Environ Sci Pollut Res (2011) 18:152–162
DOI 10.1007/s11356-010-0417-9

REVIEW ARTICLE

Hexachlorocyclohexane (HCH) as new Stockholm Convention POPs—a global perspective on the management of Lindane and its waste isomers

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Received: 2 May 2010 / Accepted: 8 November 2010 / Published online: 22 November 2010

Abstract
Purpose Hexachlorocyclohexane (HCH) isomers (α-, β- and γ- (Lindane)) were recently included as new persistent organic pollutants (POPs) in the Stockholm Convention, and therefore, the legacy of HCH and Lindane production became a contemporary topic of global relevance. This article wants to briefly summarise the outcomes of the Stockholm Convention process and make an estimation of the amount of HCH waste generated and dumped in the former Lindane/HCH-producing countries.
Results In a preliminary assessment, the countries and the respective amount of HCH residues stored and deposited from Lindane production are estimated. Between 4 and 7 million tonnes of wastes of toxic, persistent and bioaccumulative residues (largely consisting of alpha- (approx. 80%) and beta-HCH) are estimated to have been produced and discarded around the globe during 60 years of Lindane production. For

Responsible editor: Ake Bergman

This article belongs to the series "Dioxin and POP Contaminated Sites" edited by Roland Weber, Mats Tysklind and Caroline Gaus.

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approximately 1.9 million tonnes, information is available regarding deposition. Countries are: Austria, Brazil, China, Czech Republic, France, Germany, Hungary, India, Italy, Japan, Macedonia, Nigeria, Poland, Romania, Slovakia, South Africa, Spain, Switzerland, Turkey, The Netherlands, UK, USA, and former USSR. The paper highlights the environmental relevance of deposited HCH wastes and the related POPs' contaminated sites and provides suggestions for further steps to address the challenge of the legacy of HCH/Lindane production.

Conclusion It can be expected that most locations where HCH waste was discarded/stockpiled are not secured and that critical environmental impacts are resulting from leaching and volatilisation. As parties to the Stockholm Convention are legally required to take action to stop further POPs pollution, identification and evaluation of such sites are necessary.

Keywords HCH · Lindane · Stockholm Convention · POPs · Contaminated site · PCDD/PCDF

1 Introduction

Technical hexachlorocyclohexane (HCH)[1] and Lindane were one of the most extensively used organochlorine pesticides produced mainly after the Second World War until the 1990s (Breivik et al. 1999). The application of Lindane and technical HCH during the last six decades has resulted in environmental contamination of global dimensions (Li 1999; Li et al. 2003; Li and MacDonald 2005; Vijgen 2006a, b). HCH has been used as both technical HCH (containing the whole isomer mixture) and as Lindane (γ–HCH, after separation of the waste isomers). Synthesised raw HCH contains a total of eight stereoisomers which are termed α- to θ-HCH depending on the spatial arrangements of the chlorine atoms. Among these, only the α, β, γ, δ, and ε isomers are stable and are formed in the following percentages in reaction mixtures: α, 55–80%; β, 5–14%; γ, 8–15%; δ, 2–16%, and ε, 3–5%. The remaining three isomers are formed in trace amounts (Willet et al. 1998). In the late 1940s and early 1950s, technical HCH containing mixtures of several isomers was used as insecticide. It was soon discovered, however, that the application of technical HCH resulted in inedible crops, vegetables and fruits due to the organoleptic properties of some of the HCH isomers (Amadori 1993; Forter 1995; Ware 1999). Of all HCH isomers, only the γ-isomer has specific insecticidal properties. Hence, some companies began in the 1950s to isolate the active ingredient (γ-HCH; 99% purity from most suppliers), which was/is used under the name Lindane (Willet et al. 1998; Walker et al. 1999). In some countries, the change to Lindane began much later than the 1950s. For example, India used technical HCH until the late 1990s and then changed to the production and use of Lindane. In China, the use of technical HCH was banned in 1983, and Lindane use began in 1990 (Li et al. 2001).

Because of its suspected carcinogenic, persistent, bioaccumulative and endocrine disrupting properties (ATSDR 1998; ATSDR 2005; UNEP 2005a, b; WHO 1991), Lindane has become a heavily scrutinised substance and has been flagged for regulatory intervention in recent decades (Hauzenberger 2004). The use of Lindane has been banned in at least 52 countries, and various bilateral and multilateral international agreements and treaties have addressed Lindane, including, e.g. the Rotterdam Convention; the Protocol on Persistent Organic Pollutants of the Convention on Long Range Transboundary Air Pollution; the OSPAR Commission for the Protection of the Marine Environment of the Northeast Atlantic, the Great Lakes Binational Toxics Strategy between the United States and Canada, and a "North American Regional Action Plan on Lindane and Other Hexachlorocyclohexane Isomers" under the Commission for Environmental Cooperation between Canada, the United States and Mexico. On the 10th of May 2009, α-HCH, β-HCH, and Lindane[2] (industrial γ-HCH)[3] were accepted by the 4th meeting of the Conference of Parties (UNEP 2009a) for inclusion in the Stockholm Convention persistent organic pollutants (POPs) list on 26th August 2009 (Table 1). Thus, Lindane and the two key waste isomers are to be addressed on a global basis, including stockpiles and wastes remaining as a legacy from the historic use and production of HCH/Lindane (Vijgen 2006a, b; Vijgen et al. 2006). This amendment of the Convention will enter into force for parties[4] after a year, from the 26th August 2010 onwards.

To date, regulations have primarily addressed Lindane (the γ-isomer). However, a substantial fraction of other HCH isomers (85% of the raw product) are produced as by-products of Lindane. These HCH by-products generally became hazardous waste leaving considerable challenges: for each tonne of Lindane produced, 8–12 t of other HCH isomers are generated as waste (Bodenstein 1972; Vijgen 2006a, b). This waste was largely deposited in an uncontrolled manner around the various production sites

[1] 1, 2, 3, 4, 5, 6-Hexachlorocyclohexane is called "HCH" by the WHO. Another common name of hexachlorocyclohexane is "benzene hexachloride" with the abbreviation "BHC" by UN FAO and ISO, which is, however, incorrect according to the IUPAC rules.

[2] The purified γ-HCH isomer was named 'Lindane' after the Belgian chemist Van Der Linden who discovered it in 1912 (Ulman 1972)

[3] The term "Lindane" should be differentiated from γ–HCH in order to avoid confusion. γ–HCH is one of several isomers of HCH, and is contained in both technical HCH and Lindane. Lindane is the name given to 99% pure γ–HCH.

[4] Currently, 172 countries are parties of the Stockholm Convention.

