Ugine Kuhlmann) site of Huningue
Mulde River	Germany	Widespread sediment contamination originating from lindane and technical HCH production by VEB Chemie-Kombinat Bitterfeld (CKB)
Sardas Inquinosa Sabiñanigo	Spain	Remedial actions at the former Inquinosa lindane and technical HCH production facility and approaches for non-treated matrixes, minimizing dispersion
Valle del Sacco Colleferro	Italy	Sediment contamination originating from lindane and technical HCH production and storage at the Caffaro factory
Hajek	Czech Republic	Contaminant migration from a HCH landfill HCH waste from former lindane production at the Spolana Neratovice factory was disposed in a former mine
O Porriño	Spain	Contaminant migration from the lindane and technical HCH production facility of Zeltia, with widespread distribution of HCH waste
Vrakuňa	Slovak Republic	Second opinion on the selected method of containment for an HCH dump site stemming from the former lindane production at the Juraj Dimitrov Chemical Enterprises (CHZJD) in Bratislava, which caused groundwater contamination

LEVEL	Identify the magnitude of the problem	Explain the need to act & Raise awareness	Develop legislation	Create HCH ownership	Build capacity	Risk-based prioritisation	Connect with funding programmes	Establish covenants between stakeholders & authorities	Construct regional development associations	Add value to the remediation site	Mitigate/ control/ contain environmental risks	Know why sustainable management is obstructed
EU LEVEL												
EU-institutions	EU-wide inventory (Present) EU funded projects (Ongoing)	Publish paper: Need to eliminate Lindane production legacy	Develop legislation	Convince national authorities of the importance	Organize and finance R&D projects		Facilitate & stimulate	Stimulate	Stimulate			
EU Parliament	Respond & act on concerned stakeholder petitions		Establish EU legal framework for soil protection (Soil Strategy proposed) & prioritize HCH contaminated sites									
Stakeholders*	Demonstrate the problem & Submit petitions	Promote, Participate & create public pressure	Participate in public consultation	Monitor & report progress			Promote					
LINDANET	Support	Support & promote	Support based on needs of members	Extent and expand LINDANET after 2025	Establish EU community of practise, set up & extend knowledge centre	Support	Facilitate & initiate	Support & promote	Support & promote	Support & promote	Support	Support
COUNTRY/ REGIONAL LEVEL												
Authorities	Detail the country specific inventory (To be completed)	Inform citizens & stakeholders	Support the Soil Strategy introduction and its implementation, develop, adapt & enforce legislation (Varies per EU member state)	Support	Facilitate pilot projects &educate	Assess preliminary sites & risks (Use standards and guidance)	Reserve national / regional funding & apply for EU funding to co-finance	Contract stakeholders to co-finance	Contract stakeholders to co-finance	Develop urban & regional development plans & make cost benefit analysis	Facilitate, co-fund & Enforce (Legislation)	Communicate with local authorities
Stakeholders*	Participate & demonstrate the problem	Participate, support create public pressure	Participate in public consultation	Set up regional/national stakeholder organisation (like in Spain)	Participate	Participate	Apply national / regional funding & EU funding to co-finance	Participate	Participate	Participate & contribute	Participate	Participate
LINDANET	Support & encourage national authorities to complete inventory	Support & promote	Support	Set up LINDANET chapter in each country with potential HCH impacted sites	Establish National communities of practise, set up & extend knowledge centres	Support	Apply for national / regional funding & EU funding to co-finance	Participate	Participate	Support	Support	Support
CITY/ SITE LEVEL												
Site authorities	Permit, supervise evaluate (legislation)	Inform site owner & stakeholders	Apply & enforce	Development sustainable long-term town plans including HCH-sites together with site owners	Participate in R&D projects & facilitate pilot projects	Communicate, Support & advice owner	Reserve municipal budget & apply for national / reginal funding & EU funding to co-finance	Participate	Participate	Develop urban development plans & make cost benefit analysis & create project teams	Permit, supervise & Evaluate (Legislation)	Communicate with owner
Site owner	Detailed site assessment (guidance)	Participate & request for assistance when needed from Site authorities		Approach authorities for participations in town plans	Participate in R&D & Pilot projects	Assess sites & risks in detail (Use standard & guidance)	Apply for municipal & national / regional funding & EU funding to co-finance	Participate	Participate	Contract stakeholders to co-finance	Survey, design, tender, contract & implement (Guidance)	Identify bottlenecks (Know current site status)
Site Stakeholders*	Participate	Participate		Set up site-specific stakeholder organisation & participate	Participate in pilot projects	Participate	Support	Participate	Participate	Participate	Participate	Participate

