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Lead-Based Paint Remains a Major Public Health Concern: A Critical Review of Global Production, Trade, Use, Exposure, Health Risk, and Implications

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Abstract Lead exposure is a global public health concern. Elevated blood lead levels (BLLs) have been attributed to 18% of all-cause mortality in the US, making lead exposure comparable to tobacco smoke as a cause of mortality. Moreover, lead exposure is thought to cause the mental retardation of more than 0.6 million children each year. The main child lead exposure pathway is ingestion via hand-to-mouth activity, including pica behavior with deteriorated paint chips, or objects coated with lead-based paint. Lead-based paints are widely used in many low and middle-income developing countries, resulting in elevated lead contents in home surfaces and consumer products such as toys. As the bulk of global manufacturing shifts towards developing countries, lead-based paints pose an increasing cause for concern. Therefore, the international community, led by the United Nations Environment Programme (UNEP) and the World Health Organisation (WHO), is actively supporting the phase-out of lead-based paint by 2020. However, there are many significant hurdles on the way to achieving this goal. In light of the importance of the lead-based paint issue, and the urgency of achieving the 2020 phase-out goal, this review article provides critical insights from the existing scientific literature on lead-based paint, and offers a comprehensive perspective on the overall issue. The global production and international trade of lead-based paints across Asia, Africa, Latin America, and Europe are critically discussed. The sources and pathways of exposure are further described to shed light on the associated health risk and socioeconomic costs. Finally, the review offers an overview of the potential intervention and abatement strategies taking into account the complexity posed by lead-based paints. In particular, it was found that there is a general lack of consensus on the definition of lead based paint; and, strengthening regulatory oversight, public awareness, and industry acceptance are vital in combating the global issue of lead based paint.

Keywords: Lead-based paint; lead exposure; blood lead level; soil contamination

1 Introduction

According to the World Health Organization (WHO), lead exposure accounted for nearly half a million deaths in 2016, and over 9 million disability-adjusted life years (DALYs) (WHO 2017); 82% of these lead related deaths occur in low and middle-income developing countries (Landrigan et al. 2018). Lead is an abundant contaminant in the environment (Hou et al. 2017), and thus a global public health concern. However, only very recently has the remarkably large relative contribution of environmental lead exposure to mortality been quantified. Lanphear et al (2018) undertook a population-based cohort study, involving 14,289 adults in the US. In this study, the attributable fraction of blood lead level (BLL) for all-cause mortality was found to be a remarkable 18%, equating to an estimated 412,000 deaths per year in the US, thus making lead exposure comparable to tobacco smoke exposure as a cause of mortality (Lanphear et al. 2018). The authors also found that an increase in BLL from 1.0 to 6.7 µg/dL, which represented the 10th and 90th percentile BLL of the study population, was associated with a hazard ratio of 1.37 (95% CI 1.17-1.60).

Although acute lead poisoning is not a thought to be major contributor to child mortality globally, children with elevated BLLs may suffer from impaired neurological development (WHO 2010). Childhood lead exposure is thought responsible for mild to moderate mental retardation of 0.6 million children each year (Fewtrell et al. 2004). The toxic effect of lead exposure on IQ is thought irreversible, persisting for a lifetime (Gilbert and Weiss 2006). Experience in the US shows that, historically, there were three major sources of lead exposure to children, which were (i) airborne lead from leaded gasoline, (ii) chips and dust of deteriorated lead-based paint in the home, and (iii) lead in soil due to both geogenic and anthropogenic sources (Committee on Environmental Health 2005). After the ban of leaded gasoline, the primary source of children's lead poisoning has become lead-based paint and lead contaminated soil (Lofgren et al. 2000). Water may also be regarded as a potential lead exposure source in certain areas with a plumbosolvent water supply, but of little or no importance in other areas (Elwood et al. 1984).

Lead has been incorporated into mass-market consumer products such as lead-based paint for more than a century. Paint manufactures have historically added lead to paint because of its highly protective properties that make lead-based paints more durable (Gilbert and Weiss 2006), and improves paint adherence to substrates/surfaces (Lin et al. 2009), and to enhance colours (Greenway and Gerstenberger 2010). However, despite a myriad of scientific reports and studies on the detrimental health effects and the associated socioeconomic costs now being available, a UNEP published in 2017 report found that only about a third of the 193 countries investigated regulate lead in paint (UNEP 2017a).

Lead-based paints are still widely manufactured and used in many developing countries (Kessler 2014; Kumar 2009). Although most developed countries, and some developing countries, regulate lead concentration in paints used for building interiors and toys, paints for industrial usage (e.g. anti-corrosive paints) are still often unregulated. These paints pose a risk to human health and the environment if they later enter the consumer market, (IPEN 2017a) for instance in home-related products such as toys, or in deteriorated paint chips, dusts, and soils, which are often observed as a consequence of lead-based paint use. Further to this, paint production and consumption have been steadily growing in developing countries, and many countries lack legally binding controls for lead-based paint (Kessler 2014; Kumar 2009). In these countries, average lead concentrations are often in the range of tens of thousands of parts per million (ppm) in household and decorative paints (Section 2), while internationally the typical regulatory thresholds are 90 - 600 ppm, with 90 ppm being considered as protective.

In the past several years, the lead-based paint issue has drawn the attention of international organizations and non-governmental organizations (NGOs) (IPEN 2017a). The International Conference on Chemicals Management (ICCM) at its second session (ICCM-2, Geneva, 11-15 May 2009) endorsed the United Nations Environment Programme (UNEP) and World Health Organization (WHO) to establish the Global Alliance to Eliminate Lead Paint (GAELP), with the task to globally eliminate lead in paint by 2020. As of September 2017, out of the 193 member states of the UN, 67 had verified legally binding limits on lead in paint (UNEP 2017b); and as of early 2016, 53 countries had established paint labelling requirements, and 17 countries had requirements for paints to be tested and certified for lead content (UNEP 2016). Despite the international effort toward establishing regulatory controls, there remain many hurdles for achieving the GAELP's goal of eliminating lead-based paint globally by 2020. Unless addressed, these hurdles, coupled with a loss of political will among developed nations to provide the technical assistance to back such plans in developing countries (Tan and Li 2017), may lead to disappointment.

In light of the risk to human health and the environment posed by the use of lead-based paints, and the urgency for achieving the 2020 phase-out goal, we believe it is important to review the existing scientific literature regarding lead-based paint, and to provide a comprehensive perspective on the overall issue. Therefore, this review article provides critical insights into: 1) the global production, trade, and use of paints; 2) the effectiveness of regulatory controls across Asia, Africa, Latin America, and Europe; 3) the various sources and exposure pathways pertaining to lead-based paint; 4) the recent health risk management strategies developed to address lead exposure and the associated socioeconomic costs; and 5) the implications and recommendations regarding environmental management of lead-based paint.

2 Production, Trade and Use

2.1 Global Production and International Trade

According to the European Union (EU) Directive 2004/42/CE on paints and varnishes and vehicle refinishing products, paint is defined as a product which provides “a film with decorative, protective or other functional effect on a surface”, and, in the context of the directive, a “film” is “a continuous layer resulting from the application of one or more coats to a substrate” (European Parliament 2004). Paint includes both oil and water based products. Market analysis often mixes the terms “paints” with “paints and coating” or “coatings” (Valk 2014), herein we use the term “paint” collectively. Global paint consumption was estimated to be 36.1 million tons in 2006 (Betne et al. 2011). As Figure 1 shows, in recent years, the production of paint has significantly increased in developing countries, whilst a decrease in developed countries is seen. The major producers of paints and coatings manufactured 21.5 million tonnes of paints and coatings in 2004, which increased to 31.3 million tonnes in 2012. More recent data suggests that India and other Asian countries (besides China) have become more notable producers in 2016, together accounting for a similar production level to Europe (IHS 2017). All Asian countries combined produce 50~55% of total paints and coatings in the world, with China becoming the largest and fastest growing paint producer and consumer globally (IHS 2017).

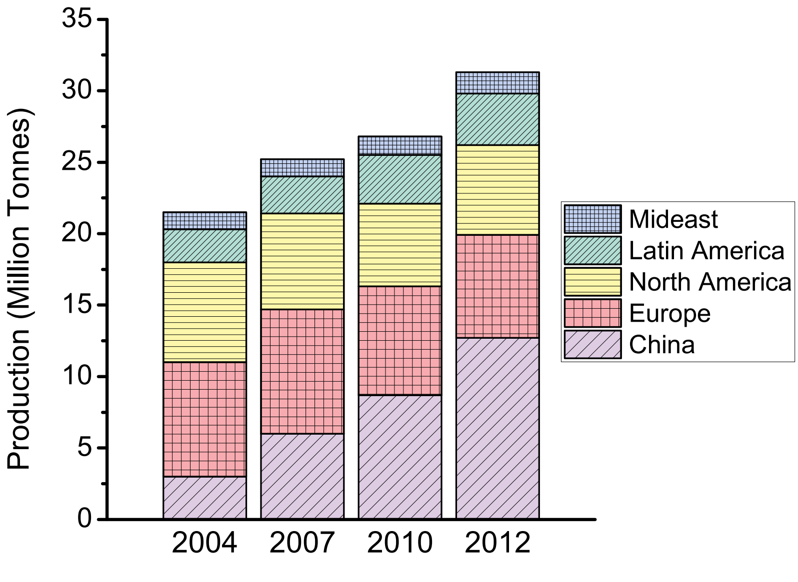

Figure 1 Global production of paints and coatings – years 2004 to 2012, Data source: (Valk 2014)

In Europe, the annual production of paint exceeded 7 million tonnes in 2010 (Figure 2), with the largest production originating from Germany (21%), Italy (18%), France (14%), and the UK (11%). There are notable imports and exports of paint products among European countries (Table 1), with many countries importing and/or exporting hundreds of thousands of tonnes of paint products each year. The production of paints in the EU is mainly via large enterprises: the largest five paint and coating suppliers in the EU had sales exceeding $29 billion (US dollars) in 2011. Besides large companies, there are approximately 1,000 small and medium sized enterprises manufacturing paints and coatings across Europe (Kougoulis et al. 2012).

