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Identifying Potential Chemicals of Concern in Children's Products in a Regulatory Context: A Systematic Evidence Mapping Approach

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Background: Children's vulnerability to chemical toxicant exposures demands strong consideration of the chemical composition of products designed for and marketed toward them. Inadequacies in health-protective legislation and lack of mandatory ingredient disclosure in most children's products have created significant gaps in protection and oversight. Scientific literature can provide insight into the chemical constituency of children's products that may be useful for prioritizing future regulatory efforts.

Objective: We aimed to present a proof of concept for applying systematic evidence mapping methodology to identify which chemicals of potential concern have been reported in the scientific literature to be present in products marketed toward children, compile a compendium of data to inform future regulatory efforts, and identify research needs.

Methods: We conducted a broad, all-encompassing survey of the available literature from four databases to identify chemicals present in children's products. Using systematic evidence mapping methodologies, we constructed a database of children's products and their chemical constituents (termed "product-chemical combinations") based on a broad survey of current and relevant environmental health literature. Our study focused on chemicals listed on the California Safer Consumer Products Program's Candidate Chemicals List, which includes chemicals with one or more known hazard traits. We then conducted an exploratory data analysis of product category and product–chemical combination frequencies to identify common chemicals in specific products.

Results: Our systematic evidence mapping identified 206 potentially hazardous chemicals in children's products, 170 of which were found in toys. In total, we found 1,528 distinct product–chemical combinations; 582 product–chemical combinations included chemicals known to be hazardous or potentially hazardous. Ortho-phthalates in plastic toys, parabens in children's creams and lotions, and bisphenols in both baby bottles and teethers were the most frequently encountered product–chemical combinations of potential concern.

Discussion: The frequently reported presence of endocrine-disrupting chemicals in multiple types of children's products raises concerns for aggregate exposures and reveals gaps in regulatory protections for this sensitive subpopulation. Our reproducible and systematic evidence-based approach serves as a case study that can guide other prioritization efforts for transparent regulatory action aimed at improving the safety of chemicals in consumer products. https://doi.org/10.1289/EHP15394

Introduction

Children are at heightened risk from chemical exposures in comparison with adults.[1,2] Due to multiple factors, children are highly susceptible to chemical exposure, and toxicants can have profound and lasting impacts on children's health and development.[3] Studies have shown that even low levels of toxicant exposure during developmental periods are associated with lasting adverse health outcomes,[4] including developmental delays,[5,6] cognitive impairments,[6] and increased risk of chronic diseases such as asthma,[4,7] obesity,[8] or other metabolic diseases.[4] Children's smaller size means that they eat more food per unit body weight, consume more oxygen,[1] and have greater skin surface to body volume ratios than adults.[9,10] In addition, children's behaviors, such as increased hand-to-mouth activities,[6,11] increase their likelihood of exposure to harmful chemicals present in their immediate environment.[12] However, the regulatory landscape in the United States is not commensurate with the disproportionate harm that chemical exposures may pose to children, with only a few chemicals of concern being banned or restricted in consumer products specifically designed for and marketed toward this population.[11] Excel Table S1 includes a detailed list of chemical restrictions that apply to children's products at the federal level in the United States as well as in the state of California.

In our experience, the lack of ingredient transparency for most children's products severely limits regulators' ability to protect children from harmful chemical exposures.[13] With the exception of personal care products and cosmetics,[14] manufacturers of toys, bedding, and other children's products do not have to disclose each individual ingredient present in their products. Although significant gaps remain, the scientific literature provides valuable insight from analytical investigations of the chemical constituents of children's products. For example, Aurisano et al. derived a list of 126 chemicals of concern in plastic toys by surveying available literature that detailed chemical composition by toy type.[15]

The scientific and regulatory communities have increasingly dedicated their efforts to identifying and assessing the specific chemical exposures that infants and children encounter through everyday consumer products. For example, the Safer Consumer Products (SCP) Program of the California Department of Toxic Substances Control (DTSC) can regulate consumer products containing one or more chemicals present on its "Candidate Chemicals List" if there is potential for exposures and significant or widespread adverse impacts to humans or the environment.[16] The SCP Program is especially concerned about the

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presence of any Candidate Chemicals that are carcinogens, developmental toxicants, endocrine disruptors, immunotoxicants, or neurotoxicants in children's products and has started researching this product category for possible regulatory action.[17,18]

The objective of this review was to present a proof of concept for applying systematic evidence mapping methodology to search for and classify literature in the field of consumer products for regulatory purposes. We applied systematic evidence mapping principles in our research to identify chemicals of potential concern that may be found in products marketed toward children, inform future regulatory efforts, and identify research needs. Using a systematic evidence mapping approach to facilitate data mining and synthesis, we constructed a novel dataset that identifies combinations of children's products and their chemical constituents (hereafter referred to as "product–chemical combinations"). We aimed to expand the scope of the substantial body of data compiled by Aurisano et al. by including other types of children's products beyond plastic toys.[15] From the chemicals identified in this literature-mining effort, we selected only those present on the DTSC Candidate Chemicals List, which could be regulated by the SCP Program. These chemicals can be either intentionally added ingredients or contaminants.[17] Our modified literature acquisition and evidence mapping methodology offer objectivity and transparency in collecting and synthesizing vast scientific evidence on chemicals in consumer products and can be applied by other regulators and policymakers for informed decision-making.[19] Our dataset allowed us to understand the diversity of potential exposures sustained during a child's day, identify the biggest research gaps, and inform the actions of the SCP Program.