Table 1 Estimated Lindane consumption for agriculture on the different continents

Continent	Amount (1,000 t)	Percentage
Europe	287.16	63.32
Asia	73.20	16.14
America	63.57	14.02
Africa	28.54	6.29
Oceania	1.03	0.23
Total	435.50	100

around the world (Vijgen 2006a, b; ACAT and PANNA 2008). These sites and the fate of the waste as well as the consequences for human and environmental health have virtually been ignored in many of the countries where HCH was produced. Thus, these sites now represent one of the globe's largest hazardous organic chemical waste challenge largely unknown to both the public and to the scientific community. Adding these HCH isomers as new POPs in the Stockholm Convention list creates a global requirement that these wastes be addressed. These challenges relate in particular to the α- and β-HCH isomers.

This paper briefly summarises the outcome of the Stockholm Convention process on Lindane and α- and β-HCH isomers and identifies steps facilitating the implementation of the provisions of the Convention in relation to these organochlorines. The review highlights in particular the stored/deposited HCH wastes and the associated contaminated sites. It gives estimates of the overall amount of wastes generated by historic HCH/Lindane production, including a comprehensive list of former and current HCH-producing countries. In addition, suggestions are made for further steps to tackle the challenge of the legacy of HCH/Lindane production. Due to the environmental relevance of the POPs contaminated sites created by deposition of HCH production wastes and possible co-deposition of polychlorinated dibenzo-*p*-dioxins/polychlorinated dibenzofurans (PCDD/PCDF) contaminated wastes (see below), this article is published within the series of Dioxin/POPs contaminated sites (Weber et al. 2008a, b).

2 Results and discussion

2.1 Listing of Lindane and α- and β-HCH in the Stockholm Convention and exemption for Lindane use

2.1.1 Proposal for listing of HCH and POPs reviewing process

The process of listing a chemical in the Stockholm Convention (Stockholm Convention 2001) is visualised in Fig. 1. As a first step, a party to the Convention has to submit a proposal for listing of a substance along with specific information required to satisfy the screening criteria under Annex D of the Convention (Stockholm Convention 2001; Fig. 1). Lindane and α- and β-HCH were proposed in 2005 and 2006 by Mexico to be included in the Stockholm Convention POPs list (UNEP 2005a; UNEP 2006a, b). At its first meeting, the POPs Review Committee (POPRC) accepted that Lindane meets the screening criteria specified under Annex D (UNEP 2005b) and confirmed this at its second meeting (UNEP 2006c, d). The risk profile and risk management evaluation for Lindane were adopted at the second and third meetings (UNEP 2006e; UNEP 2007a) and for α- and β-HCH at the third and fourth meetings, respectively (UNEP 2007a, b; UNEP 2008a, b). Finally, the POPRC recommended the listing of Lindane, α- HCH and β-HCH in Annex A of the Stockholm Convention in order to achieve the global elimination of these isomers.

2.1.2 Outcome of the Stockholm Convention COP4 meeting and exemption of Lindane use

At its fourth meeting in October 2008, the Conference of Parties decided (UNEP 2009a, d) to:

- List α- and β-HCH in Annex A of the Convention; the listing was adopted in May 2009 (UNEP 2009a, b, c)
- List Lindane in Annex A of the Convention with a specific exemption for the use of Lindane as a human health pharmaceutical for control of head lice and scabies as a second-line treatment (UNEP 2009a, d);
- Amend Part I of Annex A of the Convention; and requested the Secretariat to cooperate with the World Health Organisation (WHO) in developing, reporting and reviewing requirements for the use of Lindane as a human health pharmaceutical for the control of head lice and scabies (UNEP 2009a, d).

This amendment of the Convention was made effective from 26th August 2010. Therefore, the production and sale of Lindane are still possible for the permitted uses.

2.2 Estimation of global HCH waste in former production countries

As highlighted in the introduction, the key challenge for addressing the now listed HCH isomers on a global basis are the stockpiles and wastes generated during the last 60 years of HCH/Lindane production. The Stockholm Convention Article 6 requires that parties take measures to reduce or eliminate releases from stockpiles and wastes (Stockholm Convention 2001). Therefore, this study has been undertaken to estimate the global amount of HCH waste isomers produced and deposited/stored. This pro-

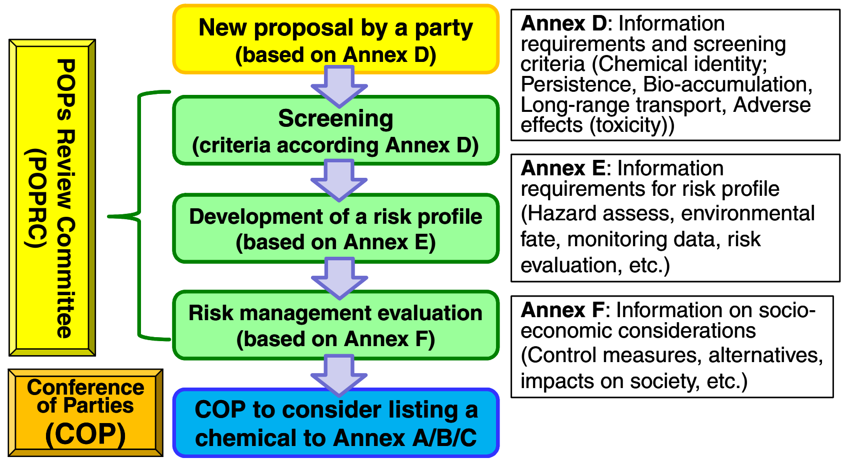

Fig. 1 Reviewing process of the Stockholm Convention for inclusion of new POPs

vides important information to estimate the scale and scope of implementation work in the future. Two approaches have been used to generate robust first estimates of total waste/stockpiles: (1) collection of information on the quantity and countries of HCH/Lindane production and (2) estimation of HCH waste as a result of total Lindane production.

2.2.1 Data collection from countries where HCH/Lindane has been produced

The first approach is based on the collection of information over the last 20 years from production sites. This includes HCH production capacities and produced amounts, as well as information on related amounts of wastes generated. Information was collated from proceedings, presentations and discussions at International HCH and pesticide forums (International HCH and Pesticide Association 2009) held from 1992 to 2009. These provided a valuable basis for estimating the production of Lindane and associated wastes. This information was used to compile a comprehensive list of the countries where HCH/Lindane production is known to have taken place together with estimates of associated waste amounts. Countries with known production histories are Albania, Austria, Argentina, Brazil, China, Croatia, Czech Republic, France, Germany (including former German Democratic Republic), Hungary, India, Italy, Japan, Macedonia (former Yugoslavia), Nigeria, Poland, Romania, Slovakia, South Africa, Spain, Switzerland, Turkey, The Netherlands, UK, USA, and the former USSR.