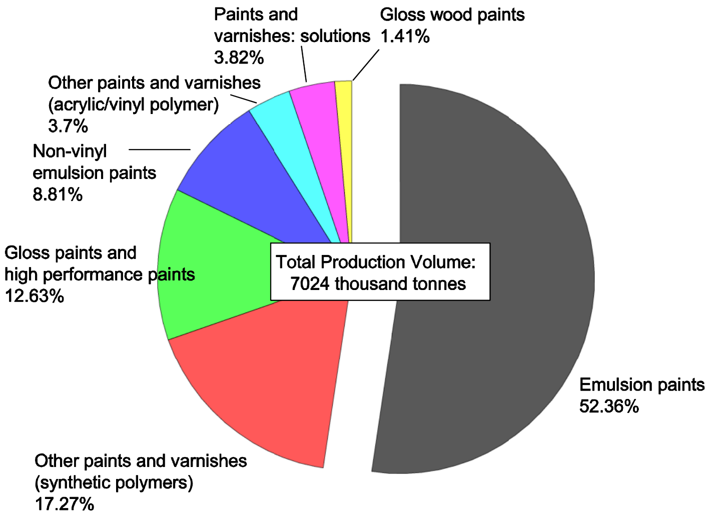

Figure 2 Paints production in Europe – Year 2010, Data source: (Kougoulis et al. 2012)

Table 1 Paint import and export by EU Countries – Year 2009 and 2008

Countries	2009 Import and Export (thousand tonnes)			2008 Import and Export (thousand tonnes)		
	Export	Import	Net Export	Export	Import	Net Export
Denmark	228	193	35	55	52	3
Greece	193	183	10	34	34	-1
Belgium	140	139	1	140	146	-6
Romania	124	125	-1	56	64	-8
Hungary	120	122	-2	46	47	-2
Portugal	113	105	8	46	31	15
Lithuania	106	78	28	20	22	-3
France	103	99	4	219	197	22
TOTAL of EU27	***2,046***	***1,933***	***113***	***1,742***	***1,641***	***101***

Note: the countries listed are the eight largest exporters by volume in 2009; data source (Kougoulis et al. 2012)

In the global market, some countries strongly rely upon the import of paint products. Clark et al (2014) found that among 26 decorative enamel paints sold in Armenia, only seven paints were manufactured domestically (Clark et al. 2014a). The other paints were imported from the United Arab Emirates, Russia, and Turkey. Moreover, seven of the paints were manufactured in one country while the headquarters of the corresponding companies were located in another country. Similarly, 26 paints purchased in Kazakhstan were manufactured in five different countries, with imports from Iran, Russia, Ukraine, and Slovenia. In contrast, other countries mostly use paints that have been manufactured domestically. For instance, Clark et al (2014) found that all 20 paints purchased in Brazil were manufactured in Brazil by Brazilian headquartered companies (Clark et al. 2014a). In Nigeria, a high import tariff is imposed on household paints, consequently, the commonly used household paints in this country are manufactured locally (Adebamowo et al. 2006).

It has been found that paint products sold under the same brand and colour can have dramatically different levels of lead in different countries. The same brand and colour paint sold in developing countries often contains lead concentrations up to thousands times higher than in developed countries (Figure 3); and the same brand and colour paints sold in countries without regulatory thresholds are often found to contain much higher lead concentrations than those sold in countries with regulatory thresholds (Figure 4).

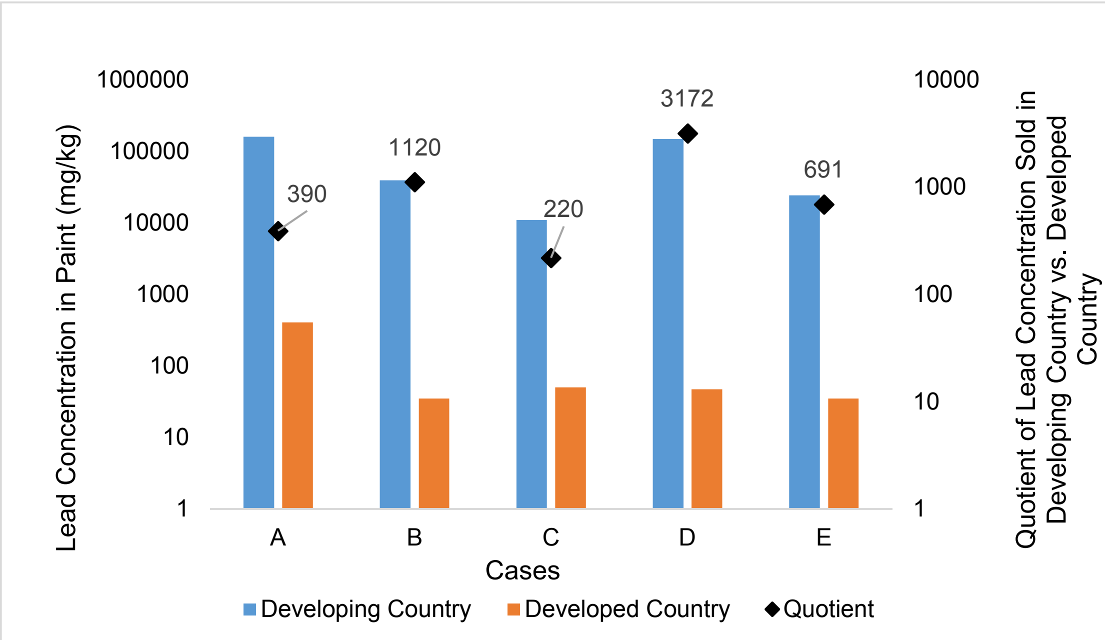

Figure 3 Lead levels in paints of the same brand and same colour being sold in developing countries vs. those sold in developed countries (data source: Clark, 2006)

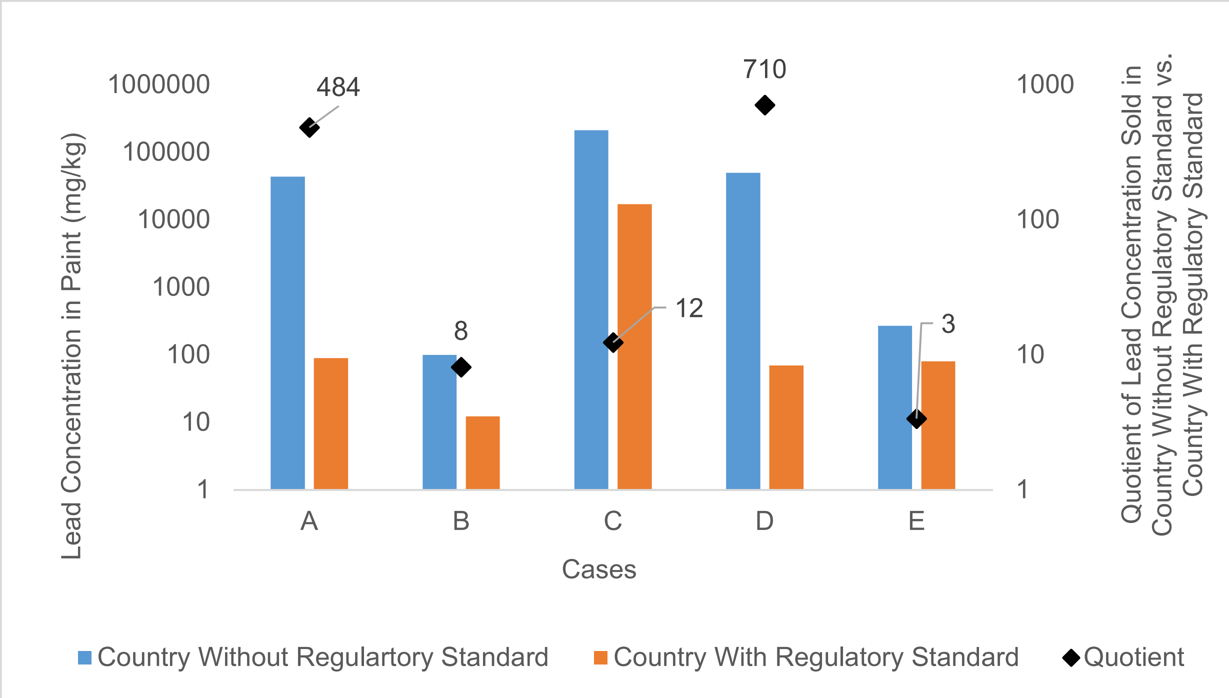

Figure 4 Lead levels in paints of the same brand and same colour being sold in developing countries with no regulatory standard vs. those sold in developing countries with voluntary regulatory standards (data source: (Betne et al. 2011))

2.2 China

China is globally both the largest paint producer and consumer, reaching 19.0 million tonnes in 2016 (Wu et al. 2017). China's regulatory thresholds on lead in paint are based on both total lead concentrations and soluble lead concentrations. The soluble lead concentration is used to evaluate the hazard level associated with bioavailable lead fraction that can be ingested into the body, and the testing method is very different from that for total lead (see Section 5.1 for further discussion). China has enacted a mandatory limit on lead in paint since 1986 (historically, 2,500 mg/kg for total lead and 250 mg/kg for soluble lead), which was strengthened in 2001 (to 90 mg/kg for soluble lead) (see Table 2). However, lead-based paints with lead levels above criteria are often available in the market, despite these mandatory regulations (Table 3).

Clark et al (2009) sampled 64 enamel paints manufactured by 19 companies. It was found that 10 companies had at least one sample with lead concentrations exceeding 10,000 mg/kg (Clark et al. 2009). In a study by Lin et al (2009), a total of 58 new paint samples were collected in China, among these it was found that the maximum lead concentration was 153,000 mg/kg. They also showed that 55% of the samples exceeded the 90 mg/kg soluble lead threshold applicable in China, and 50% of had >600 mg/kg total lead concentrations. In a series of regulations enacted since 2008, the Chinese government further strengthened the regulatory threshold to 1,000 mg/kg total lead for exterior paints, 600 mg/kg total lead for toy paints, and 90 mg/kg soluble lead for most other paints, with the exception of fingernail paint for which the threshold is lower (25 mg/kg soluble lead). Random sampling by the government showed that between 2010 and 2015, 93% of paints for interior walls met regulatory standards. However, it must be noted that China has over 20 regulatory standards for various types of products/applications, and it is known that many lead-based paints are allowed to be sold for industrial applications, which poses a big challenge for controlling lead content in products available in the market (Wu et al. 2017). The discrepancy between the findings from the government tests and the published research may be due to the fact that the published research focused on oil-based paints which are often used for industrial applications rather than interior wall application.

Table 2 Summary of China's key regulatory thresholds pertaining to lead-based paint

Protective targets	Regulatory Limits (mg/kg)		Effective date	Source
	Total Pb	Soluble Pb		
Paint coating on toys	2,500	250	February 1, 1987 (superseded)	(Lin et al. 2009)
Solvent based color paint for woodenware	N/A	90	January 1, 2002 (superseded)	(GAQSIQ 2001a)
Water based interior wall paint	N/A	90	January 1, 2002 (superseded)	(GAQSIQ 2001b)
All paints used in toys	N/A	90	October 1, 2004 (superseded)	(GAQSIQ 2003)
Water based interior wall paint	N/A	90	October 1, 2008	(GAQSIQ 2008b)
Solvent based color paint for woodenware	N/A	90	June 1, 2010	(GAQSIQ 2008a)
Water and solvent-based exterior paint	1000	N/A	June 1, 2010	(GAQSIQ 2009a)
Coating paints used in toys	600	90	October 1, 2010	(GAQSIQ 2009b)
All paints used in toys (except for finger paint)	N/A	90	January 1, 2016	(GAQSIQ 2014b)
Finger paint	N/A	25	January 1, 2016	(GAQSIQ 2014a)

Table 3 Lead content of new paints in China

Location	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Shanghai	2006	Paint	9	N/A		3,280	73,400	56%	(Clark et al. 2006)
N/A	2009	EP	64	15,070	169	34	N/A	33%	(Clark et al. 2009)
Guangzhou	2009	Home paints	58	N/A	N/A	552	153,000	50%	(Lin et al. 2009)
Taiwan [c]	2011	EP	25	23,980	561	2,574	158,000	56%	(Ewers et al. 2011)
8 Cities	2016	EP	141	16,424	819	510	116,000	50%	(Insight Explorer 2016)
Taiwan [c]	2016	Home paints	47	37,000	N/A	N/A	440,000	66%	(TWI 2016)
AVERAGE	***2011***	***N/A***	***57***	***23,119***	***N/A***	***N/A***	***188,080***	***52%***	***N/A***
AVERAGE (weighted by n [b])	***2013***	***N/A***	***88***	***20,284***	***N/A***	***N/A***	***180,431***	***50%***	***N/A***

Abbreviations: EP= enamel paint; NA=not available.
Note: [a] the year of publication; [b] n=number of samples; [c] regulatory thresholds in Taiwan are different from those in mainland China.