Methods

Study Design

We based our study design on a modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol.[20] We developed a series of search terms to capture studies relating to chemical constituents in the following children's product categories, which are consistent with the definition of children's products used in the California SCP Program[17] (adapted from the State of Washington's definition of children's products): toys, children's beauty and personal care products (hereafter referred to as cosmetics), children's jewelry, products designed to help a child with sucking or teething (i.e., teething/sucking products), products designed to facilitate sleep and relaxation (i.e., sleeping/relaxation products), products designed for the feeding of a child (i.e., feeding products), and child safety seats designed to attach to an automobile seat.[21] Each search result was independently reviewed by two researchers in a double-blind screening process to determine its relevance to the project's objective and criteria. We extracted data from studies satisfying our project inclusion criteria to produce a dataset of product–chemical combinations among the prespecified children's product categories.

Search Term Development

Standard systematic review or evidence mapping projects typically require all components of a Population, Exposures, Comparators, and Outcomes (PECO) statement to be integrated into the search term development process.[22] The PECO statement creates structure and outlines the approach to defining the research objectives.[22]

We aimed to conduct a broad, all-encompassing survey of the available literature to identify chemicals present in children's products, regardless of whether or not an adverse impact or outcome was identified or measured in the study. Therefore, the framing of our research question did not include a comparator and outcome, and our search terms solely reflect the population and exposure components of the PECO statement (Table 1).

The "population of interest" for our project was human children, including infants. Our scope included all chemical "exposures" associated with the types of children's products listed above in the "Study Design" section. The keywords we used to identify studies applicable to this population and exposures are provided in Table 2.

Literature Search

We connected the population and exposure keywords using Boolean terms to construct literature search terms (Table 2). Search terms were applied in PubMed, EMBASE, EBSCO, and ScienceDirect databases for all relevant peer-reviewed studies published between 1 January 2012 and 1 June 2022. This time frame was established with the intention of capturing studies that reported data from 2010 or later. In PubMed, time bounds were restricted by appending "AND 2012/06/01: 2022/06/01 [dp]" to each of the search strings presented in Table 2. Publication date restrictions were applied in other databases manually by toggling relevant publication years in each respective database's advanced search tool. The literature search was updated to extend through 1 June 2024 in the PubMed and ScienceDirect databases, because these were the primary databases from which included studies were obtained in the initial literature search. The final search date was on 8 October 2024, on which search results from each database were downloaded and subsequently uploaded to SysRev, an open-access web-based platform optimized for transparent scientific literature screening.[23] Our initial search aimed to be as broad as possible, covering a wide scope of study types, including those

Table 1. Modified Population, Exposures, Comparators, and Outcomes (PECO) statement.

PECO component	Description
Population	Human infants and children under the age of 12 y
Exposure	Chemicals: Any mention of a chemical. All potential routes of exposure are considered relevant. Products: Children's products, defined in accordance with SCP's 2021–2023 Priority Work Plan[17] to include any of the following products primarily intended for or marketed to children under the age of 12 y: 1. Toys 2. Children's cosmetics 3. Children's jewelry 4. Any product designed or intended by the manufacturer to help a child with sucking or teething 5. Products to facilitate sleeps or relaxation 6. Products for the feeding of a child 7. Child safety seats designed to attach to an automobile seat "Children's product" does not include the following: 1. Batteries 2. Slings and catapults 3. Sets of darts with metallic points 4. Toy steam engines 5. Bicycles and tricycles 6. Video toys that can be connected to a video screen and are operated at a nominal voltage exceeding 24 volts 7. Chemistry sets 8. Consumer and children's electronic products, including but not limited to personal computers, audio and video equipment, calculators, wireless phones, game consoles, and handheld devices incorporating a video screen, used to access interactive software and their associated peripherals.

Table 2. Population, Exposures, Comparators, and Outcomes (PECO) Statement component search terms.