Additionally, information was systematically gathered by a questionnaire survey. The questionnaire was developed 01/2004 to obtain more detailed information on production amount, export, waste quantities and deposition of wastes and sent to stakeholders. More than 50, mainly governmental and industrial organisations, and individuals were contacted. Extensive support for the investigation was provided by the US Environmental Protection Agency (EPA) and facilitated by their overview of data available from the reports from Superfund projects and other projects managed by the EPA or other environmental authorities (US EPA 2003). However, of the 50 contacts made, only Albania, Australia, Austria, Belgium, Brazil, Hungary, Japan, Pakistan and Poland officially responded.

Efforts to interview persons and organisations gave similar limited results. Intensive efforts in France, one of the major HCH-producing countries, consisting of repeated requests and phone calls to various ministries and regional authorities, were not responded to. A second round addressing 30 governments was made again in October and November 2004 in an attempt to improve the quality of the information. This effort provided some supplementary information. Repeated requests to the governments of China and India to obtain information on Lindane production were not answered. Accordingly, for France, Poland and the former Soviet Union, only a preliminary estimate of HCH waste could be made. Recently, as part of an exchange between US and China, a study has been conducted on the production of Lindane and its HCH waste (Peking University 2005; Ren 2006). Surprisingly, this study did not reveal substantial amounts of HCH waste around the Chinese production sites. The high Lindane production versus low amount of HCH wastes may indicate an extensive recycling of HCH waste isomers in China (see below).

Estimates of deposited and stockpiled HCH waste isomers using the first approach (i.e. literature survey, IHPA Forum meetings and questionnaire) has resulted in preliminary estimates of 1.6–1.9 million tonnes of HCH waste. The countries with historical HCH/Lindane production capacity together with associated preliminary estimates of HCH waste quantities are presented in the HCH waste world map (Fig. 2). The outcome of this approach is undoubtedly an underestimate (see below) given the incomplete reporting and the likely existence of as yet unidentified productions sites and waste deposits.

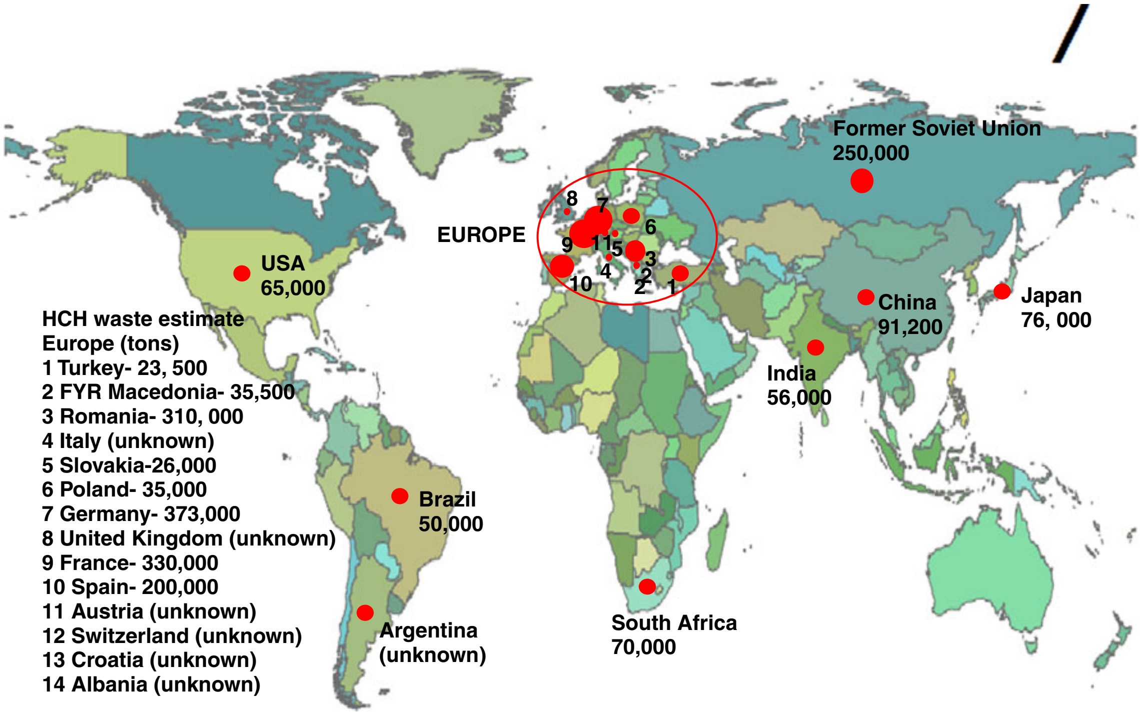

Fig. 2 Preliminary estimate on quantities of stored/deposited HCH waste isomers present in countries from the questionnaire process, gathering information from HCH & Pesticide Forums and from literature survey

2.2.2 Estimation of HCH waste by global Lindane use

Using the second approach, the total quantity of HCH waste can be estimated by using the proportion of waste isomers produced per tonne of Lindane used. Global historical Lindane use for agricultural purposes between 1950 and 2000 is estimated to have been in the region of 450,000 t (Table 1). In general, peak production of Lindane occurred in the 1960s and the early 1970s. Although the use of Lindane had stopped in several European countries by the 1970s, the largest share of its use (and production) was within Europe. This accounted for approximately 63% of the total global Lindane consumption (Table 1, Fig. 2). Additional use of Lindane on livestock, in forestry applications, in human pharmaceuticals and for other purposes has also been considered in the total production figure and is estimated at 150,000 t (Vijgen 2006a, b), bringing the total global figure to an estimated 600,000 t.

According to Bodenstein (1972), the total HCH waste isomer generation per tonne of Lindane produced was about 8 t of HCH isomer waste. Other experts have estimated about 10 t (Krum 1982) and 10–12 t (Treger 2004). Using the range of these approximates (8 to 12 t) leads to a total estimated amount of between 4.8 and 7.2 million tonnes HCH waste produced worldwide as best and worst case figures, respectively. This can be compared to the global production of polychlorinated biphenyls (PCB) which is estimated to be 1.3 to 2.0 million tonnes in total (Breivik et al. 2002; De Voogt and Brinkmann 1989; Fiedler 2001).

2.2.3 Discrepancy of known and estimated quantities of HCH waste and further inventory tasks

When comparing the estimated amount based on the relatively reliable calculation from Lindane production data (4.8 to 7.2 million tonnes) and the compiled information from country surveys (1.6 to 1.9 million tonnes), it appears that detailed country information relating to the great majority of HCH production waste (2.9 to 5.6 million tonnes) is missing. A part of this missing HCH waste has been recycled to chlorobenzenes, which are known to be associated with the formation of PCDD/PCDF contaminated waste (see below).

The gathered information and data are on one hand a very valuable basis for establishing detailed global inventories on HCH waste isomers which are necessary for planning the implementation of the Stockholm Convention. Nonetheless, the gaps in the information indicate that the complete compilation of this information remains a work-intensive challenge. This is illustrated by considering the difficulties encountered in compiling the current data, and that many production sites have closed down more than 30 years ago.