2.3 India

The paint production industry in India is composed of an organized sector, with 10~12 main players accounting for 57% of total market share, and an unorganized sector of over 2000 small to medium players accounting for 43% of total market share (Betne et al. 2011). India's previous voluntary standard of 1000 mg/kg lead content in paints (Betne et al. 2011) was lowered to 300 mg/kg in 2011 (Mohanty et al. 2013). However, lead-based paints are still widely available in the paint market (Table 4). In a study published in 2009, Clark et al (2009) sampled 72 enamel paints manufactured by 9 companies; it was found that 6 companies have at least one product with lead concentration exceeding 10,000 mg/kg (Clark et al. 2009). In a more recent study, Toxic Links (2015), found that of 101 paints purchased in 6 cities, 84% contained lead above 600 mg/kg.

There are large differences between the organized sector and the unorganized sector in India. In a study by Mohanty et al (2013), of 57 samples of paints manufactured by the unorganized sector, 53 (93%) exceeded 300 mg/kg (Mohanty et al. 2013), The average lead concentrations of paints manufactured by 6 small-to-medium size companies ranged from 4,213 mg/kg to 18,981 mg/kg, whereas the average lead concentrations in paints manufactured by 4 multinational and large Indian companies ranged from 15 mg/kg to 231 mg/kg.

Table 4 Lead content of new paints in India

Location	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Vallabh, Vidyanagar, Gujarat, Diu	2006	Paint	17	N/A	N/A	16,720	187,200	100%	(Clark et al. 2006)
Delhi, Mumbai	2008	EP	62	26,130	N/A	7,800	140,000	84%	(Kumar and Gottesfeld 2008)
N/A	2009	EP	22	9,411	N/A	25	49,593	36%	(Kumar 2009)
N/A	2009	EP	72	29,660	4,801	9,630	N/A	82%	(Clark et al. 2009)
Delhi	2011	EP	9	5,810	N/A	N/A	N/A	N/A	(Betne et al. 2011)
N/A	2014	EP	26	16,600	N/A	N/A	134,000	35%	(Clark et al. 2014a)
WB and Jharkhand	2014	EP	148	N/A	N/A	N/A	80,350	34%	(Mohanty et al. 2013)
N/A	2014	ODEP	250	22,800	N/A	N/A	160,000	83%	(Brosché et al. 2014)
6 cities	2015	EP	101	N/A	N/A	N/A	118,000	84%	(Toxic Links 2015)
AVERAGE	***2011***	***N/A***	***79***	***18,402***	***N/A***	***N/A***	***124,163***	***67%***	***N/A***
AVERAGE (weighted by n [b])	***2013***	***N/A***	***149***	***23,008***	***N/A***	***N/A***	***128,190***	***70%***	***N/A***

Abbreviations: EP= enamel paint; ODEP=oil based, enamel decorative paint; NA=not available; WB= West Bengal.
Note: [a] the year of publication; [b] n=number of samples.

2.4 Other Asian Countries

Market analysis suggests that the global paint and coating market is growing most rapidly in Asia. Besides China, where the market is growing by 6-7% annually, India is growing at 6.6%, Iran is growing at 4-5%, and Saudi Arabia is growing at 3-4% (IHS 2017). In 2006, the average per capita consumption of paint in the Asia Pacific region was 3.1 kg/person, while the world average was 6.6 kg/person. The yearly per capita consumption in less developed countries remains low, for instance, it was only 0.25 kg/person in Bangladesh in 2006. Therefore, there is potential for tremendous further growth in paint consumption to be seen in Asia (Betne et al. 2011).

In recent years, a number of research institutions and NGOs have conducted studies on lead-based paint in the open market in various Asian countries. As shown in Table 5, the average lead concentration in paints purchased in Asian countries typically ranged from thousands of ppm to tens of thousands of ppm. The percentage of paint samples with lead concentration above 600 mg/kg was around 50-70% in most countries. One exception is Singapore, where average lead content was typically in the thousands of ppm range; with only 9% of paint and 37% enamel paint samples exceeding 600 mg/kg.

These published studies also consistently show that coloured paints tend to have a much higher lead content than white paints. In many cases, the average lead concentration in coloured paint was found to be an order of magnitude higher than in white paint, suggesting that lead had been added for colour enhancement. It is also noted that the geometric mean, as estimated in only a few studies, was much lower than the average (arithmetic mean), suggesting that the average lead concentration was primarily driven by a small number of extremely high concentrations.

Table 5 Lead content of new paints in other Asian countries

Location	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Armenia	2014	EP	26	25,000	N/A	N/A	130,000	77%	(Clark et al. 2014a)
Bangladesh	2011	Paint	6	42,287	N/A	N/A	N/A	N/A	(Betne et al. 2011)
Bangladesh	2011	Paint	29	5,783	N/A	N/A	N/A	N/A	(Betne et al. 2011)
Bangladesh	2014	ODEP	90	11,900	N/A	N/A	123,000	64%	(Brosché et al. 2014)
Indonesia	2009	EP	11	14,770	2,642	3,474	N/A	73%	(Clark et al. 2009)
Indonesia	2014	ODEP	78	17,300	N/A	N/A	116,000	62%	(Brosché et al. 2014)
Indonesia	2015	EP	121	17,217	N/A	4,567	102,000	78%	(BaliFokus 2015)
Jordan	2012	Paints	17	322	N/A	N/A	4,387	12%	(LHAP 2012)
Kazakhstan	2014	EP	26	15,700	N/A	N/A	71,000	77%	(Clark et al. 2014a)
Kazakhstan	2016	Home paints	45	N/A	N/A	N/A	150,000	56%	(Greenwomen 2016)
Lebanon	2015	EP	15	48,300	N/A	30,100	236,000	73%	(Clark et al. 2015)
Malaysia	2006	Paint	32	N/A	N/A	21,300	143,000	72%	(Clark et al. 2006)
Malaysia	2009	EP	72	24,510	769	614	N/A	50%	(Clark et al. 2009)
Malaysia	2016	EP	39	21,429	1,036	200	150,000	41%	(CAP 2016)
Mongolia	2017	Home paints	56	7,706	761	555	71,000	48%	(Zorig 2017)
Nepal	2011	Paint	24	6,575	N/A	N/A	73,966	N/A	(Betne et al. 2011)
Nepal	2011	Paint	12	28,417	857	190	212,700	33%	(Betne et al. 2011)
Nepal	2014	Paint	75	23,367	3,395	5,100	200,000	71%	(Gottesfeld et al. 2014)
Nepal	2014	ODEP	49	16,600	N/A	N/A	130,000	65%	(Brosché et al. 2014)
Nepal	2015	EP	87	18,326	4,390	6,200	124,000	83%	(CEPHED 2015)
Philippines	2009	EP	15	28,354	N/A	3,199	189,163	60%	(Kumar 2009)
Philippines	2014	ODEP	122	18,500	N/A	N/A	156,000	52%	(Brosché et al. 2014)
Philippines	2015	EP	140	21,820	1,286	2,770	153,000	56%	(EcoWaste 2015)
Philippines	2017	Home paints	104	N/A	N/A	N/A	100,000	16%	(EcoWaste 2017)
Singapore	2006	Paint	22	N/A	N/A	9	3,500	9%	(Clark et al. 2006)
Singapore	2009	EP	41	6,988	163	N/A	N/A	37%	(Clark et al. 2009)
Sri Lanka	2009	EP	19	25,210	N/A	5,137	137,325	68%	(Kumar 2009)
Sri Lanka	2014	ODEP	94	11,600	N/A	N/A	131,000	50%	(Brosché et al. 2014)
Sri Lanka	2015	EP	56	N/A	N/A	N/A	44,000	54%	(CEJ 2015)
Tajikistan	2016	ODEP	51	N/A	N/A	N/A	80,000	82%	(Dastgir 2016)
Thailand	2009	EP	18	19,410	7,281	15,170	N/A	89%	(Clark et al. 2009)

Location	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Thailand	2009	EP	17	61,893	N/A	35	505,716	47%	(Kumar 2009)
Thailand	2014	ODEP	120	19,100	N/A	N/A	95,000	69%	(Brosché et al. 2014)
Thailand	2015	EP	100	19,205	827	2,109	112,00	58%	(EARTH 2015)
Vietnam	2016	Paint	26	4,364	687	970	21,000	54%	(CGFED 2016)
AVERAGE	***2013***	***N/A***	***53***	***20,067***	***N/A***	***N/A***	***129,819***	***57%***	***N/A***
AVERAGE (weighted by n [b])	***2014***	***N/A***	***80***	***18,050***	***N/A***	***N/A***	***122,715***	***58%***	***N/A***

Abbreviations: EP= Enamel paint; ODEP=oil based, enamel decorative paint.
Note: [a] the year of publication; [b] n=number of samples.

2.5 African Countries

Africa represents a small portion of the global paints and coating market, representing only 1% of global sales in 2005 (Akzo Nobel 2006). Despite a relatively small international market share for global paint and coatings, domestically made lead-based paint remains an important lead exposure source. Adebamowo et al (2007) found that the lead levels in 96% of household paints purchased in Nigeria were above 600 mg/kg. They also found that lead levels in paints were associated with colour, with lead levels increasing from white (3,035 mg/kg), blue (3,457 mg/kg), green (15,976 mg/kg), red (23,744 mg/kg), to yellow (42,271 mg/kg). Paints of the same colour but purchased from different manufacturers generally contained similar levels of lead (Adebamowo et al. 2007). A number of additional studies were conducted in several African countries including Seychelles, Egypt, Cameroon from 2009 to 2015. They found that average lead content typically fell in the range of tens of thousands of ppb, and the number of samples with lead exceeding 600 mg/kg was typically more than half (Table 6).