	Search string		
	PubMed	SciDirect	EMBASE
Population-related search terms:	("Child" or "Preschool" or "Infant" or "Baby" or "Newborn" or "Toddler" or "School age")	(child OR infant OR baby)	("child" OR "preschool" OR "infant" OR "baby" OR 'newborn' OR "toddler" OR "school age")
Exposure-related search terms:			
Feeding	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("bottle" or "bib" or "breast pump" or "spoon" or "cutlery" or "placemat")	(Chemical or exposure) AND (bottle or feeding)	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("bottle" or "bib" or "breast pump" or "spoon" or "cutlery" or "placemat")
Toys	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("toys" or "putty" or "slime" or "dolls" or "blocks" or "paint sets" or "face paint")	(Chemical or exposure) AND toys AND (fabric OR metal OR wood NOT plastic)	("chemical" OR "ingredient" OR "exposure" OR "toxic" OR "toxicity" OR "toxin") AND "toys" AND (fabric OR metal OR wood) NOT plastic
Jewelry	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("necklace" or "bracelet" or "earrings" or "jewelry" or "rings" or "tiaras" or "hair accessories" or "jewel")	(Chemical or exposure) AND (jewelry or "hair accessories")	("chemical" OR "ingredient" OR "formulation" OR "exposure" OR "toxic" OR "toxicity" OR "toxin") AND ("jewelry" OR 'tiaras' OR "hair accessories")
Sleeping/relaxation	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("bedding" or "blankets" or "cots" or "nap" or "crib" or "bunk beds" or "bedsheets" or "comforters" or "pillows" or "pillowcases" or "quilts" or "cradle" or "sleep" or "swaddle" or "basket" or "bassinet" or "pacifier" or "relax" or "soothe")	(Chemical or exposure) AND (bedding or crib or sleep)	(chemical OR "ingredient' OR "formulation" OR "exposure" OR "toxic" OR "toxin") AND (bedding OR "crib" OR "bassinet" OR "cradle" OR "sleep")
Sucking/teething	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("ring" or "teething" or "suck" or "pacifier" or "teether")	(Chemical or exposure) AND (pacifier OR teething or "teething ring")	("chemical" OR "ingredient" OR "formulation" OR "exposure" OR "toxic" OR "toxicity" OR "toxin") AND ("ring" OR "teething" OR "suck" OR "pacifier" OR "teether")
Car seats	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("Booster seat" or "car seat" or "automobile seat" or "seat" or "safety seat")	(Chemical or exposure) AND ("Booster seat" or "car seat" or seat)	("chemical" OR "ingredient" OR "formulation" OR "exposure" OR "toxic" OR "toxicity" OR "toxin") AND ("booster seat" OR "car seat" OR "automobile seat" OR "seat" OR "safety seat")
Cosmetics/personal care products	("Chemical" or "ingredient" or "formulation" or "exposure" or "toxic" or "toxicity" or "toxin") AND ("children's cosmetics" or "children's makeup" or "Halloween makeup" or "children's nail polish" or "face paint" or "children's fragrances" or "children's lip products" or "baby lotion" or "baby shampoo" or "baby powder" or "children's toothpaste" or "children's shampoo")	(Chemical or exposure) AND (cosmetics or makeup) OR ("baby lotion" or "baby shampoo" or "baby powder") OR ("children's toothpaste" or "children's shampoo")	("chemical" OR "ingredient" OR "formulation" OR "exposure" OR "toxic" OR "toxicity" OR "toxin") AND ("cosmetics" OR "makeup" OR "Halloween makeup" OR "nail polish" OR "face paint" OR "fragrances" OR "lip products" OR "baby lotion" OR "baby shampoo" OR "baby powder" OR "toothpaste" OR "hair products")

aiming to characterize the presence of chemicals in particular consumer products or the adverse impacts of product use, as well as exposure assessments and case studies. We harvested additional relevant papers from the bibliography of the review papers identified within the initial screening. The final dataset included only articles that explicitly identified the presence of chemicals in children's products.

Identification of Relevant Studies in the Two-Step Screening Process

To determine which publications were relevant to our project scope, we conducted a double-blind two-step screening process as follows: *a*) a title and abstract screen using the SysRev software and *b*) a full-text review. During both steps, a minimum of two independent reviewers screened and assessed the studies according to the set of eligibility criteria based on the modified PECO statement (Table 1). Additional details regarding "inclusion" and "exclusion" criteria are provided in Table 3. Conflicts among inclusion or exclusion labels were resolved through a group discussion or were elevated to an additional reviewer. Title and abstracts were first screened using SysRev.[23] The first screen results (inclusion vs. exclusion) were recorded in SysRev, and studies that did not meet our inclusion criteria were discarded. Studies marked for inclusion during the initial screening process were subject to full-length review. In addition, if the applicability of the publication was unclear based on the abstract alone, publications were marked for inclusion to progress to the full-length text review phase for additional deliberation. For example, a considerable amount of literature on product–chemical combinations did not explicitly specify whether a product was designed for children's use. In such cases, in the absence of keywords in the title or abstract (e.g., the words "children," "child," or "child's"), the study was marked for inclusion so that a full-text review could be conducted prior to making a decision that may prematurely exclude it from the dataset.

After the full-text review, we excluded studies that did not meet inclusion criteria. For example, some studies did not provide information on product–chemical combinations related to "children's products." This lack of specificity occurred mainly for cosmetics, where it was often unclear whether the product was intended for children or not. Because they did not provide explicit evidence of a chemical present in a product, we also excluded the following types of publications: those that aimed to characterize the exposure of children to certain chemicals (e.g., biomonitoring studies measuring endocrine-disrupting chemicals

Table 3. Inclusion and exclusion criteria for study selection.

	Types of publications	Chemical exposure	Products
Inclusion criteria	1. Human studies that involve subjects of any age or any gender 2. Experimental animal studies (mammal and non-mammal) 3. *In silico* and *in vitro* studies involving any cell line 4. Review papers	Any type of chemical exposure	Product primarily intended for or marketed for children under the age of 12 y that falls into one of these categories: 1. Toys 2. Children's cosmetics, including any topical personal care products and diapers 3. Children's jewelry 4. Any product designed or intended by the manufacturer to help a child with sucking or teething 5. Products to facilitate sleeps, relaxation, or the feeding of a child 6. Child safety seats designed to attach to an automobile seat
Exclusion criteria	1. Letters, editorials, commentaries, and corrigenda unrelated to specified outcome(s) 2. Non-English language papers for which reviewers did not have a means of translation 3. Any full-text publications unable to be retrieved via available networks by reviewers	Studies that lack any exposure data or assessment	1. Children's products besides those considered in scope of this study, such as the following: a. Batteries b. Slings and catapults c. Sets of darts with metallic points d. Toy steam engines e. Bicycles and tricycles f. Video toys that can be connected to a video screen and are operated at a nominal voltage exceeding 24 volts g. Chemistry sets h. Consumer and children's electronic products, including but not limited to personal computers, audio and video equipment, calculators, wireless phones, game consoles, and handheld devices incorporating a video screen, used to access interactive software and their associated peripherals 2. Product–chemical combinations that have already been regulated by US federal or state authorities (see Table S1)