*Ensuring stakeholders are represented at site-, country- and EU-level

Fig. 6. Matrix of proposals for an EU-wide strategy to eliminate the legacy of Lindane production.

campaign is crucial. If this legacy receives the political priority it deserves and financial instruments are set in place, the EU soil remediation community is resourceful enough to solve the technical issues around the identification, the characterization, and finally the remediation of these sites.

An EU-wide strategy for managing HCH-contaminated site sustainably provides several advantages:

1. Leverage the successes in assessing and managing sites in Member States to prevent each country from trying to reinvent the wheel and make the same mistakes;
2. Facilitate and stimulate countries learning from each other;
3. Provide financial instruments for countries with fewer resources available to deal with this environmental legacy;
4. Guide and support parties that have taken the initiative to sustainably manage these sites.

4. Conclusion

A range of projects to address the HCH legacy have been conducted in the EU. "The HCH in EU project" developed the first comprehensive and structured inventory of sites where lindane/HCH was handled in Europe along the life cycle of production, use, and disposal. The 299 locations identified included 54 priority sites from lindane production and HCH disposal. These should be further assessed and addressed, as they may have the highest HCH release and exposure risk. Climate change and related flooding risks should be considered when assessing future risks of contaminant release. At 31 sites where certain HCH uses occurred, such as for wood treatment, the level of pollution cannot be estimated but might be significant and need further assessment.

A report detailing the assessment was developed to help local and regional authorities further refine the inventories and generate more information to best secure and remediate high-risk sites (Fokke and Bensaiah [94]). The network of authorities responsible for large HCH sites should further be strengthened. A strategy report with needed tasks and actions Fig. 6 was also developed to support competent authorities, including the EU institutions, to further address the HCH legacy in Europe. Established networks can be used to stimulate and facilitate learning among countries. Countries and stakeholders that have taken the initiative to sustainably manage these contaminated sites should be guided and supported – best by additional EU-coordinated projects. The strategy also recommends having financial instruments so that EU countries with fewer available resources can deal with this POPs legacy. This is currently addressed in the EU Interreg Project LINDANET (See Section 3.1.3).

The first complete excavation and destruction of a large HCH deposit was completed in France in 2019 by the owner of the site and has demonstrated that this is feasible. In particular, for priority sites with high risk of contaminant release and exposure, site remediation is a sustainable solution since it does not pass on this pollution legacy to the next generation. While the cost of such excavation might be high, it is comparable to or even lower than the long-term cost of containment, which frequently involves pumping, monitoring, and other containment measures with costs that add up over decades and centuries. The indirect costs of human health impact on a global scale are impossible to assess but are significant and provide a reason to manage these sites in a sustainable manner.

Cooperative assessments of POPs contaminated sites can facilitate information exchange among affected member states. Similar HCH production, formulation, use, and disposal sites exist in Africa, Asia, and South America. Experiences gained in Europe could possibly be transferred to developing countries, taking their circumstances into account. Alternatively, developing countries with large HCH legacies from production could possibly be included in the EU network for sharing experiences and lessons learned.

Furthermore, there are other POPs with large contaminated sites (e.g., PFOS/PFOA, PCBs, HCB/HCBD) where such a coordinated assessment could be of benefit. In particular, PFOS/PFOA-contaminated sites are of increasing concern and should be systematically assessed and addressed in the EU.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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