In June 2016 to July 2017, IPEN conducted studies of paint in 15 African countries (IPEN 2017b). However, the format of the IPEN report differed from other referred academic studies, and did not typically include average concentrations or the percentage of samples exceeding 600 mg/kg (Table 6); therefore, it is hard to compare these results with other studies. Nevertheless, the latest study by IPEN confirmed that lead-based paints are still widely available in African countries, with more than half of the 593 analysed samples exceeding 90 mg/kg, and almost a quarter of samples exceeding 10,000 mg/kg (IPEN 2017b).

Table 6 Lead content of new paints in African countries

Location	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Benin	2017	Home paints	28	N/A	N/A	N/A	180,000	N/A	(IPEN 2017b)
Cameroon	2013	Paint	61	N/A	N/A	2,150	500,000	64%	(Gottesfeld et al. 2013)
Cameroon	2015	EP	35	N/A	N/A	N/A	N/A	51%	(CREPD 2015)
Cameroon	2017	Home paints	65	N/A	N/A	N/A	220,000	N/A	(IPEN 2017b)
Egypt	2009	EP	20	26,200	1,338	4,717	N/A	65%	(Clark et al. 2009)
Egypt	2014	EP	52	14,300	N/A	N/A	122,000	48%	(Clark et al. 2014b)
Egypt	2017	Home paints	58	N/A	N/A	N/A	43,000	N/A	(IPEN 2017b)
Ethiopia	2013	EP	23	18,500	N/A	N/A	130,000	83%	(UNEP 2013)
Ethiopia	2015	EP	36	N/A	N/A	N/A	110,000	78%	(PAN 2015)
Ethiopia	2017	Home paints	36	N/A	N/A	N/A	100,000	N/A	(PAN 2017)
Ghana	2013	EP	18	5,030	N/A	N/A	42,000	28%	(UNEP 2013)
Guinea	2017	Home paints	18	N/A	N/A	N/A	9,700	N/A	(IPEN 2017b)
Ivory Coast	2013	EP	20	8,700	N/A	N/A	42,000	65%	(UNEP 2013)
Ivory Coast	2015	EP	44	N/A	N/A	N/A	190,000	75%	(JVE 2015)
Ivory Coast	2017	Home paints	51	N/A	N/A	N/A	470,000	N/A	(JVE 2017)
Kenya	2012	EP	31	14,900	N/A	N/A	69,000	81%	(iLima 2012)
Kenya	2017	Home paints	51	N/A	N/A	N/A	160,000	N/A	(CEJAD 2017)
Morocco	2017	Home paints	33	N/A	N/A	N/A	140,000	N/A	(SMTCA 2017)
Mozambique	2017	Home paints	32	N/A	N/A	N/A	25,000	N/A	(IPEN 2017b)
Nigeria	2007	Home paints	21	14,500	N/A	N/A	50,000	96%	(Adebamowo et al. 2007)
Nigeria	2009	EP	25	15,750	7,341	N/A	N/A	96%	(Clark et al. 2009)
Nigeria	2009	EP	23	36,989	N/A	23,866	129,837	100%	(Kumar 2009)
Nigeria	2017	Home paints	54	N/A	N/A	N/A	160,000	N/A	(IPEN 2017b)
Senegal	2009	EP	21	5,866	N/A	2,771	29,717	76%	(Kumar 2009)
Seychelles	2009	EP	28	24,880	1,167	2,527	N/A	61%	(Clark et al. 2009)
South Africa	2009	EP	29	19,862	N/A	11	195,289	62%	(Kumar 2009)
Sudan	2017	Home paints	25	N/A	N/A	N/A	71,000		(IPEN 2017b)
Tanzania	2009	EP	20	14,537	N/A	4,130	120,862	95%	(Kumar 2009)
Tanzania	2015	EP	56	12,541	N/A	N/A	99,000	57%	(AGENDA 2015)
Tanzania	2017	Home paints	46	N/A	N/A	N/A	84,000	N/A	(IPEN 2017b)
Togo	2017	Home paints	27	N/A	N/A	N/A	42,000	N/A	(IPEN 2017b)
Tunisia	2013	EP	30	17,900	N/A	N/A	170,000	63%	(UNEP 2013)
Uganda	2017	Home paints	30	31,694	2,106	1,450	150,000	57%	(NAPE 2017)
Zambia	2017	Home paints	39	14,500	N/A	15,800	50,000	N/A	(CEHF 2017)
AVERAGE	***2014***	***N/A***	***35***	***17,839***	***N/A***	***N/A***	***132,480***	***68%***	***N/A***
AVERAGE (weighted by n [b])	***2015***	***N/A***	***40***	***17,784***	***N/A***	***N/A***	***154,940***	***66%***	***N/A***

Abbreviations: EP= Enamel paint.

Note: [a] the year of publication; [b] n=number of samples.

2.6 Other Countries

In general, developed countries have better enforced environmental regulations for lead-based paint than developing countries. In particular, the US is now considered to undertake best practice in regulating lead-based paint (Bodel 2010), with a variety of regulations designed to protect homes and child-occupied facilities (see Table 7). Historically, white coloured house paint in the US contained up to 50% lead, however, this changed in 1971 when the federal government placed a ban on paint containing more than 1% lead. The threshold was lowered to 600 mg/kg (0.06%) in 1977, and further lowered to 90 mg/kg (0.009%) in 2009. Although paint for bridges and marine uses are exempted from this regulatory threshold (ATSDR 2017).

Table 7 Summary of US regulations pertaining to lead-based paint exposure

Receptors	Protective measures	Effective date	Source
Homes and child-occupied facilities	Firms and workers performing RRP must be EPA- or state-certified to prevent lead contamination	April 22, 2010	(USEPA 2008)
Homes and child-occupied facilities	Lead abatement must be trained and certified by EPA or an authorized State.	August 29, 1996	(USEPA 1996b)
Homes	For housing sales or lease, the owner must disclose information about lead hazards and give time for a lead inspection	March 3, 1996	(USEPA 1996a)
Homes	Identified hazard conditions of lead in paint: 1) >40 µg/sf of Pb in dust on floor; 2) >250 µg/sf of Pb in dust on interior window sills; 3) >400 mg/kg Pb in surface soil in children's play areas; 4) >1200 mg/kg Pb in the rest of the yard; 5) paint in deteriorating condition; 6) paint on a friction surface, or impact surface, or certain chewable surfaces.	March 6, 2001	(USEPA 2001a)
Consumer paints	Maximum level allowed < 600 mg/kg	February 28, 1978	(USCPSC 1977)
Household paint & product	Lead in household paint and coating in children's products should be <90 mg/kg	August 12, 2012	(USCPSC 2011)

Note: TSCA= Toxic Substances Control Act; RRP= performing renovation, repair and painting projects that disturb lead-based paint; sf=square foot.

Regulations to limit lead-based paints were introduced in the UK in the 1970s. However, whilst this has greatly reduced the number of children exposed to lead (Horner 1994), many painted surfaces still remain a lead poisoning hazard in some older UK properties and facilities. For instance, lead concentrations were found to be elevated on historically painted surfaces in urban areas; for instance, as high as 36,900 mg/kg on handrails (Turner and Sogo 2012), up to 389,000 mg/kg in telephone kiosks (Turner and Solman 2016), and up to 152,000 mg/kg on public playground structures (Turner et al. 2016). Therefore, lead exposure from paint is an on-going issue in the UK which should not be neglected, however, the literature search revealed no recent studies regarding lead concentration in new paints sold in the UK market.

Recent studies have examined lead content in new paints in Portugal and several eastern European countries. It was found that paint products purchased in Russia contained elevated concentrations of lead (average 8,340 mg/kg, maximum 53,000 mg/kg) as shown in Table 8 (Clark et al. 2015). The children's play paints purchased in Portugal were all determined to be below 2 mg/kg (Rebelo et al. 2015). Recent studies also examined new paints available in Latin America (see Table 9). It was found that the average lead concentrations in new paints were typically in the range of tens of thousands of mg/kg, with a few exceptions in Chile and Uruguay, where the average lead concentration was much lower (52.6 mg/kg and 9.8 mg/kg, respectively). An exceptional case occurred in Brazil, where the lead concentrations of some brands were reported by Toxic Links/IPEN before a mandatory regulation was enacted, after which, paint from the same brand was tested again and found to contain lead concentrations that were nearly four orders of magnitude lower (Clark et al. 2014a).

Table 8 Lead content of new paints in Europe

Country	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Armenia	2016	DP	49	N/A	N/A	N/A	180,000	57%	(AWHHE 2016)
Azerbaijan	2013	EP	30	2,600	N/A	N/A	20,000	67%	(UNEP 2013)
Belarus	2009	EP	22	5,557	N/A	1,678	59,387	68%	(Kumar 2009)
Belarus	2016	Home paints	48	N/A	N/A	N/A	91,000	62%	(CES 2016)
Georgia	2016	Home paints	37	N/A	N/A	N/A	68,000	32%	(Gamarjoba 2016)
Kyrgyz	2016	Home paints	51	N/A	N/A	N/A	39,000	55%	(IEE 2016)
Moldova	2016	Home paints	28	N/A	N/A	N/A	83,000	36%	(EcoContact 2016)
Russia	2015	EP	21	8,340	N/A	2,140	53,000	67%	(Clark et al. 2015)
Russia	2016	Home paints	72	N/A	N/A	N/A	50,000	49%	(Eco-Accord 2016)
Portugal	2015	Artist paints	54	0.52	N/A	N/A	1.98	0%	(Rebelo et al. 2015)
Portugal	2015	Gouaches	20	0.65	N/A	N/A	1.94	0%	(Rebelo et al. 2015)
Portugal	2015	Acrylics	5	0.29	N/A	N/A	0.42	0%	(Rebelo et al. 2015)
Portugal	2015	Watercolors	23	0.54	N/A	N/A	1.98	0%	(Rebelo et al. 2015)
Portugal	2015	Fingerpaints	6	ND	N/A	N/A	ND	0%	(Rebelo et al. 2015)
Portugal	2015	Face paints	12	0.29	N/A	N/A	0.71	0%	(Rebelo et al. 2015)
Ukraine	2016	Home paints	53	N/A	N/A	N/A	30,000	26%	(MAMA-86 2016)
AVERAGE	***2015***	***N/A***	***33***	***2,062***	***N/A***	***N/A***	***44,893***	***32%***	***N/A***
AVERAGE (weighted by n [b])	***2015***	***N/A***	***44***	***2,008***	***N/A***	***N/A***	***53,765***	***39%***	***N/A***

Abbreviations: EP= Enamel paint; DP=Decorative paint; ODEP=oil based, enamel decorative paint; ND=not detected.

Note: [a] the year of publication; [b] n=number of samples.