(EDCs) in the serum or as urinary metabolites), those investigating the health-related impacts of exposures to either products or chemicals, in which a product–chemical combination could not be inferred, and those consisting of only an abstract (e.g., conference abstracts). We also excluded "reviews" from our dataset (to avoid duplicating data with the original research manuscripts); instead, the reference lists of these reviews were mined for studies that met PECO statement requirements and were published after 1 January 2012 (see "Identification of studies via other methods" in Figure 1).

We also excluded from further review all studies reporting on data from before 2010. Moreover, we excluded all studies of product–chemical combinations that have already been regulated by federal or California state authorities, such as lead in children's toys[24] and heavy metals in children's jewelry,[25] because these studies would not inform future regulatory efforts.

Data Extraction Strategy

The studies determined to meet inclusion criteria per the full-text review were subject to data extraction as outlined in Table 4. Two independent reviewers reviewed each study. Discrepancies or disagreements in information extraction were elevated to an additional team member.

As shown in Table 4, we were especially interested in studies that investigate the presence of chemicals in children's products, applying analytical methods (e.g., mass spectrometry or high-performance liquid chromatography) to identify one or more chemicals in a product. Medical case studies, such as allergy patch tests, also showed explicit connection between a product and a chemical and were included in our dataset. Further, the studies that satisfied our criteria were categorized according to their associated product category. If available, we extracted further details on the type of product assessed in the study, such as the specific type of toy or children's cosmetic product. Some studies reported chemicals in multiple categories of children's products. We extracted all product-chemical or product–chemical class combinations from the studies and included information on any related California state and US federal legislation or regulations. This level of specificity allowed us to gauge whether a study could facilitate prioritizing specific product–chemical combinations for future regulatory action in California. For example, we excluded studies identifying bisphenol A (BPA) in children's feeding bottles because the use of BPA in bottles or cups intended for children 3 y of age or younger is already banned in California (Table S1). On the other hand, we included studies identifying the presence of other bisphenol analogs, such as bisphenol F (BPF) or bisphenol Z (BPZ), because regulations for these chemicals do not yet exist. We also excluded children's products with per- and polyfluoroalkyl substances (PFAS) because juvenile products containing PFAS have been banned in California.[26]

We constructed our dataset by considering each individual chemical constituent identified in a particular product type. In other words, each row within our dataset represented a product–chemical combination. Applicable product categories and reference information for the corresponding publication are also provided in each row.

Data Synthesis and Mapping

Chemicals of potential concern. To prioritize chemicals of potential concern to children's health, we cross-referenced the chemicals found in the literature against the Candidate Chemicals