2.3 Attempts to recycle HCH stockpiles and related PCDD/PCDF generation

One uncertainty factor in the estimation of deposited waste isomers is the amount of recycled HCH. The problems encountered with the waste isomer management ("white mountains" and dump sites) led to efforts to recycle the HCH waste. The HCH waste isomers are a relatively pure waste product containing 70% of chlorine by mass. Several attempts have been made to use these residuals for the production of trichlorobenzene/tetrachlorobenzene and HCl with further marketable products like 2,4,5-T or PCP (Vijgen 2006b, Fig. 3; Jürgens and Roth 1989; Sievers and Friesel 1989; Weber et al. 2006; CAPE 2005; Peking University 2005). However, it is not known how many of the factories have made such attempts and what quantity of waste isomers was finally recycled through such routes. The only thoroughly investigated and documented case of recycling of waste HCH isomers at a factory in Hamburg/Germany has revealed that the thermal recycling of HCH to chlorobenzenes resulted in waste streams highly contaminated with unintentionally produced POPs (UPOPs) in particular PCDDs/PCDFs (Table 2). In total, more than 370 kg toxicity equivalent (TEQ) was deposited in wastes generated in this factory over 40 years of operation (Jürgens and Roth 1989; Weber et al. 2006, 2008b; University Bayreuth 1995; Varbelow and Weber 2009). Residues from a similar HCH decomposition process operated in China resulted in similarly highly contaminated waste (Bao et al. 1994) but with a slightly different PCDD/PCDF homologue and congener pattern (Table 2). In total, approximately 360 kg TEQ PCDDs/PCDFs were released in wastes from the Chinese factory between 1990 and 1994 (Bao et al. 1994; Zheng et al. 1999). In the Hamburg case, these PCDD/PCDF-contaminated residues resulted in the closure of the chemical factory by the state authorities (Jürgens and Roth 1989). The remediation and securing measures directed at sites contaminated by this factory and the production site have been ongoing for more than a decade and will be described in more detail in another paper in this series (Varbelow and Weber 2009). Some of the recycled products (Tri/TetraCBz) from this factory were sent to another factory in Germany (Rheinfelden) where they were further chlorinated to hexachlorobenzene (HCB) and used to synthesise sodium pentachlorophenate. In this process, high PCDD/PCDF-containing residues (kg TEQ) and HCB-containing residues (tonnes) were also generated and deposited (Weber et al. 2008a, b; Otto et al. 2006). The cases from Germany and China highlight the importance of evaluating the recycling practises of each HCH production site by assessing the production areas and production waste deposits for possible PCDD/PCDF and other UPOPs contamination. Other factories known to have recycled at least a part of their waste isomers were located in China (Bao et al. 1994; Peking University 2005; Ren 2006), Czech Republic, France, Spain and Russia (Vijgen 2006b; Weber et al. 2006) and in India (Jit et al. 2010; CAPE 2005).

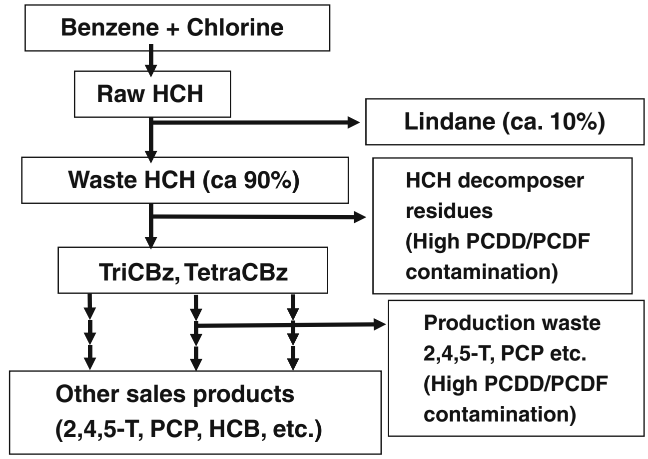

Fig. 3 Simplified recycling scheme of a HCH production and marketable products

2.4 Storage practises and deposition

HCH production residues were often stockpiled in open piles known as 'white mountains' or muck (see Vijgen 2006a, b). The uncovered HCH powder contaminated neighbouring areas due to distribution by wind. For example, it has been found that cow's and human milk have been highly contaminated by HCH in the vicinity of the Ugine-Kuhlmann company (Huningue, France bordering Switzerland) which produced Lindane from 1947 to 1974 (Forter 1995). Similar contamination was recently documented for the last working Lindane production site in India (Jit et al. 2010).

Most of the residuals from the production processes have been deposited without special care over the last 60 years, which has created an extensive environmental hazard. Originally, the production residuals were considered harmless and relatively insoluble in water. No particular objections were therefore raised in the 1950s to 1970s to the practise of using residuals for construction purposes, e.g. backfilling available gravel pits and other holes wherever they were encountered in the vicinity of the factories (Forter 1995; Amadori 1993; Vijgen 2006a, b). However, all isomers of HCH exhibit relatively high water solubility (Willet et al. 1998; Walker et al. 1999) and moderately high vapour pressure (Willet et al. 1998; Walker et al. 1999) when compared to most other persistent organochlorine pesticides, PCBs or PCDDs/PCDFs. Therefore, HCH can enter the environment by volatilisation into the atmosphere or dissolution into water bodies/groundwater (Bidleman et al.

Table 2 PCDD/PCDF contamination (ng/g) in HCH decomposition residues from recycling of HCH from a German (Jürgens and Roth 1989 and analysis of a stored batch) and a Chinese (Bao et al. 1994) Lindane production

	HCH decomposer Hamburg 1[a]	HCH decomposer Hamburg 2	HCH decomposer China[b]
2,3,7,8-TCDD	400	300	1,450
Sum TCDD	37,000	12,300	2,100
1,2,3,7,8-PeCDD	29,000	7,000	570
Sum PeCDD	449,000	207,000	12,800
1,2,3,4,7,8-HxCDD	27,000	4,500	2,056
1,2,3,6,7,8-HxCDD	55,900	15,000	18,170
1,2,3,7,8,9-HxCDD	23,200	6,500	7,170
Sum HxCDD	3,121,000	940,000	634,000
1,2,3,4,6,7,8-HpCDD	49,640	30,000	327,500
Sum HpCDD	7,635,000	4,400,000	41,609,000
OCDD	12,061,000	7,600,000	81,408,000
2,3,7,8-TCDF	2,300	1,300	178
Sum TCDF	309,000	23,000	26,000
1,2,3,7,8-PeCDF	3,600	45	3,693
2,3,4,7,8-PeCDF	3,300	4,500	4,380
Sum PeCDF	609,000	56,500	473,000
1,2,3,4,7,8-HxCDF	160,000	65,000	1,153,000
1,2,3,6,7,8-HxCDF	36,000	17,000	226,000
2,3,4,6,7,8-HxCDF	37,000	13,000	3,940
1,2,3,7,8,9-HxCDF	21,000	n.d.	5,300
Sum HxCDF	1,121,000	325,000	2,155,000
1,2,3,4,6,7,8-HpCDF	683,000	370,000	1,195,000
1,2,3,4,7,8,9-HpCDF	70,000	10,000	425,000
Sum HpCDF	1,088,000	495,000	2,322,000
OCDF	1,051,000	200,000	1,273,000
I-TEQ	230,482	89,775	607,969
WHO TEQ 1998	233,181	86,255	533,841
WHO TEQ 2005	231,203	84,785	544,995

n.d. not detected

[a] Jürgens and Roth 1989

[b] Bao et al. Environ Chem 1994 (Chinese) (average of three analysed batches)