Table 9 Lead content of new paints in Latin America

Country	Year [a]	Product Type	n [b]	Average (mg/kg)	Geometric mean (mg/kg)	Median (mg/kg)	Max (mg/kg)	>600 mg/kg (%)	Reference
Argentina	2013	EP	30	17,000	N/A	N/A	130,000	23%	(UNEP 2013)
Brazil	2009	EP	24	15,004	N/A	N/A	170,258	37%	(Kumar 2009)
Brazil	2014	EP	10	36,000	reported before regulation			90%	(Clark et al. 2014a)
Brazil	2014	EP	10	4.5	same brand after regulation			0%	(Clark et al. 2014a)
Brazil	2014	EP	10	11,300	other brand after regulation			50%	(Clark et al. 2014a)
Chile	2013	EP	23	52.6	N/A	N/A	N/A	4%	(UNEP 2013)
Colombia	2016	Home paints	39	N/A	N/A	N/A	250,000	64%	(Colnodo 2016)
Ecuador	2009	EP	10	31,960	2,178	13,460	N/A	60%	(Clark et al. 2009)
Mexico	2009	EP	20	51,860	N/A	N/A	163,812	100%	(Kumar 2009)
Paraguay	2015	EP	15	23,100	N/A	<9	169,000	27%	(Clark et al. 2015)
Peru	2009	EP	10	11,550	3,259	N/A	N/A	80%	(Clark et al. 2009)
Uruguay	2013	EP	30	9.8	N/A	N/A	N/A	0%	(UNEP 2013)
AVERAGE	***2012***	***N/A***	***19***	***17,986***	***N/A***	***N/A***	***126,319***	***45%***	***N/A***
AVERAGE (weighted by n [b])	***2013***	***N/A***	***24***	***16,476***	***N/A***	***N/A***	***130,246***	***41%***	***N/A***

Abbreviations: EP= Enamel paint.
Note: [1] the year of publication; [2] n=number of samples.

3 Source of Exposure and Pathways

There are a variety of exposure pathways linking lead-based paint with human receptors. The most notable exposure pathways are associated with toys, deteriorated paint chips in home, contaminated dust, and contaminated soil, as discussed below.

3.1 Toys

As children are the most vulnerable receptors to lead exposure, the lead content in painted toys is naturally of great concern. Children's mouthing behavior with toys has been identified as an important lead exposure pathway (Lanphear and Roghmann 1997). Moreover, typical photochemical air pollutants, including NO_2 and O_3, can react with and remove polymeric binders in paint, making pigment granules available for transfer to a child's skin on contact. It was revealed that lead concentrations in wipe samples of painted surface increased by almost a factor of 3 after exposure to NO_2 and by more than a third after exposure to O_3 (Edwards et al. 2009).

Various countries have specific regulatory limits for paint used in toys. For instance, China has a regulatory standard of 600 mg/kg for total lead concentration in toy paint, and 90 mg/kg for the dissolvable lead concentration (GAQSIQ 2014b); Columbia also regulates soluble lead at 90 mg/kg (Mateus-Garcia and Ramos-Bonilla 2014); and the

US has the more stringent regulatory standard of 90 mg/kg for total lead concentration in toy paint (USCPSC 2011).

Despite regulatory limits of lead in paints for toys in many countries, lead exceedance in painted toys has been found in many cases (see Table 10). China is the largest exporter of toys in the international market. Famously, the US Consumer Product Safety Commission issued recalls of millions of units of lead containing toys in 2007, most of which were manufactured in China (Meyer et al. 2008). Lead paint on toys has been the target of some criticism, which caused damage to the reputation of Chinese manufacturers (Beamish and Bapuji 2008). On the other hand, the Chinese government has introduced increasingly stringent regulatory thresholds for paint on toys (see Section 2.2). The current Chinese standard for paints used in toys has been lowered to 90 mg/kg for soluble lead and 600 mg/kg for total lead. A recent study by Shen et al (2018) analysed 100 toys purchased from the three largest online shopping platforms in China for lead content. It was found that the toys sold on the two platforms considered “organized sellers”, had much lower lead content than toys sold by “unorganized sellers” on the third platform. Approximately 12% of the toys purchased from the unorganized platform contained paint with total lead concentrations exceeding China's latest regulatory standard (Shen et al. 2018a).

Toys containing lead-based paint may be a more notable issue in developing countries due to a lack of regulatory requirements. In a study conducted in Columbia, 116 paint samples were collected from 96 toys randomly bought from local stores, 91 of which were made in China. Of the Chinese manufactured toys, only one sample exceeded 600 mg/kg (1.1%), and the average lead concentration was 173 mg/kg for the 91 samples. In comparison, 24% of the toys made locally in Columbia exceeded 600 mg/kg, resulting in an average lead concentration of 6,057 mg/kg for the 25 samples (Mateus-Garcia and Ramos-Bonilla 2014).

Table 10 Concentrations of lead in paints used in toys

Country	Year [1]	Comments	n [2]	Level [3] (mg/kg)	Max (mg/kg)	>600 mg/kg	Reference
China	2009	Toys	5	10,700 [b]	51,800	80%	(Lin et al. 2009)
US	2010	Toys	535	N/A	N/A	5.4%	(Greenway and Gerstenberger 2010)
US	2010	*PVC*	145	325 [a]	N/A	14%	(Greenway and Gerstenberger 2010)
US	2010	*Non-PVC*	390	89 [a]	N/A	2%	(Greenway and Gerstenberger 2010)
US	2010	*Yellow*	115	216 [a]	N/A	15%	(Greenway and Gerstenberger 2010)
US	2010	*Non-yellow*	420	94 [a]	N/A	3%	(Greenway and Gerstenberger 2010)
US	2013	Paint on metal toys	12	<64 [a]	N/A	0%	(Guney and Zagury 2013)
US	2014	Toys from bargain stores	46	532 [a]	N/A	17%	(Hillyer et al. 2014)
US	2014	Toys from retail stores	46	10 [a]	N/A	0%	(Hillyer et al. 2014)
Colombia	2014	Paints from 96 toys	116	1,024 [a]	47,600	4.3%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Black*	14	7 [a]	21	0%	(Mateus-Garcia and Ramos-Bonilla 2014)

Country	Year [1]	Comments	n [2]	Level [3] (mg/kg)	Max (mg/kg)	>600 mg/kg	Reference
Colombia	2014	*Blue*	19	15 [a]	55	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Brown*	13	7,436 [a]	47,600	13%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Green*	14	37 [a]	457	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Orange*	13	1,143 [a]	14,750	7.7%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Red*	14	8 [a]	39	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*White*	12	41 [a]	449	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Yellow*	17	337 [a]	5,398	5.9%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: China*	91	173 [a]	14,750	1.1%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: Colombia*	17	6,057 [a]	47,600	24%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: Germany*	1	3 [a]	3	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: Indonesia*	1	6 [a]	6	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: Malaysia*	3	3 [a]	3	0%	(Mateus-Garcia and Ramos-Bonilla 2014)
Colombia	2014	*Origin: Thailand*	3	7 [a]	7	0%	(Mateus-Garcia and Ramos-Bonilla 2014)

Note: [1] the year of publication; [2] n=number of samples; [3] lead concentrations in paint of toys reported as arithmetic mean [a], median [b], or geometric mean [c].

3.2 Deteriorated paint chips

Deteriorated paint chips are a major pathway for children exposed to lead-based paint (Jacobs et al. 2002). Lanphear and Roghmann have suggested that lead-based paint was a more significant contributor to BLL than lead contaminated soil (Lanphear and Roghmann 1997). In a study in the Philippines, 21% of 2861 children surveyed were found to have BLL exceeding 10 µg/dL. The investigators found interior and exterior paints containing lead above 5000 mg/kg in 12% of the Children's households (Riddell et al. 2007). In the US, there was an estimated 4 billion m^2 of lead-based paint on exterior surfaces of households, and 2.1 billion m^2 on interior surfaces in 1990 (HUD 1990). Jacobs et al (2002) estimated that approximately 14% of US housing units have significantly deteriorated lead-based paint chips. Lanphear et al (1998) reported that children with BLL above 55 µg/dL tend to display paint chips in abdominal radiographs, and most children with BLL above 25 µg/dL have reportedly put paint chips in their mouths. For more moderately elevated BLL (i.e. BLL between 10 and 25 µg/dL), the major sources of lead were found to be house dust and contaminated soil (Lanphear 1998).

A ban on lead-based paint, which was introduced in the US in 1978, did not immediately bring an end to its use. A study by Jacobs et al (2002) found that for houses built between 1978 and 1998, 3% of houses had some component (primarily trim) of exterior surface painted with lead-based paint, and 1% of houses had some component (primarily window frames) of interior surfaces painted with lead-based paint. This may have been due to one of two plausible reasons: 1) stock of residential lead-based paint remained available for purchase immediately after the ban; or 2) industrial or marine lead-based paint, which was exempted from the ban, being illegally/unknowingly used (Jacobs et al. 2002). Nevertheless, the number of housing units with lead-based paint decreased from 64 million in 1990 to 38 million in 2000 due to the lead abatement efforts (Jacobs et al. 2002). Jacobs et al (2002) further argued that the decrease in number of homes with lead-based paint may have made significant contribution to the overall decline of population BLL in the US (Jacobs et al. 2002).

The environmental fate of lead in paint is important in determining its exposure risk. As discussed in section 3.1, photochemical atmospheric pollutants, e.g. O_3 and NO_2, can accelerate lead paint degradation (Cohan et al. 2009). Exterior paint may also be removed by weathering and contribute to elevated lead concentrations in urban storm water runoff and surface waterways (Davis and Burns 1999). Detached paint chips from playground equipment is also a concern. In a study conducted in Tokyo, Japan, paint chips found in five public parks were tested (Takaoka et al. 2006). It was revealed that paint chips from flowerbeds contained the highest levels of lead (55,100 - 84,900 mg/kg), followed by swings (2,600 - 56,900 mg/kg) and slides (7,700 - 45,800 mg/kg). Lead concentration in surficial soil ranged from 15 - 237 mg/kg, with higher lead concentrations found in soil located near painted equipment.

3.3 Dust

It has been found that US children's BLLs are highly correlated with lead concentration in house dusts (Farfel and Chisolm Jr 1990). Jacobs et al (2002) estimated that approximately 16% of US housing units contained indoor lead-contaminated dust (Jacobs et al. 2002). Studies have shown that window components, especially window wells (i.e. the portion of window that receives the sash when the window is closed) where dust tends to accumulate, can have dust lead concentrations over 60 times higher than floor dust (Table 11). Traditional lead abatement practices do not remove lead-based paint on most components of windows (Farfel and Chisolm Jr 1990). The opening and closing of old windows can further deteriorate lead-paint surfaces, resulting in both the accumulation of lead-dust and detachment of lead-paint chips, which may be ingested by children directly. Besides indoor lead-based paint, soil lead can contribute to indoor dust lead levels (Clark et al. 2004). For example, in the US, approximately 2.7 million homes without lead-based paint contained lead dust hazards, which may be due to lead-contaminated soil tracked into homes (Jacobs et al. 2002).