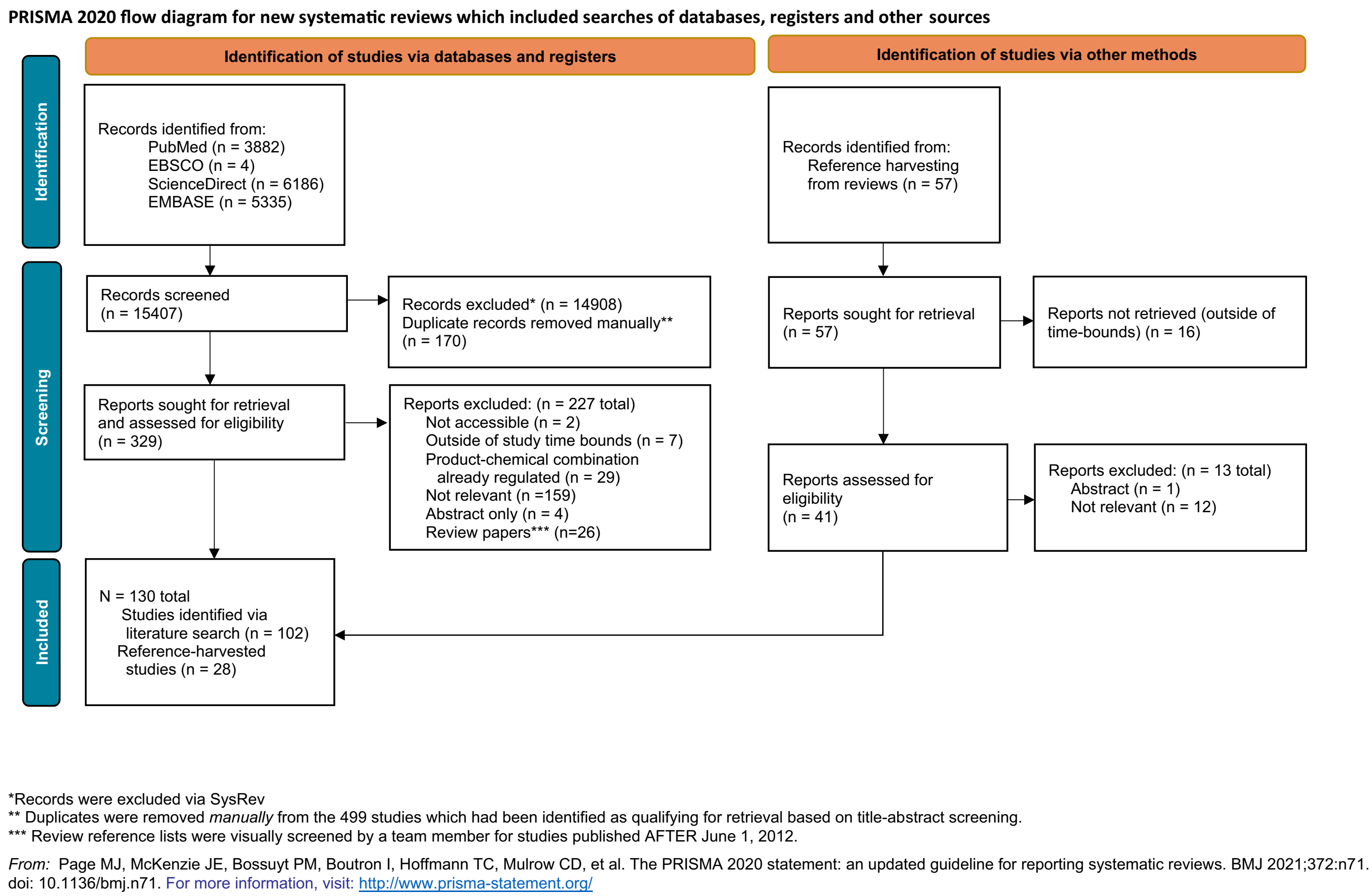

Figure 1. PRISMA flow diagram of our literature screening process. Adapted from Page et al.[20]

List maintained by the SCP Program of the California DTSC.[16] To address the diversity of chemicals and the prevalence of synonyms, we developed a separate table that tracked chemical classifications, Chemical Abstracts Service (CAS) registry numbers (CAS RNs), and other identifiers to compensate for differing publication styles. CAS RNs provide a streamlined way of matching chemical identities to the DTSC Candidate Chemicals List; however, authors rarely indicated CAS RNs in the studies identified in our screening process. Thus, we used the batch search[27] of the US Environmental Protection Agency (US EPA) CompTox Dashboard to identify missing CAS RNs using chemical names. We manually processed the chemicals for which CAS RNs were not identified or were identified incorrectly. After identifying the CAS RNs, we referenced the June 2024 version of the DTSC Candidate Chemicals List to label the chemicals in the dataset as either being a "Candidate Chemical" or "not [a] Candidate Chemical."

We consolidated certain chemicals into broader classes to facilitate data analysis. For instance, we grouped all individual ortho-phthalates together because they are present on the DTSC Candidate Chemicals List as a chemical class. We similarly grouped bisphenols, cyclosiloxanes, and parabens. Although the DTSC Candidate Chemicals List does not list parabens as a class, all individual parabens identified in the literature were present on the DTSC Candidate Chemicals List.[16]

Product categories. Product descriptions varied greatly in the studies we reviewed. For cosmetics, product names ranged from broad descriptions, such as "personal care products" and "leave-

Table 4. Types of data extracted.

Information category	Details
Bibliographic information	Author and year of publication
Product category	Possible options: Car seats, cosmetics, toys, feeding, teething/sucking, sleeping/relaxation, jewelry
Product type	Specific forms of products with defined features and uses. A product type is more detailed and specific, focusing on the distinct qualities or functions of a product. Examples in the toys product category: plastic toys, dolls, plastic swords.
Chemical	List of chemicals identified in the product types of interest, either as intentional ingredients or as impurities. Chemicals that the study authors screened for but did not detect or found to be below the limit of detection (LOD) were not included in this list.
Potential product-chemical combination	Combinations of product types and specific chemical constituents that were identified in the studies reviewed and could potentially be considered for regulation in California.
Publication type	Options include primary research, not peer-reviewed, case studies/reports
Scope of study	Options include presence-in-product study, exposure studies,[a] adverse impact studies,[a] abstracts,[a] reviews[a]
Location of study	Where the study took place, e.g., the geographic location where the product samples were collected from. If this information was unavailable in the study, we reported the country of origin of the first author.

[a]Not included in the data extraction phase of the systematic evidence mapping exercise.

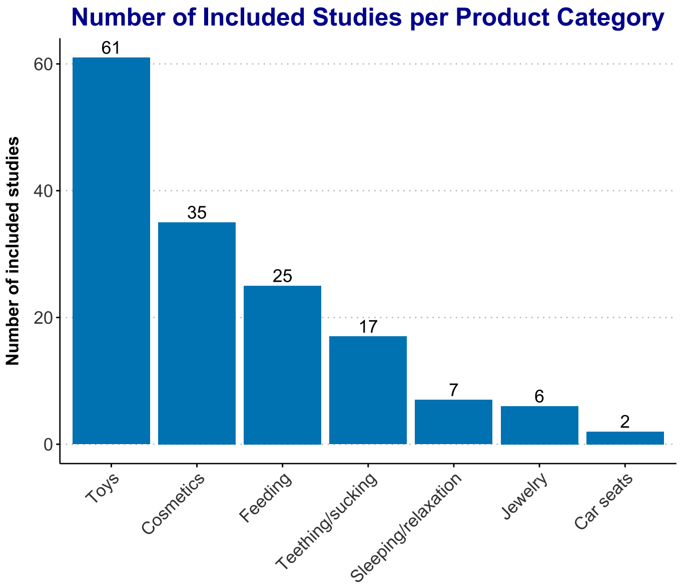

Figure 2. Distribution of publications by product category within our dataset. Please note that some publications assessed products from more than one product category (generated using Excel Table S2).