1992). Hence, HCH waste deposits tend to evolve over time into POP-contaminated megasites with considerably larger pollution footprint in ground water and soil than the original dumpsite (Vijgen 2006a, b; ACAT and PANNA 2008; Weber et al. 2010; Wycisk et al. 2010). Most of the deposits and storage sites were not adequately secured or monitored. Evaluation of such disposal practises and addressing resultant pollution (Vijgen 2006a, b; Abhilash and Singh 2009a, b; Jit et al. 2010) represent key challenges in the upcoming implementation of the Stockholm Convention. Furthermore, the volatilisation of these deposits into the atmosphere results (via long-range atmospheric transport) in ongoing contamination of higher latitudes, including polar regions. This distribution pathway is an important consideration when evaluating existing wastes and stockpiles.

2.5 Recent and current Lindane production

The global production of Lindane has decreased significantly in recent years. In China, the production of Lindane ceased in 2003 (Peking University 2005). Romania reported the production of 90 t of Lindane in 2005 and 12 t in 2006 (Romania 2008), and it was noted in a Stockholm Convention document that the production has stopped recently (UNEP 2006e). India is the only country known where Lindane is currently produced. The production of technical HCH has effectively ceased in India during 1997 through a national ban on technical HCH use. Total installed capacity of Lindane production in India was reported at 1,300 t per annum by two major producers (1) Kanoria Chemicals Ltd (1,000 t/a capacity) and (2) India Pesticide

Ltd (300 t/a capacity) (IPEN 2005; Abhilash and Singh 2009a, b). Kanoria Chemicals has now stopped Lindane production (Abhilash and Singh 2009a, b), leaving India Pesticide Limited (IPL, Lucknow) as the only operating plant worldwide. It has been shown that the production and storage practises of Lindane producers in India were not adequate and lead to pollution of the surrounding areas (CAPE 2005; Abhilash and Singh 2009a, b; Jit et al. 2010). A detailed analysis of the pollution around IPL (Lucknow) and the associated waste storage sites is described in another paper in this series (Jit et al. 2010).

Additionally, the recycling practises of both Indian producers have been reported (CAPE 2005). For IPL, Lucknow, this is verified by the current production portfolio offering products from the recycling of HCH—commercial grade trichlorobenzene, 1,2,4-TriCBz and onward reaction products like 2,4,5-trichloroaniline, 1,2,4-trichloro-5-nitro benzene and even hexachlorobenzene (India Pesticide Limited 2009). The cases of PCDD/PCDF contamination during recycling of HCH (see above; Table 2) and reported also from the subsequent production of certain chlorinated aromatic chemicals which act as PCDD/PCDF precursors (Jürgens and Roth 1989; Sievers and Friesel 1989; Weber et al. 2006, 2008b) indicate that there is a high potential for substantial PCDD/F contamination of the products and waste streams at the Lucknow and other factories, which is poorly evaluated to date. In addition, the inclusion of α- and β-HCH isomers in the Stockholm Convention requires that the waste isomers produced in the current Lindane manufacturing need to be treated in accordance with the requirements in Article 6. Thus, the producing company would have to demonstrate environmentally sound management of the waste isomers and adequate occupational and public health safety standards, and the Indian government would have to ensure that the requirements of the Stockholm Convention are met.

2.6 Preliminary remediation/securing attempts

At several former HCH/Lindane production sites, preliminary site securing activities have started (Vijgen 2006a, b). For most of these projects, this has entailed site encapsulation. At a few sites, some wastes have been destroyed (Vijgen 2006a, b). In the case of two sites in South East Brazil, remediation attempts have failed and have resulted in widespread contamination of people and the environment with HCH and PCDD/PCDF (Braga et al. 2002; Fróes-Asmus et al. 2008; Torres et al. 2010). These cases highlight that particular care has to be taken in POPs remediation projects and that inappropriate POPs destruction technologies can lead to severe contamination with POPs and PCDD/PCDF (Braga et al. 2002; Weber 2007). This is a particular risk for countries having little or no experience in POPs management and lacking appropriate destruction technologies. The documentation and compilation of not only best practise projects but also case studies which failed could help with the environmentally sound management and proper remediation of other sites.

2.7 Mapping and database of productions and related storages/dump sites

The countries where HCH production has taken place (see above; Fig. 1) and many of the individual HCH production sites are well-known. By contrast, detailed information on the deposits of HCH waste for most of these sites is incomplete or absent. In order to collect and compile detailed information for such sites, a web database has been launched to map and document production and disposal sites in countries with a known history of Lindane production (http://www.ihpa.info/actions/2010/02/10/hch-map/) (Watson et al. 2009). The mapping project intends to update and improve the estimates of the wastes deposited at the sites. In addition to recording the location of production and deposition sites, the implementation processes taking place under the Stockholm Convention are planned to be documented.

2.8 Substitution of Lindane for the permitted exempted uses (lice and scabies)

An important step towards the complete cessation of Lindane production worldwide is the identification of suitable alternatives to the pesticide in exempt uses. Recent articles in the peer-reviewed literature, the risk management evaluation of Lindane the POPs Reviewing Committee (UNEP 2007a) and a summary documentation of the International POPs Elimination Network (IPEN 2009) have documented the safe, efficacious use of alternatives to Lindane for treatment of head lice, including hot air treatments (Goates 2006), wet combing, cetaphil cleanser and dimethicone lotion (Pearlman 2005). The efficacy of these alternatives matched or exceeded that of Lindane without the development of resistance or toxic effects in the patient. Effective alternative chemicals are Permethrine, Bioallethrin and piperonyl butoxide, Pyrethrin and piperonyl butoxide, Malathion, and Disulfiram with benzylbenzoate (UNEP 2007a, b).

In relation to scabies treatment, a variety of safer but effective alternatives to the use of Lindane are documented including sulphur in petrolatum, Permethrin, oral Ivermectin in combination with topical Permethrin and keratolytic therapy, as well as certain medical oils (Heukelbach and Feldmeier 2006; UNEP 2007a; IPEN 2009).

According to the decision accorded by the Conference of Parties, the Stockholm Secretariat shall cooperate with the World Health Organisation in the identification of pharmaceuticals which could replace Lindane in exempt uses.