Lead concentrations in dust are related to the floor surface material/texture, with smooth floors tending to have lower lead levels than rough wooden floors (Farfel and Chisolm Jr 1990). Friction and impact surfaces on window frames tends to relate to higher lead concentrations in dust located nearby than other areas of the house (Dixon et al. 2007). Studies suggest that lead dust loading (i.e. weight of lead in dust per unit of surface area) is a better indicator than lead concentrations in dust (i.e. weight of lead per unit weight of dust) for predicting children's BLL (Lanphear 1998). The USEPA proposed a floor lead standard of 0.5 mg/m^2 in 1998; however, Lanphear argued that this standard was not sufficiently protective based on the USEPA's own objective (Lanphear 1998).

Table 11 lists lead loading and BLL that were found in a number of studies from 1990 to 2017. These data generally show that higher lead levels in dust corresponded to higher BLL. Moreover, Table 11 shows that, in general, lead dust loading levels determined in these studies has decreased with time. Taking dust on window sills in the US as an example, a study in 1990 found an average lead dust loading of 15.6 mg/m^2 (n=344); two studies in 1996-1998 found an average lead dust loading of 2.5-3.3 mg/m^2 (n=186); and two studies in 2004-2006 found an average lead dust loading of 0.53-0.81 mg/m^2 (n=639).

A confounding factor of dust lead contamination is the issue of cross-contamination by lead-based paint in adjacent housing units. Lead isotopic and SEM investigations have found that decontaminated houses can be re-contaminated within several months by lead-based paint in poor condition in adjacent buildings (Gulson et al. 1995). Public education and training of workers can reduce the risk of cross contamination during the renovation and maintenance work on housing units containing lead-based paint (Jacobs et al. 2002).

Table 11 Concentrations of lead in dust within in houses with lead-based paint

Country	Year	Surface Type	n [1]	Lead level [2] (mg/m^2)	BLL [3] (μg/dL)	Reference
US	1990[4]	Floors	362	2.8 [c]	35.8 [a]	(Farfel and Chisolm Jr 1990)
US	1990	Window sills	344	15.6 [c]	35.8 [a]	(Farfel and Chisolm Jr 1990)
US	1990	Window wells	186	172.2 [c]	35.8 [a]	(Farfel and Chisolm Jr 1990)
US	1996	Window channels	8	423 [a]	N/A	(Howden et al. 1996)
US	1996	Window sills	3	3.3 [a]	N/A	(Howden et al. 1996)
US	1998	floors, window sills and troughs	183	2.5 [a]	7.6 [a]	(Lanphear 1998)
US	1998		183	1.1 [c]	6.2 [c]	(Lanphear 1998)
US	1998	Floor	5	0.34 [a]	N/A	(Hunt et al. 1998)
US	2004	Exterior entry	30	5.0 [a]	N/A	(Clark et al. 2004)
US	2004	Exterior entry w/ST[5]	259	11 [a]	N/A	(Clark et al. 2004)
US	2004	Interior floor	75	0.10 [a]	N/A	(Clark et al. 2004)
US	2004	Interior floor w/ST[5]	466	0.12 [a]	N/A	(Clark et al. 2004)
US	2004	Interior entry	75	0.06 [a]	N/A	(Clark et al. 2004)
US	2004	Interior entry w/ST[5]	466	0.10 [a]	N/A	(Clark et al. 2004)
US	2004	Interior window sill	75	0.53 [a]	N/A	(Clark et al. 2004)
US	2004	Interior window sill w/ST[5]	466	0.68 [a]	N/A	(Clark et al. 2004)
US	2006	Child bedroom sill	59	0.81 [c]	N/A	(Brown et al. 2006)
US	2006	Other sill	39	0.56 [c]	N/A	(Brown et al. 2006)

Country	Year	Surface Type	n [1]	Lead level [2] (mg/m^2)	BLL [3] (μg/dL)	Reference
US	2006	Room floor	72	0.09 [c]	N/A	(Brown et al. 2006)
US	2006	Entry floor	72	0.13 [c]	N/A	(Brown et al. 2006)
France	2012	All floors	471	0.02 [a]	N/A	(Lucas et al. 2012)
France	2012	Children's room	455	0.01 [a]	N/A	(Lucas et al. 2012)
France	2012	Maximum room	471	0.04 [a]	N/A	(Lucas et al. 2012)
France	2012	Common room	114	0.13 [a]	N/A	(Lucas et al. 2012)
France	2012	Outdoor hard surface	53	0.10 [a]	N/A	(Lucas et al. 2012)
Australia	2014	Vacuum dust	60	489 mg/kg [a]	N/A	(Laidlaw et al. 2014)
Australia	2014	Exterior dust gauge (28 d)	67	0.17 [a]	N/A	(Laidlaw et al. 2014)
Australia	2014	Petri-dish attic (28 d)	22	0.08 [a]	N/A	(Laidlaw et al. 2014)
Australia	2014	Petri-dish house (28 d)	21	0.01 [a]	N/A	(Laidlaw et al. 2014)
Canada	2011	Floors	6	578 mg/kg	N/A	(Beauchemin et al. 2011)
Canada	2014	Floor	305	0.01 [c]	1.35 [c]	(Levallois et al. 2014)
Canada	2014	Window sills	263	0.08 [c]	N/A	(Levallois et al. 2014)
Canada	2017	Kitchen floor	92	0.01 [c]	1.41 [c]	(Safruk et al. 2017)
Canada	2017	Play area floor	70	0.01 [c]	1.41 [c]	(Safruk et al. 2017)

Note: [1] n=number of samples; [2] lead dust loading, defined as the weight of lead in dust per unit of surface area, are reported as arithmetic mean [a], median [b], or geometric mean [c]; [3] blood lead concentration in children are reported as arithmetic mean [a], median [b], or geometric mean [c]; [4] the year of publication; [5] for residential building with soil treatment.

3.4 Soil

Soil around housing units can often contain substantially elevated lead concentrations, Table 12 lists soil lead concentrations at lead-paint housing sites. Andra et al (2006) examined soil lead concentrations at housing units with lead-based paint. It was found that soil lead concentrations averaged 1,697 mg/kg for 10 housing units in San Antonio, USA, and 697 mg/kg for 10 housing units in Baltimore City, USA (Andra et al. 2006). Approximately 70% of these housing units had soil lead concentrations exceeding the USEPA regulatory threshold value of 400 mg/kg. In comparison, the typical background soil lead concentration was 20 mg/kg. Moreover, soils from residential sites built after the US ban of lead-based paints was introduced, had maximum soil lead concentrations of only 5 mg/kg (Andra et al. 2006). Jacobs et al (2002) estimated that, overall, approximately 7% of US housing units had soil lead levels exceeding regulatory standards. The elevated soil lead levels were mostly related to the deterioration of exterior lead-based paint. For instance, it was found that soil lead exceedance was 24% for housing units with deteriorated exterior lead-based paints, as compared to only 4% for housing units without exterior lead-based paint (Jacobs et al. 2002). Soil lead levels measured at foundation perimeters are often much higher than found in other garden areas. In a study by Howden et al (1996), samples collected around the foundation perimeter contained lead concentration as high as 12,460 mg/kg, while samples collected from the lawn area contained only 234 mg/kg of lead.

The cleanup of soil contaminated by lead can be achieved by using traditional techniques, such as soil washing and stabilization (Shen et al. 2018b; Song et al. 2018); however, the remediation community is increasingly aware of the secondary impacts associated with remediation, and calls for green and sustainable remediation (Hou and Al-Tabbaa 2014; Hou et al. 2016).

Table 12 Concentrations of lead in soil in lead-paint housing sites

Country	Year	Soil Type	n [1]	Lead level [2] (mg/kg)	Reference
US	1975[3]	15~30 meters away	4	320 [a]	(Bogden and Louria 1975)
US	1996	Foundation	6	12,460 [a]	(Howden et al. 1996)
US	1996	Lawn	3	234 [a]	(Howden et al. 1996)
US	1996	Road	3	17.6 [a]	(Howden et al. 1996)
US	1997	Foundation perimeter soil	182	981 [c]	(Lanphear and Roghmann 1997)
US	1998	Foundation perimeter soil	169	3,386 [a]	(Lanphear 1998)
US	1998		169	1,022 [c]	(Lanphear 1998)
US	2006	Sides of house	10	1,697 [a]	(Andra et al. 2006)
US	2006	Sides of house	10	697 [a]	(Andra et al. 2006)
US	2008	Within 30 cm of building	4	437 [a]	(Bachofer 2008)
France	2012	Play area	315 [4]	74 [a]	(Lucas et al. 2012)
Australia	2014	1 m from house	15	535 [a]	(Laidlaw et al. 2014)
Canada	2011	Garden soil	1	54	(Beauchemin et al. 2011)
Canada	2017	Yard	91	82 [b], 75 [c]	(Safruk et al. 2017)

Note: [1] n=number of samples; [2] lead concentration in soil are reported as arithmetic mean [a], median [b], or geometric mean [c]; [3] the year of publication; [4] lead-based paint only present at 25% of these housing units.

4 Health Risk Management and Socioeconomic Cost

4.1 Health risk management

The health risk imposed by lead exposure has long been recognized. The adsorption of lead by the human body results in an elevated BLL, the measurement of which is the most widely used biomarker for lead exposure. The amount of lead adsorbed by the body depends upon external factors, such as particle size of the object exposed to, as well as the solubility and bioavailability of the specific lead compounds, and internal factors of the exposed subject, such as age, sex, nutritional status, genetic background, etc. (Barbosa Jr et al. 2005). Whilst BLL has a relatively short half-life of ~40 days (Rabinowitz et al. 1976), lead in blood can be incorporated into bone, and the half-life of bone-lead can range from 10 - 30 years (Rabinowitz 1991). Chelation is the most commonly used treatment technique when BLL is elevated; however, treatment of children with moderately elevated BLL does not improve cognitive test scores, suggesting that the damage maybe irreversible (Committee on Environmental Health 2005). Continuous back-release of lead from bone into the blood may explain the limited success of lead hazard control measures after exposure.

High dosages of lead can result in diseases such as colic, anaemia, and depression of the central nervous system, and may cause symptoms such as coma, convulsions and even death (WHO 2010). At low dosages, neurodevelopmental toxicity is the most important consequence of lead exposure to children, with elevated BLL being associated with cognitive impairment as measured IQ testing. Studies have shown that as BLL increases by increments of ~10 µg/dL, IQ scores at 5 years old and older decrease by increments of 2 to 6 points (Canfield et al. 2003; Committee on Environmental Health 2005). The magnitude of decrease in IQ is shown to be most alarming for the initial 0 to 10 µg/dL increase in BBL, with an associated 13.7 points drop in IQ estimated by a linear model, or a 7.4 points drop based on a non-linear model (Canfield et al. 2003). An international pooled analysis, using data collected from 1,333 children in 7 studies, found that as BLL increased from 2.4 to 10 µg/dL, from 10 to 20 µg/dL, and, from 20 to 30 µg/dL, there were associated IQ losses of 3.9, 1.9, and 1.1 points, respectively (Lanphear et al. 2005). The neurobehavioral symptoms of child lead exposure include cognitive impairment, shortening of attention span with increased risk for attention deficit or hyperactivity disorder, and increased risk for antisocial and criminal behavior (Landrigan et al. 2018). These effects can last for a lifetime and result in decreased school performance and decreased economic productivity, and increased drug abuse and likelihood of incarceration (Landrigan et al. 2018).