on products," to more specific identifications, such as "diaper cream" and "eye shadow." To simplify our dataset, we shortened the names of products that had the word "baby" preceding the product type (e.g., "baby shampoo") to consist of the product type only (e.g., "shampoo"). We categorized as "creams and lotions" all product types that included the word "lotion" or "cream," except for products intended for use in the diaper area. We combined all topical diaper-related products (e.g., diaper cream, diaper prep, and diaper ointment) into the "diaper creams and preps" product type within the cosmetics category. Similarly, we categorized as "soap" all products that included the word "soap" (e.g., hand soap, body soap, and liquid soap) within our dataset.

Toy-related studies also reported product descriptions with varying degrees of specificity. Product names ranged from general classifications such as "plastic toys," "toys," or "miscellaneous toys" to specific product types such as "doll," "slime," or "yellow plastic banana." Some even included manufacturer information in their descriptions. Though we recorded the toy names exactly as reported in the original publications, we also reclassified them for simplicity of further analysis and visualization by relabeling all toys made of plastic, rubber, or foam as "polymer toys." The original nomenclature from the papers can be viewed in Excel Table S2.

Data analysis. A team member who did not have a role in the data-mining processes validated the dataset by ensuring logical consistency and data entry accuracy. After the data validation, we analyzed the dataset for product category and product–chemical combination frequencies, stratified by the presence of the chemical on the DTSC Candidate Chemicals List (see Figure 2 and Figure 3). We further conducted exploratory data analysis of each product category by product type (e.g., mattresses within the sleeping/relaxation product category) to better understand the types of chemicals/chemical classes that may be frequently found in specific products (Figures 4–7). All data analysis and figure generation were conducted in RStudio (version 2024.09.1; Posit Software).

Results

Dataset Characteristics

Applying our search terms in PubMed, EMBASE, EBSCO and ScienceDirect yielded a total of 15,407 search results that we

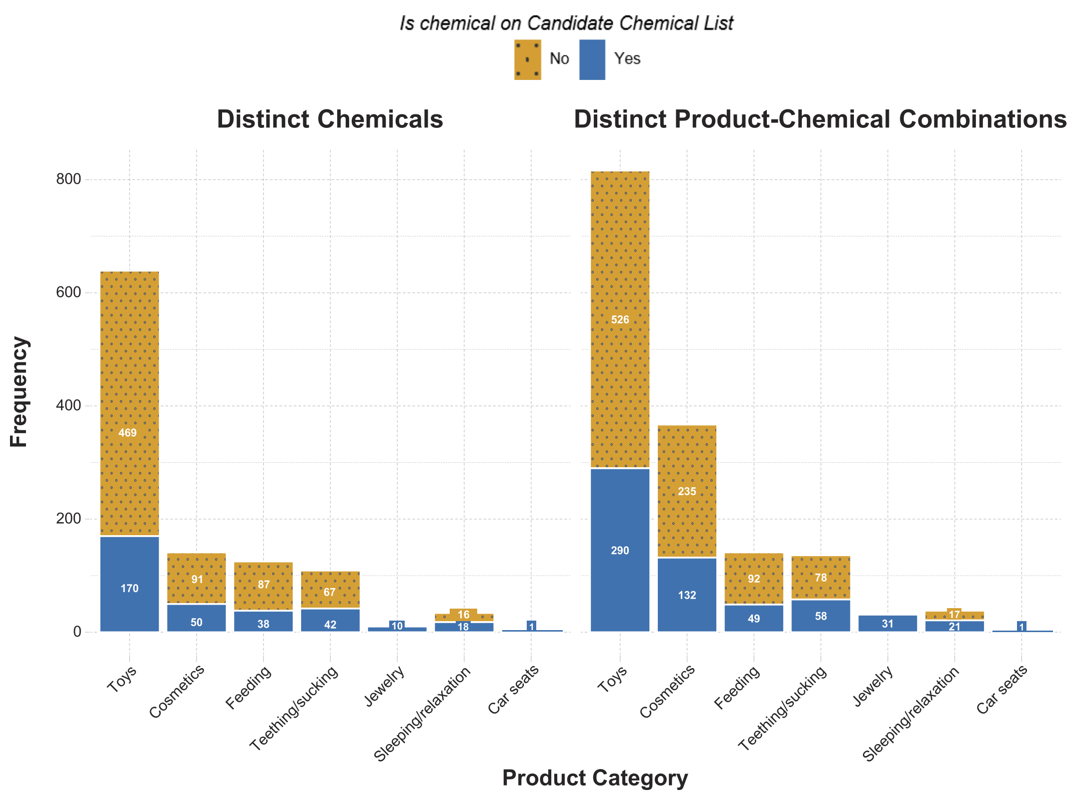

Figure 3. Distribution of (A) distinct chemicals and (B) distinct product-chemical combinations by product categories within our dataset, including the proportion of chemicals present on the DTSC Candidate Chemicals List (generated using Excel Table S2). Note: DTSC, Department of Toxic Substances Control.