2.9 Some key considerations for the implementation of the Stockholm Convention

Identification and mapping of individual HCH/Lindane production sites provide a global overview on the HCH-waste problem. To achieve these, available information for each site would need to be compiled and collected prior to assessment by specialists. An important component of such an assessment is the evaluation of the individual sites for their environmental impact and threat to human health. A final aim should be the development of an environmentally sound strategy for the management and elimination of deposited HCH waste in a sustainable manner. National governments, GEF, and its implementing agencies UNEP, UNIDO, FAO and UNDP, as well as the Stockholm Convention Secretariat together with the respective industries would have the key responsibility for these tasks, and to ensure that the National Implementation Plans of the respective countries can be updated in a timely manner. The hazardous waste management and disposal of existing stocks together with the remediation of contaminated sites could be costly for companies/countries involved. The POPs Reviewing Committee concluded in this respect that financial and/or technical assistance to transition/developing countries might be needed, and therefore, international mechanisms of co-financing to establish incentives would be crucial to reduce the environmental legacies of obsolete HCH stockpiles and contaminated soils (UNEP 2008c). In addition, the evaluation, monitoring and remediation process would benefit from international research collaboration and multi-stakeholder processes, similar to that established by the International HCH and Pesticide Association (www.ihpa.info).

To date, the progress on global PCB and POPs pesticide management under the framework of the Stockholm Convention was relatively slow and requires enormous financial and human resources to compile and repeatedly refine POPs inventories. This suggests that improvements to the inventory process may need to be considered. The activities described in the current paper and the information gathered over the last 20 years may provide a basis for national and global inventories for three of the nine new listed POPs. In addition, the implementation of the Stockholm Convention regarding HCH would certainly benefit from proactive participation by the (formerly) HCH-producing companies as stakeholders. The organochlorine-producing industries have the key experience and capacity to manage and destroy organochlorine waste and may be able to use the HCl produced from destruction processes.

The mismanagement of HCH waste isomers from Lindane productions and their continuing impact even decades after their disposal is a key example which demonstrates the need for intensive evaluation of former deposits of the organochlorine industries. Further, the production of Lindane and dumping and recycling of waste HCH isomers highlight the necessity of integrated pollution prevention and control strategies for the organochlorine industry at large including those in developing and transition countries which may lack appropriate waste destruction capacity. The experiences gained in evaluating and documenting the waste legacy of HCH/Lindane production on a global scale should be applied for other bulk products of the organochlorine industry which may have resulted in the production and deposition of POPs/UPOPs wastes.

3 Conclusions

With α-HCH, β-HCH and Lindane entering the Stockholm Convention in 2009, parties to the Convention are obliged to consider these new POPs within its framework from August 2010 onwards. The implementation of the Stockholm Convention for three HCH isomers as new POPs creates a challenge of global dimensions in relation to the wastes produced by these industries. Between 4 and 7 million tonnes of toxic, persistent and bioaccumulative residues—largely consisting of α-HCH (80%) and β-HCH POPs waste—are estimated to have been dumped during 60 years of Lindane production. The extent of the HCH waste/stockpiles therefore exceeds present estimates of other obsolete pesticides such as the pesticide stockpiles in Africa (estimated at 55,000 t) (Africa Stockpiles Programme 2009) and in the Eastern European region with an estimated 150,000 to 500,000 t (Int. HCH and Pesticides Forum 2001; Rippen 1996). It is the single largest POPs stockpile with overall quantities exceeding those of all other Stockholm Convention POPs wastes combined. With the exception of some locations in industrialised countries, which have been "contained and controlled" by various means, it can be anticipated that at most locations, the wastes/stockpiles are not secured, and that environmental impacts are taking place by leaching and volatilisation of wastes. Appropriate and urgent measures are required to stop further POPs pollution from HCH waste deposits and establish environmentally sound management and destruction of HCH wastes, including the wastes generated by the last operating Lindane production facility in India.

Acknowledgements The authors want to express their thanks to all who answered the questionnaires and supported the study with information.

P.C. Abhilash and Nandita Singh are thankful to the Director of NBRI for his encouragements.

Thanks go to Eurofins ERGO for the analysis of a HCH decomposer residue.

References

Abhilash PC, Singh N (2009a) Seasonal variation of HCH isomers in open soil and plant-rhizospheric soil system of a contaminated environment. Environ Sci Pollut Res Int 16:727–740

Abhilash PC, Singh N (2009b) *Withania somnifera* Dunal-mediated dissipation of Lindane from simulated soil: implications for rhizoremediation of contaminated soils. J Soils Sediments 10:272–282

ACAT and PANNA (2008) Alaska Community Action on Toxics (ACAT) and Pesticide Action Network North America (PANNA). Annex F Submission for Lindane to the POPs Reviewing Committee

Africa Stockpiles Programme (2009) http://www.africastockpiles.org/pressroom.html

Amadori E (1993) The production and use of HCH, HCH and halogenated pesticides—state of the art for risk assessment and technology development, *IWU – Tagungsberichte*, 1993 Magdeburg, (See http://www.ihpa.info/library.htm 1st & 2nd Forum)

ATSDR Agency for Toxic Substances and Disease Registry (1998). Toxicological profile for alpha-, beta-, gamma-, and delta-hexachlorocyclohexane. Draft for public comment (update). U. S. Department of Health & Human Services

ATSDR (2005) Toxicological profile for hexachlorocyclohexanes. U. S. Department of Health & Human Services. Public Health Service. Agency for Toxic Substances and Disease Registry. August, 2005. http://www.atsdr.cdc.gov/toxprofiles/tp43.html

Bao Z, Wang K, Kang J, Zhao L (1994) Analysis of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans in pyrolysis residue of HCH. Environ Chem 13:409–414 (in Chinese)

Bidleman TF, Cotham WE, Addison RF, Zinck ME (1992) Organic contaminants in the Northwest Atlantic atmosphere at Sable Island, Nova Scotia, 1988–89. Chemosphere 24:1389–1412

Bodenstein G (1972) Disposal of wastes from Lindane manufacture. In: E. Uhlmann, Verlag K (eds) Lindane monograph of an insecticide. Schillinger, Freiburg im Breisgau, Germany, pp 23–77

Braga AMCB, Krauss T, dos Santos CRR, de Souza PM (2002) PCDD/F-contamination in a hexachlorocyclohexane waste site in Rio de Janeiro, Brazil. Chemosphere 46:1329–1333

Breivik K, Pacyna JM, Munch J (1999) Use of α-, β-, γ- hexachlorocyclohexane in Europe, 1970–1996. Sci Total Environ 239:151–163

Breivik K, Sweetman A, Pacynaa JM, Jones K (2002) Towards a global historical emission inventory for selected PCB congeners—a mass balance approach 1. Global production and consumption. Sci Tot Environ 290:181–198