In the US, the regulatory threshold regarding children's BLL was introduced as 60 µg/dL in 1960, and has been lowered six times since (Figure 5). Based on the findings of neurobehavioral development studies, scholars have argued for lowering the BLL action level further, to as low as 2 µg/dL (Gilbert and Weiss 2006). In 2012, an advisory committee to the Centers for Disease Control and Prevention (CDC) recommended a 5 µg/dL BLL threshold value based on the 97.5th percentile of the US population of children aged 1 to 5, which has been adopted as the current US threshold value (ACCLPP 2012). In 2015, the US National Institute for Occupational Safety and Health (NIOSH) also selected 5 µg/dL as the BLL threshold for adults. Previously, this threshold was set at 10 µg/dL (2009-2015).

Encouragingly, the percentage of children in the US with BLL >10 µg/dL (i.e. the 1991 threshold) has dropped from ~7.5% in 1997 to ~0.5% in 2015, and the percentage of children with BLL >5 μg/dL (i.e. the 2012 threshold) has dropped from ~6.5% in 2010 to ~3.5% in 2015 (Figure 5). In many high-income and some middle-income countries, the BLL of children has been observed to have decreased by >90% (Landrigan et al. 2018). However, it should be noted though that it has been suggested that there may be no threshold BLL value below which there are no observable health effects (Canfield et al. 2003).

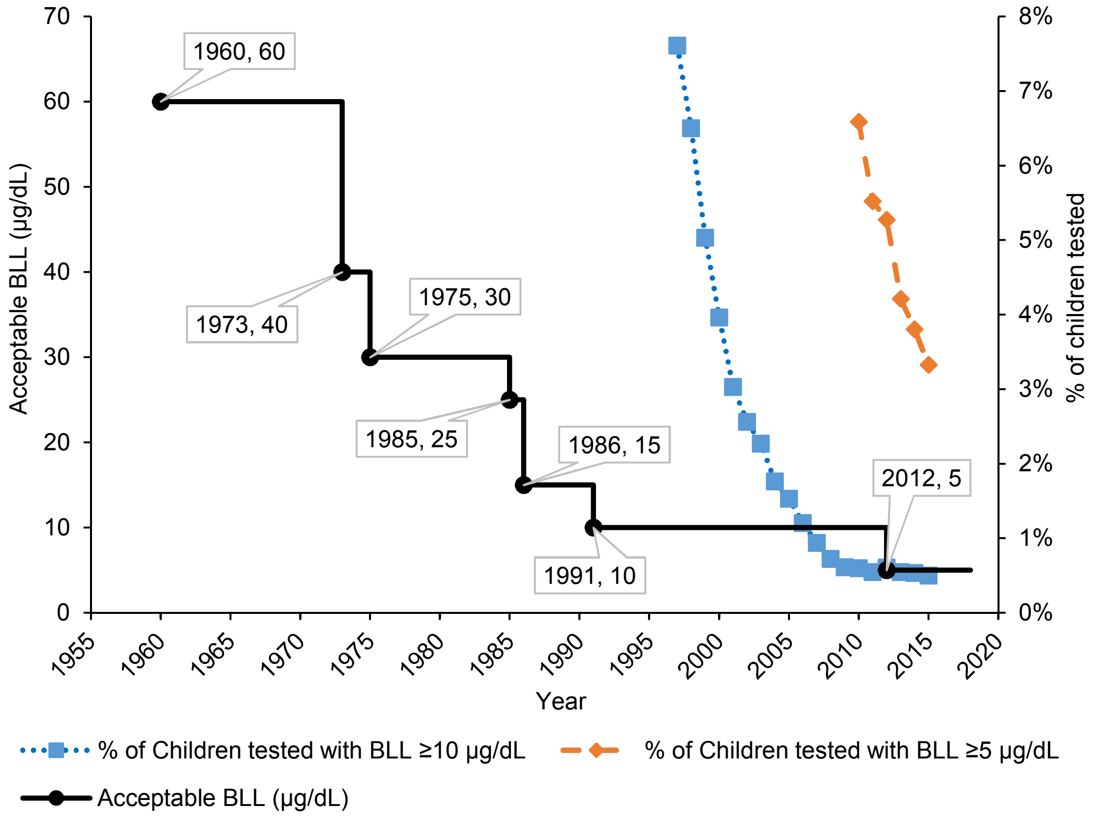

Figure 5 Increasingly stringent regulatory thresholds for BLL in the US (left axis). Data sources: (ACCLPP 2012; Gilbert and Weiss 2006); elevated BLL as a % of children tested (right axis). Data source: data publicly available from the Centers for Disease Control and Prevention

4.2 Abatement of Residential Lead-Based Paint

Abatement of residential lead-based paint refers to actions in which lead-based paint in residential housing units is removed/managed. Such practices date back to the 1950s, when concerns of symptomatic lead poisoning in children first arose (Farfel and Chisolm Jr 1990). There are various techniques that can be employed to abate residential lead-based paint. Encapsulation and enclosure render the lead hazard inaccessible, whereas chemical stripping, abrasive removal, hand-scraping and component replacement permanently remove lead-based paints from housing units (HUD 1990). Full removal of residential lead-based paint in the US has been estimated to cost $1,200-$10,800, with an average of $7,000 per housing unit (Gould 2009). Studies have shown that the removal of lead paint can result in high return: every $1 spent on lead remediation can lead to $2.6 in housing value increase (Billings and Schnepel 2017). However, some lead abatement practices have been found to be ineffective, and, unfortunately, resulted in an acute increase in lead contaminated dust and children's BLL (Farfel and Chisolm Jr 1990).

Ryan (2013) argued against the removal of lead-based paint from US housing, considering it not to be a practical option, particularly, a one-size-fits-all approach for full lead-paint removal from all housing units. Instead, assessment of the ability and cost-effectiveness of different lead mitigation measures for different types of housing was argued. Moreover, the use of both short and long-term strategies may be beneficial, because fully removing paint from all US homes identified as lead hazards, will likely take decades to complete, whereas a more immediate intervention is deemed necessary for the current occupants (Ryan 2013). For instance, a one-time professional clean of dust and debris can substantially reduce lead dust load; however, it should be noted that the lead dust load can rebound significantly afterwards. Furthermore, it is hard to control children's behavior regarding lead exposure if lead is not fully removed. For example, a study by Farfel and Chisolm showed that at homes in an abatement program approximately a third of children reportedly had contact with home surfaces, against the advice of the city health department.

4.3 Socioeconomic Costs of Lead Exposure

The socioeconomic costs of child exposure to neurodevelopmental toxicants, such as lead, are potentially huge. Large economic and social gains can be realized through prevention of these disorders (Landrigan et al. 2018). It has been estimated that the direct and indirect economic costs of elevated BLL in the US amount to $868 billion US dollars over a 20-year period (i.e. one generation) (Gilbert and Weiss 2006). For children with elevated BLL, health care costs are estimated to be in the range of $74 to $3,444 per child, depending on recommended intervention actions (Gould 2009). Decreased cognitive function and economic productivity of children exposed to low amounts of lead can result in a significant reduction in lifetime earnings. Gould (2009) estimated that each IQ point loss represented an earnings loss of $17,815 (in 2006 US Dollars) (Gould 2009). Using a marginal tax rate of 15%, this financial loss was translated into loss of tax revenue of $2,672 per IQ point loss. Additional socioeconomic costs are also incurred from elevated BLLs relating to special education for children with low IQ, and associated increased crime rates (Gould 2009).

Grosse et al (2002), estimated the economic benefit from the reduction of childhood BLLs in the US as a result of the control or elimination of lead exposure. They calculated that late 1990s preschool-aged children had IQs that were 2.2–4.7 points higher than they would otherwise would have been, had childhood BLLs not been reduced from 1970s levels. This was projected to improvements in worker productivity, with estimated economic benefits in the range of 110 - 319 Billion US dollars (2000 dollars) for each annual cohort of 2-year-old children (i.e. 3.8 million people) (Grosse et al. 2002). Removal of lead from paint may be likened to the historic removal of lead from gasoline, which has returned an estimated $6 trillion in economic activity to-date through increased cognitive function and enhanced economic productivity (Landrigan et al. 2018).

Despite significant progress being made in the US in reducing childhood BLL (Figure 5), lead poisoning continues to be an issue in many local areas. This is particularly the case for low-income communities, where a larger proportion of the population dwell in deteriorating housing built before the introduction of the ban on lead-based paint on residential properties (Kennedy et al. 2016). As such, lead exposure also impacts social justice, not only because lead contamination tends to be more serious in poorer regions, but also because disadvantagFed populations will suffer disproportionally when exposed to an agent which may affect IQ (Gilbert and Weiss 2006). Globally, lead exposure in children incurs an estimated economic cost of $977 billion dollars per year for low-income and middle-income countries, accounting for 1.9%, 2.0%, and 4.0% of the GDP of Asia, Latin America, and Africa, respectively (IPEN 2016). Such high socioeconomic costs imply that the cost invested in eliminating lead-based paint will have high investment returns.

5 Environmental Management Implications

Lead-based paint is still widely available on the global paint and coating market, especially in developing countries where lead-paint regulations do not exist, or are not yet sufficiently enforced (Section 2). This has important implications for governments and international organizations that are developing, reforming, and promoting environmental policy and management.

5.1 Lead-based Paint: A Vague Definition Requiring Harmonization

There is much difficulty in defining lead-based paint, including decorative lead-based paints, because of the variation of regulatory thresholds among various countries, as well as for different types of paint products within one country (e.g. in China, see Section 2.2). It is also difficult to define lead-based paint because of different testing methods (i.e. total concentration vs. soluble concentration), as well as temporal variations in regulatory standards adopted by specific countries (e.g. increasingly stringent standards in the US). Some countries like Columbia use soluble lead concentration in determining lead exceedance; some countries like China use both soluble lead and total lead concentrations in determining lead exceedance; while most countries, including the US, solely depend on total lead concentrations.

The method employed, and the quality assurance/quality control (QA/QC) protocol used, for sampling and analysing lead content in paint is critical. For instance, Adebamowo et al (2006) analysed 19 brands of the most commonly used household paints in Nigeria, and found that the maximum lead levels were below 600 mg/kg in all samples (Adebamowo et al. 2006). However, in this case, the paint samples were taken directly from the paint container, thus representing a wet state. Moreover, it is unclear from the protocol whether the digestion was complete or not. In a follow-up study, five different paints were again purchased from the Nigeria market, but this time the samples were sent to an accredited laboratory in the US for analysis. Instead of digesting wet paint, the paint was first applied to clean and unused wooden blocks, allowed to dry, and then the paints were scraped off and extracted using nitric acid plus hydrogen peroxide according to USEPA method PB92-114172 (USEPA 2001b). In contrast with the previous results, the follow-up study found that 96% of the paints exceeded the 600 mg/kg threshold (Adebamowo et al. 2007).