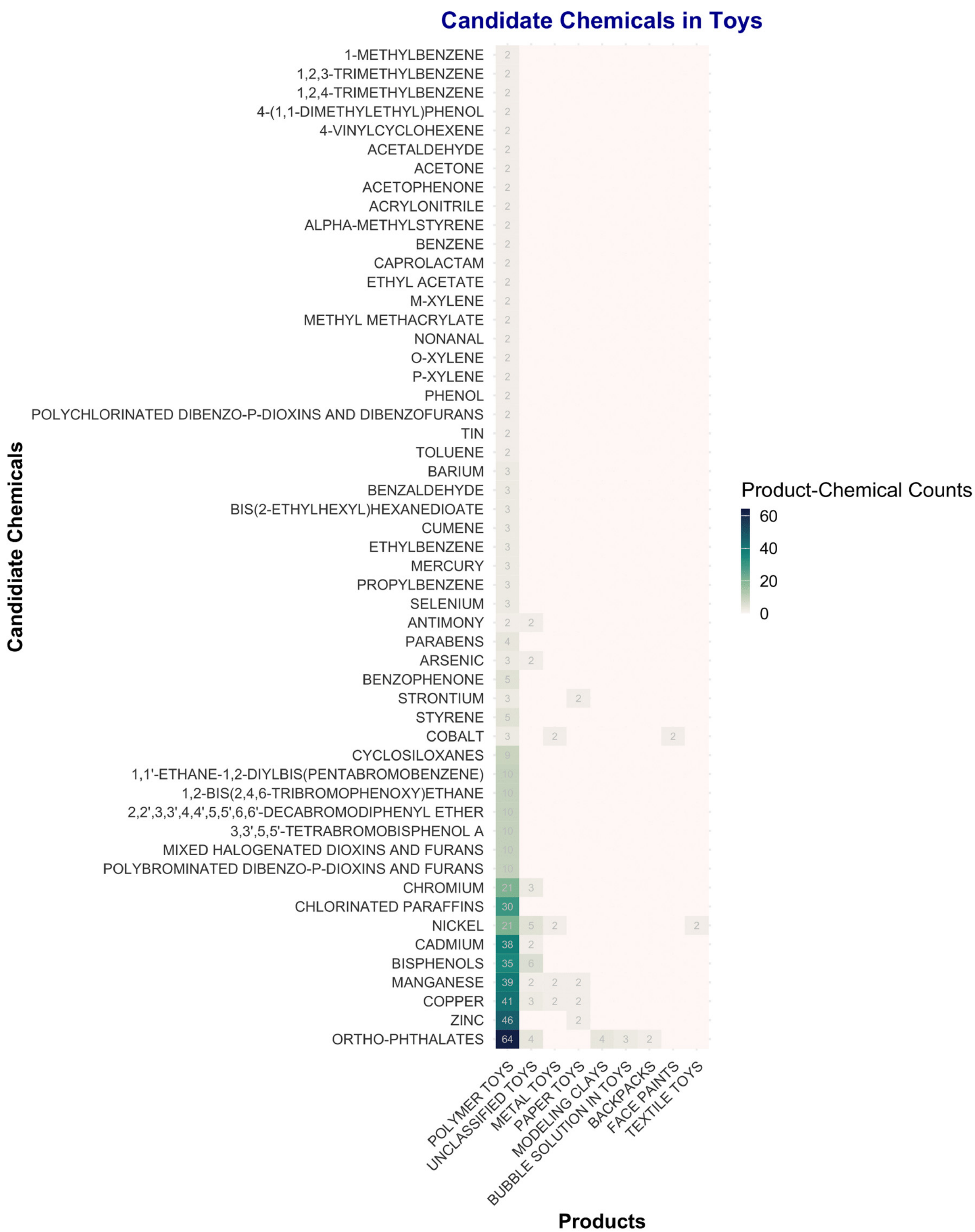

Figure 4. Heatmap representing the reported presence of Candidate Chemicals in children's toys. Only candidate chemicals that appeared two or more times within a toy type are shown (generated using Excel Table S2).

uploaded to SysRev for further screening. Figure 1 presents a schematic diagram of our literature search and screening process. Based on our initial double-blind title and abstract screen, we marked 499 studies for inclusion. Of these studies, we manually removed 170 duplicates from the list, leaving a remainder of 329 distinct studies for full-text review and further evaluation. Of these 329 studies, we excluded 227 because they did not satisfy study inclusion criteria (Figure 1). A total of 102 studies satisfied our modified PECO statement criteria and provided relevant information on one or more product–chemical combinations in alignment with our stated goals. An additional 28 studies were identified and added to this list through reference harvesting from review studies, yielding a total of 130 studies that provided information on the presence of specific chemicals in children's products that were used to construct our dataset (Tables S2).

Toys were the product category most frequently investigated by the studies in our dataset (61 out of 130 studies), followed by children's cosmetics (35 studies), feeding products (25 studies),