CAPE (Community Action for Pesticide Elimination) (2005) Lindane's dirty secret: Indian facilities dump toxic waste May 2005 http://www.docstoc.com/docs/27574041/LINDANES-DIRTY-SECRET (Accessed 05/2010)

De Voogt P, Brinkman UAT (1989) Production, Properties and Usage. In: R.D. Kimbrough und A.A. Jensen (Hrsg.): Halogenated Biphenyls, Terphenyls, Naphthalenes, Dibenzodioxins and Related Products. Elsevier Science Publishers

Fiedler H (2001) Global and local disposition of PCB. In: Robertson LW, Hansen LG (eds) PCBs—recent advances in the environmental toxicology and health effects. University Press of Kentucky, Lexington, pp 11–15

Forter M (1995) Umweltnutzung durch die chemische Industrie am Fall Beispiel der HCH-Fabrik Ugine- Kuhlmann, Hüningen (France), Lizentiatsarbeit, 1995, Universität Basel, Schweiz

Fróes-Asmus CIR, Alonzo HGA, Palácios M, Silva AP, Filhote MIF, Buosi B, Câmara VM (2008) Assessment of human health risk from organochlorine pesticide residues in Cidade dos Meninos, Duque de Caxias, Rio de Janeiro, Brazil Cad. Saúde Publica Rio Janeiro 24(4):755–766

Goates BM (2006) An effective non-chemical treatment for head lice. Pediatrics 118(5):1962–1970

Hauzenberger I (2004) Reports on substances scheduled for re-assessments under the UNECE POPs Protocol, Technical Review Report on Lindane, Austria http://www.unece.org/env/lrtap/TaskForce/popsxg/2004/Dossier_Lindane.pdf (Accessed 07.08.2010)

Heukelbach J, Feldmeier H (2006) Scabies. Lancet 367:1767–1774

India Pesticide Limited (2009) Dye intermediates http://www.indiapesticideslimited.com/dye.html (Accessed 01.05.2010)

IPEN International POPs Elimination Network (2005) Lindane. Answers to common questions http://www.ipen.org/ipenweb/documents/work%20documents/lindane%20answers_english.pdf (Accessed 05.09.2010)

IPEN International POPs Elimination Network (2009) Lindane: pharmaceutical and agricultural alternatives. http://www.akaction.org/REPORTS/Alternatives%20to%20Lindane%20Report%204-29-09.pdf (Accessed 01.05.2010)

International HCH and Pesticides Forum (2001) 6th Int. HCH and Pesticides Forum meeting, 20–22 March 2001, Forum Book, 31–32 CIEL., Verlag K.Schillinger, Freiburg im Breisgau. http://www.ihpa.info/docs/library/libraryPPI.php

International HCH and Pesticide Association (2009) Abstracts submitted to the International HCH and Pesticide Forums: http://www.ihpa.info/resources/library/

Jit S, Dadhwal M, Kumari H, Jindal S, Kaur J, Lata P, Niharika N, Lal D, Garg N, Kumar Gupta S, Sharma P, Bala K, Singh A, Vijgen J, Weber R, Lal R (2010) Evaluation of hexachlorocyclohexane contamination from the last Lindane production plant operating in India. Env Sci Pollut Res (in press)

Jürgens H-J, Roth R (1989) Case study and proposed decontamination steps of the soil and groundwater beneath a closed herbicide plant in Germany. Chemosphere 18:1163–1169

Krum W (1982) Lindan- ja, HCH –nein, Lindan-Workshop, Hannover, Germany 1982; K. Schillinger, C.I.E.L.-Redaktion (Freiburg i. Br/Germany)

Li Y-F (1999) Global technical hexachlorocyclohexane usage and its contamination consequences in the environment: from 1948 to 1997. Sci Total Environ 232(3):121–158

Li Y-F, Cai DJ, Shan ZJ, Zhu ZL (2001) Gridded Usage Inventories of Technical Hexachlorocyclohexane and Lindane for China with 1/6° Latitude by 1/4° Longitude Resolution. Arch. Environ. Contam. Toxicol. 41, 261–266

Li Y-F, Trevorscholtz M, Van Heyst BJ (2003) Global gridded emission inventories of *beta*-hexachlorocyclohexane. Environ Sci Technol 37:3493–3498

Li Y-F, MacDonald R (2005) Sources and pathways of selected organochlorine pesticides to the Arctic and the effect of pathway divergence on HCH trends in biota: a review. Sci Total Environ 342:87–106

Otto W, Schönberger H, Burger D, Weber R (2006) Case study on remediation of a German city contaminated by a chloralkali plant and PCP production. Organohalogen Compd. 68, 880–885

Pearlman D (2005) Cetaphil cleanser cures head lice. Pediatrics 116 (6):1612–1613

Peking University (2005) College of Environmental Sciences, Beijing, P. R. China, Report on China—Joint project to promote the reduction of Lindane emissions in China (Phase 1), November 2005

Ren N (2006) China—Canada joint project on reduction of Lindane usage in China and its impact globally and on North America. April 2006

Rippen G (ed) (1996) Handbuch Umweltchemikalien *(laufend aktualisierte Ausgabe)*. Ecomed, Landsberg am Lech

Romania (2008) Annual report 2008 to EU Commission on POPs (English), 16 June 2009

Sievers S, Friesel P (1989) Soil contamination patterns of chlorinated organic compounds: looking for the source. Chemosphere 19:691–698