China has a large number of regulations mandating lead level in various paint products (Table 2). Some of these regulations have thresholds for both total lead concentration and soluble lead concentration, but most pertain to soluble lead concentrations. Taking the most recent regulatory standard as an example, China mandates that paint materials for toys shall contain less than 90 mg/kg soluble lead, and finger paint shall contain less than 25 mg/kg of soluble lead. The soluble lead is measured by a hydrochloric acid (HCl) extraction procedure, in which samples are mixed with a dilute HCl solution in a 1:50 solid:liquid ratio adjusted to pH 1.0~1.5, agitated, and allowed to settle for a total of 2 hours. This procedure was designed as a bioaccessibility test to mimic gastrointestinal digestion. The test allows for no more than 0.7 μg/day of lead adsorption by human bodies, assuming accidental ingestion of 8 mg/day of toy material.

The Global Alliance to Eliminate Lead in Paints developed the following criteria as a working basis for defining “lead paint” (GAELP 2010): (i) The term “lead paint” includes paints, varnishes, lacquers, stains, enamels, glazes, primers or coatings used for any purposes; (ii) lead is added; and (iii) the total lead concentration is defined on a weight percentage of the total non-volatile portion of the product, or in the weight of the dried paint film. This definition may be a good basis for international harmonization. However, international harmonization of both regulatory thresholds and testing methods remain necessary for the global control of lead-based paint. Moreover, because various studies have shown that lead-based industrial paint can enter consumer markets for home use, regulating lead in industrial paint is also required.

The world’s largest and second largest paint producers, PPG and Akzo Nobel, have either achieved or plan to achieve complete removal of lead in all paint products by 2020. This commitment from the industry suggests that completely eliminating lead from all paints is both technically feasible and economically viable. Some countries, such as the Philippines and Nepal, have already adopted regulations to control lead content in all paint products, suggesting that national bans on the full range of lead-based paints are achievable. For the different testing methods, we consider that the use of total lead concentration thresholds to be superior to soluble concentrations, for the following reasons: i) the standard two hour lead solubility test may not sufficiently represent lifetime bio-chemical processes within the body; ii) due to photochemical reactions, painted surfaces may deteriorate in the environment, resulting in higher solubility when it has aged as compared to fresh samples; iii) the measurement of soluble concentrations has higher uncertainty/imprecision due to other influencing factors, i.e. pH, temperature, and agitation levels may affect solubility, whilst total concentration is more definite; iv) historical scientific studies have relied upon total lead concentrations, largely due to regulatory requirements in the US and scientific studies funded by US institutions, and, therefore, solubility data cannot be evaluated against the majority of other studies.

5.2 Strengthening of Regulatory Oversight

Regulatory oversight, e.g. mandating the labelling of lead content on all paint products, may be an effective measure in lowering paint lead levels. In general, developed countries have more stringent and enforced regulatory requirements than developing countries. A consequence is that it has been found that the lead concentration of paints of the same brand and colour to differ by many orders of magnitude between developing and developed countries (Section 2.1). Regulatory oversight is particularly important for small to medium-sized paint manufacturers in developing countries. A study in India revealed that the average lead concentrations in paints made by small to medium sized companies are typically two orders of magnitude higher than those made by large companies (Mohanty et al. 2013).

Verification of paint label contents is essential. A study by IPEN showed that 95 out of 803 paints purchased in seven countries in south and southeast Asia claimed to be lead free on the paint can labels; however, 17 of those paints contained lead concentrations above 90 mg/kg, ranging from 230 to 56,000 mg/kg. The authors suggested that third-party verification should be necessary before making such lead free claims. Third party certification may assist in making informed decisions by consumers. For example, in the US, the Philippine Association of Paint Manufacturers (PAPM) and several stakeholder groups jointly established the world's first lead paint certification program, verifying paints containing less than 90 mg/kg of total lead (IPEN 2016).

Regulatory oversight is also required for mitigating lead exposure in painted products such as toys. For instance, in 2007, Columbia issued a regulation banning lead-based paint in toys; however, a study in 2014 indicated that, 30% of toys still exceeded criteria (Mateus-Garcia and Ramos-Bonilla 2014). This non-compliance is partly due to a lack of surveillance programs. Independent verification or certification of lead-free paint may help solve this problem.

5.3 Awareness and Education

Information disclosure and awareness campaigns help to mitigate exposure risk in homes containing lead-based paint. There are an estimated 20 million homes in the US with lead-based paint hazards, as well as 37 million with intact lead paint (Ryan 2013). As discussed in Section 2.3 and listed in Table 7, US landlords and home sellers are required to disclose the presence of lead-based paint in their housing units. Bae (2012) revealed that this disclosure mandate has resulted in an increase in homebuyer's lead testing, the removal of peeling paint in hold homes, and a decrease in the number of old households with young child occupants. These results suggest that information disclosure is an effective tool for enhancing the management of risk associated with household lead-based paint. On the other hand, it was also found that the disclosure rule did not result in a substantial switch from old houses to new houses for any particular socioeconomic status group, and that the rule introduction did not cause a lowering of the value of old houses, suggesting the rule had limited detrimental effect on the market for old houses (Bae 2012).

Community-based comprehensive education and home visits have been found to be an effective tool for enhancing lead awareness and lowering exposure. In a randomized trial conducted in Rhode Island, USA, Brown et al (2006) found that an intervention program reduced dust lead levels by up to 75%, and the population geometric mean BLL declined by 47% (Brown et al. 2006). New York City used a public health media campaign to engage the public and increase awareness of the lead-based paint issue. This campaign encouraged behavior change to prevent child poisoning from peeling lead paint (Greene et al. 2015).

5.4 Counter Arguments

There are many scientific studies placing lead-based paint at centre stage for lead exposure. The US government and the international community are also putting a strong focus on eliminating lead-based paint. Nevertheless, there are counter arguments against making lead-based paint the main focus. Many community-wide BLL issues have been associated with mining or smelting activities (Cotter-Howells and Thornton 1991; Hilts 2003). Moreover, lead contamination in soil is ubiquitous and may derive from both lithogenic origin and anthropogenic activities including traffic activities, fertilizer usage and industrial waste discharge (Hou et al. 2017). Zahran et al (2013) studied atmospheric concentrations of soil and lead aerosols, and compared them with BLL in 367,839 children aged 0–10 in Detroit, USA, from 2001 to 2009. They found that the resuspension of lead contaminated soil caused an increase in atmospheric lead concentration, which correlated with a seasonal temporal variation in children's BLL. It was revealed that a 1% increase in the amount of suspended soil increased atmospheric lead concentrations by 0.39% (an increase of 0.0069 µg/m3 in atmospheric lead) which related to a 10% increase in one-year-old children's BLL.

Therefore, the authors suggested that future primary prevention actions should focus on lead contaminated soil (Zahran et al. 2013). There are also potential issues associated with lead-alternatives as paint ingredients, some are significantly more expensive than lead-based ingredients, and others render weaker colouring effects (Wu et al. 2017). It is also important to take into consideration the opinions of stakeholders who will be affected by regulatory controls of lead-based paint. Stakeholder engagement would be key to the success of lead controlling actions.

6 Conclusion and Future Outlook

Lead-based paint remains a global an issue, requiring urgent international attention. The production and consumption of paint is still growing in developing countries, with the potential for huge growth to come. However, there is a general lack of regulatory control of lead-based paint; and in countries where regulatory thresholds exist, the limits only apply to certain types of paint and can be weakly enforced. Lead concentrations in home paints, particularly enamel paints, are often above 10,000 ppm, in countries such as India, most south-east Asian, African, and Latin American countries, as well as many east European countries. The percentage of sampled paints exceeding 600 mg/kg, a commonly used regulatory threshold, reaches nearly 50% in many countries. These data suggest that the production, trade, and use of lead-based paint is still wide-spread globally. This will certainly pose a serious global threat to public health from surfaces painted with these products for many decades to come. While many countries have banned lead-based paint for home use (e.g. architectural or decorative paint), industrial paints are often exempted. It is hard to distinguish household paints and industrial paints from labelling; consequently, industrial paints have been found in consumer markets in both developed and developing countries. This is a serious challenge in the elimination of lead-based paint. Future regulatory measures should take industrial paint into account, to minimize the “exempted” types of paint, to prevent access to such exempted lead-based paints by consumers and contractors who work on domestic surfaces. The commitment by two of the world's largest paint producers to completely remove lead in all of their paint products suggests that this is technologically feasible, and would not cause a major disruption in the supply chain of various industrial sectors relying on paints. However, the lack of research is a great hindrance to policy making and regulatory enforcement, therefore, further research need to be conducted in the following areas:

1) Benchmarking and harmonizing the range of lead concentrations in all types of paints in different countries. Published lead analysis data are often not available for various types of paints, including industrial paints, for many countries. This is particularly the case for developed countries and countries with regulatory controls in place. At present there is little published literature available regarding lead levels in all types of new paints in developed countries such as the USA and the UK.

2) Assessing and implementing a means of verification for the effectiveness of existing regulatory controls. Countries like China have long-standing regulatory controls on several types of paints. However, a limited number of market survey studies show high percentage of exceedance of oil-based paints sold in the market. Because there is a disconnection between the make and the use of paints, it is unclear whether this represents a problem with paint manufacturing, or paint usage. More studies are warranted in order to determine the effectiveness of the regulatory controls, and, consequently, to provide more information for policy makers to improve existing policies where needed.

3) Examining the factors which may influence the effectiveness of regulatory controls on lead-based paint. These factors may include both extrinsic factors linked to personal and organizational behavior (e.g. manufacturer's perception of the consequences for violating regulations, and user's intention to use what are perceived as higher "quality" leaded products), and intrinsic factors linked to the feasibility of such regulatory controls (e.g. factory capability and capacity in reaching regulatory goals, and difficulty in distinguishing products which are regulated versus those that are not regulated).

This review article has revealed that the reporting of analytical results can be highly inconsistent between publications. Average lead concentration (i.e. arithmetic mean) is probably the most valuable data from an "expected" exposure scenario; however, many studies, especially studies conducted by NGOs, have not published the arithmetic mean of measured concentrations. Nearly all studies have reported the maximum lead concentration, which is useful, but not such a valuable piece of information in a scientific assessment. The geometric mean is also a useful indicator because the distributions of both lead concentrations in paints and BLL tend to be closer to log-normal distribution than normal distribution, for which the geometric mean and geometric standard deviation are useful for characterization. However, most studies have not reported the geometric mean. As for the "exceedance" of lead content, there are also inconsistencies across studies. The most common regulatory thresholds used include 90 ppm, 600 ppm, and 1,000 ppm. It is recommended that future studies be undertaken to report the exceedance rate of all of these three thresholds, thus allowing across-country comparisons. Overall, the lead-based paint issue is an urgent issue that not only requires urgent attention from international organizations and national governments, but also scientific research. More informed policy making is only possible with greater scientific knowledge.

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Lead-based paint remains a major public health concern: A critical review of global production, trade, use, exposure, health risk, and implications

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