Stockholm Convention (2001) Stockholm Convention on persistent organic pollutants; http://chm.pops.int/. http://chm.pops.int/Convention/tabid/54/language/en-US/Default.aspx#convtext
Torres JPM, Fróes-Asmus CIR, Weber R, Vijgen JMH (2010) HCH/DDT contamination around former organochlorine productions in Brazil and preliminary human risk assessment. Organohalogen compounds 72 http://www.xcdtech.com/dioxin2010/pdf/1304.pdf
Treger YA (2004) Data on production of HCH in the former USSR. FSUE Research Institute "Sintez", Moscow, 12 October 2004
Ulman E (1972) Lindane, monograph of an insecticide. Verlag K Schillinger, Friebur im Breisgau
UNEP (2005a) Consideration of chemicals proposed for inclusion in Annexes A, B and C of the Convention: Lindane. Lindane proposal. UNEP/POPS/POPRC.1/8. 24 August 2005
UNEP (2005b) Decision POPRC-1/6: Lindane. UNEP/POPS/POPRC.1/10. November 2005
UNEP (2006a) Consideration of chemicals newly proposed for inclusion in Annexes A, B or C of the Convention: Alpha-hexachlorocyclohexane. UNEP/POPS/POPRC.2/15. 7. August 2006; The POP Reviewing Committee texts can be downloaded at the following website http://chm.pops.int/Convention/POPsReviewCommittee/Chemicals/tabid/781/language/en-US/Default.aspx
UNEP (2006b) Consideration of chemicals newly proposed for inclusion in Annexes A, B or C of the Convention: Beta-hexachlorocyclohexane. UNEP/POPS/POPRC.2/16. 7. August 2006[12]
UNEP (2006c) Decision POPRC-2/9: Alpha hexachlorocyclohexane. November 2006[12]
UNEP (2006d) Decision POPRC-2/10: Beta hexachlorocyclohexane. November 2006[12]
UNEP (2006e) Report of the Persistent Organic Pollutants Review Committee on the work of its second meeting Risk profile on Lindane UNEP/POPS/POPRC.2/17/Add.4. 21. November 2006[12]
UNEP (2007a) Report of the Persistent Organic Pollutants Review Committee on the work of its third meeting. Risk management evaluation on Lindane. 4. December 2007[12]
UNEP (2007b) Report of the Persistent Organic Pollutants Review Committee on the work of its third meeting. Risk profile on beta hexachlorocyclohexane. UNEP/POPS/POPRC.3/20/Add.9. 04. December 2007[12]
UNEP (2008a) Report of the Persistent Organic Pollutants Review Committee on the work of its third meeting. Risk profile on alpha hexachlorocyclohexane. UNEP/POPS/POPRC.3/20/Add.8. 18. January 2008[12]
UNEP (2008b) Report of the Persistent Organic Pollutants Review Committee on the work of its third meeting. Risk management evaluation for alpha hexachlorocyclohexane. UNEP/POPS/POPRC.4/15/Add.3. 30. October 2008[12]
UNEP (2008c) Report of the Persistent Organic Pollutants Review Committee on the work of its third meeting. Risk management evaluation for beta hexachlorocyclohexane. UNEP/POPS/POPRC.4/15/Add.4. 30. October 2008[12]
UNEP (2009a) Report of the Conference of the Parties of the Stockholm Convention on Persistent Organic Pollutants on the work of its fourth meeting. UNEP/POPS/COP.4/38. 8 May 2009; http://chm.pops.int/Programmes/NewPOPs/DecisionsRecommendations/tabid/671/language/en-US/Default.aspx
UNEP (2009b) SC-4/10: Listing of alpha hexachlorocyclohexane. UNEP/POPS/COP.4/SC-4/10. May 2009[13]
UNEP (2009c) SC-4/11: Listing of beta hexachlorocyclohexane. UNEP/POPS/COP.4/SC-4/11. May 2009[13]
UNEP (2009d) SC-4/15: Listing of Lindane. UNEP/POPS/COP.4/SC-4/15. May 2009[13]
Universität Bayreuth, Tritschler & Partner GmbH (1995) Dioxin-Bilanz für Hamburg, p. 21, http://www.hamburg.de/contentblob/112354/data/dioxinbilanz.pdf
US EPA (2003) Five-year review fact sheet, Geigy Chemical Corp. Site, Aberdeen, Moore County, North Carolina, Oct. 2003
Varbelow G, Weber R (2009) Remediation and securing activities at a former 2,4,5-T and HCH production site in Germany. Presentation at the 10th International HCH and Pesticide Forum, 07–10 September 2009, Brno, Czech Republic http://www.hchforum.com/10th/presentations/pdf/06-01_Varbelow_ Weber.pdf
Vijgen J (2006a) The legacy of lindane HCH isomer production. Main report. IHPA, Holte, January 2006 http://ew.eea.europa.eu/Agriculture/Agreports/obsolete_pesticides/lin dane_production.pdf
Vijgen J (2006b) The legacy of Lindane HCH isomer production. Annexes. IHPA, Holte, January 2006 http://ew.eea.europa.eu/Agriculture/Agreports/obsolete_pesticides/lin dane_annexes.pdf (Accessed 01.05.2010)
Vijgen J, Li YF, Martin F, Lal R, Weber R (2006) The legacy of Lindane and technical HCH production. Organohal Compd 68:899–904
Walker K, Vallero DA, Lewis RG (1999) Factors influencing the distribution of Lindane and other hexachlorocyclohexanes in the environment. Environ Sci Technol 33:4373–4378
Ware GW (1999) An introduction to insecticides, 3rd edn. Department of Entomology, University of Arizona, Tucson
Watson A, Forter M, Lal R, Jopkova M, Torres J, Li Y, Weber R, Vijgen J (2009) Global mapping of former HCH production sites and their waste dumps. Presentation at the 10th International HCH and Pesticide Forum, 07–10 September 2009, Brno, Czech Republic http://www.hchforum.com/10th/presentations/pdf/01-06_Weber%20et%20al.pdf
Weber R, Behnisch PA, Brouwer A, van Bavel B, Lindstroem G, Zennegg M, Schilling B, Paepke O (2006) Contemporary relevance of dioxin and dioxin-like compound contaminations in residues from recycling of HCH waste. Organohalogen Comp 68:905–910
Weber R (2007) Relevance of PCDD/PCDF Formation for the Evaluation of POPs Destruction Technologies - Review on Current Status and Assessment Gaps. Chemosphere 67:109–117
Weber R, Gaus C, Tysklind M, Johnston P, Forter M, Hollert H, Heinisch H, Holoubek I, Lloyd-Smith M, Masunaga S, Moccarelli P, Santillo D, Seike N, Symons R, Torres JPM, Verta M, Varbelow G, Vijgen J, Watson A, Costner P, Woelz J, Wycisk P, Zennegg M (2008a) Dioxin- and POP-contaminated sites—contemporary and future relevance and challenges. Env Sci Pollut Res 15:363–393
Weber R, Tysklind M, Gaus C (2008b) Dioxin—contemporary and future challenges of historical legacies (editorial). Env Sci Pollut Res 15:96–112
WHO (1991) Environmental program on chemical safety. Environmental health criteria.124, Lindane, World Health Organization, Geneva, Switzerland. http://www.inchem.org/documents/ehc/ehc/ehc124.htm
Weber R, Watson A, Forter M, Oliaei F (2010) POPs in landfills—persistent organic pollutants and landfills—a review of past experiences and future challenges. Waste Management & Research (in press)
Willet KL, Utrich EM, Hites RA (1998) Differential toxicity and environmental facts of hexachlorocyclohexane isomers. Environ Sci Technol 32:2197–2207
Wycisk P, Stollberg R, Neumann C, Gossel W, Weber R, Weiss H (2010) Methodology for exposure route assessment of HCH groundwater pollution from multi-source contaminated mega sites—a case study. Env Sci Pollut Res (submitted).
Zheng M, Liu P, Bad Z, Xu X (1999) Aspects of formation and degradation of polychlorinated dibenzo-p-dioxins and dibenzofurans. Chinese Science Bulletin 44:1249–1257, http://www.springerlink.com/content/l342q683084l1n96/fulltext.pdf (Accessed 04.2010)