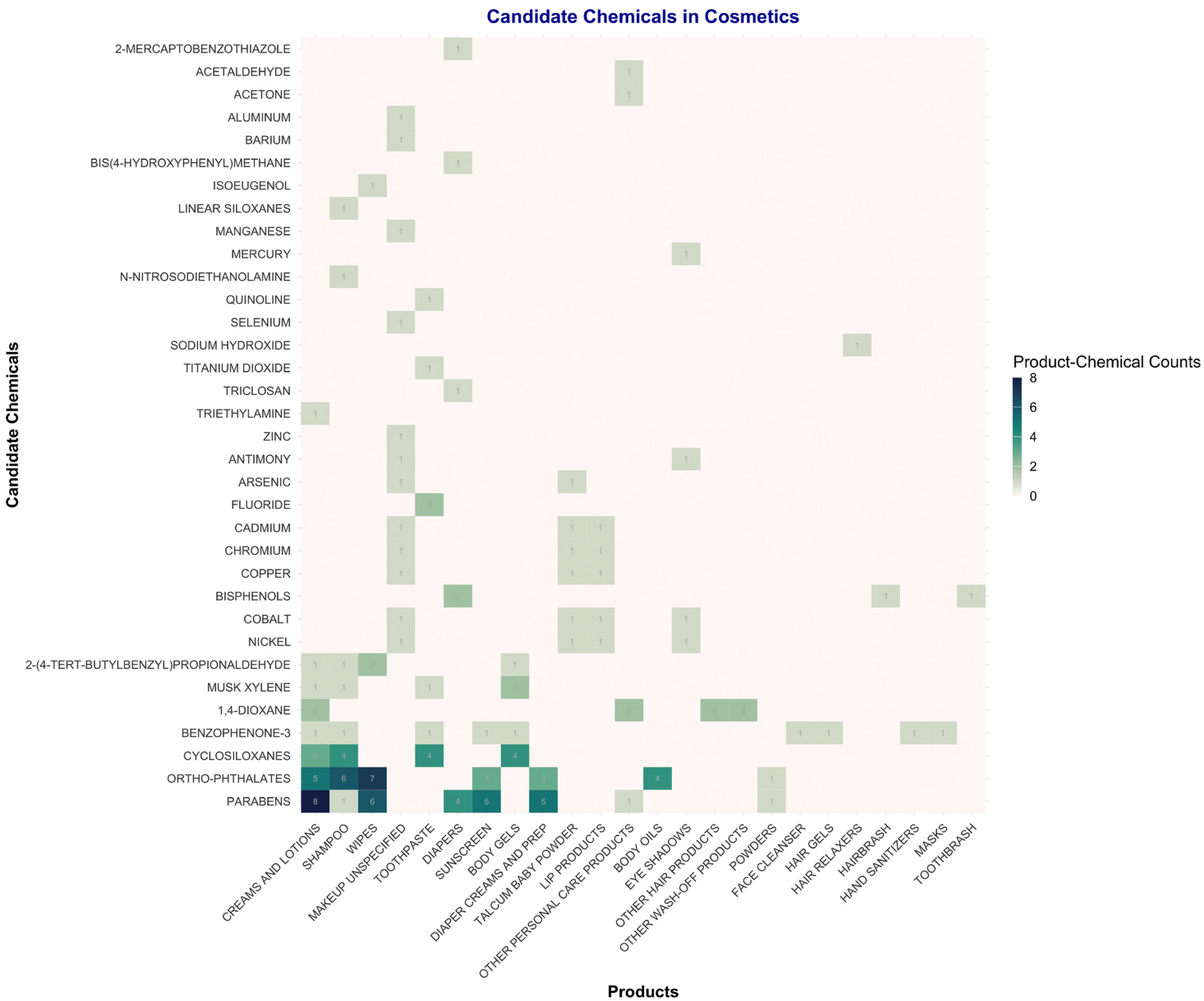

Figure 5. Heat map representing the reported presence of Candidate Chemicals in children's cosmetics (generated using Excel Table S2).

teething/sucking products (17 studies), sleeping/relaxation products (7 studies), and children's jewelry (6 studies). Only two studies in our dataset investigated chemicals in car seats (Figure 2). Several studies provided information for multiple product categories (e.g., a study investigated the presence of a chemical in both toy products and children's jewelry).

We identified 206 distinct Candidate Chemicals (with distinct CAS RNs) in our dataset. Multiple chemicals with distinct CAS RNs appeared in multiple categories. The majority ($n = 170$) of these Candidate Chemicals were found in toys (Figure 3A). Fifty Candidate Chemicals were reported in children's cosmetics, 42 in teething/sucking products, 38 in feeding products, 18 in sleeping/relaxation products, 10 in children's jewelry, and 1 in car seats (Figure 3A).

Our dataset totaled 1,528 distinct product–chemical combinations, 582 of which included Candidate Chemicals. We found mor than a thousand distinct product–chemical combinations related to toys, which became 816 total combinations after reclassification of toy names as discussed above in the section titled "Product categories." We found 367 distinct product–chemical combinations related to children's cosmetics, 141 related to feeding products, 136 related to teething/sucking products, 38 related to sleeping/relaxation products, 31 related to children's jewelry, and 1 related to car seats (Figure 3B).

Though most study authors referenced individual chemicals (e.g., D4 or methylparaben), some referenced chemical groups (e.g., cyclosiloxanes or parabens) without specifying chemicals. Such instances accounted for <2% of our data and are part of the final dataset.

Product–Chemical Combinations by Product Categories

Toys. The 24 toy product types identified in our dataset were reported to contain 654 distinct chemicals, 175 of which are on the DTSC Candidate Chemicals List[16] (Figure 3A). Toys made of polymers dominated this category (74% of all toys). The frequency of Candidate Chemicals within each specific toy type is presented in Figure 4. Ortho-phthalates were the most frequently identified chemical class in the toys present in our dataset ($n = 79$), followed by heavy metals such as zinc ($n = 58$), copper ($n = 54$), manganese ($n = 51$), and cadmium ($n = 42$), as well as bisphenols ($n = 41$).

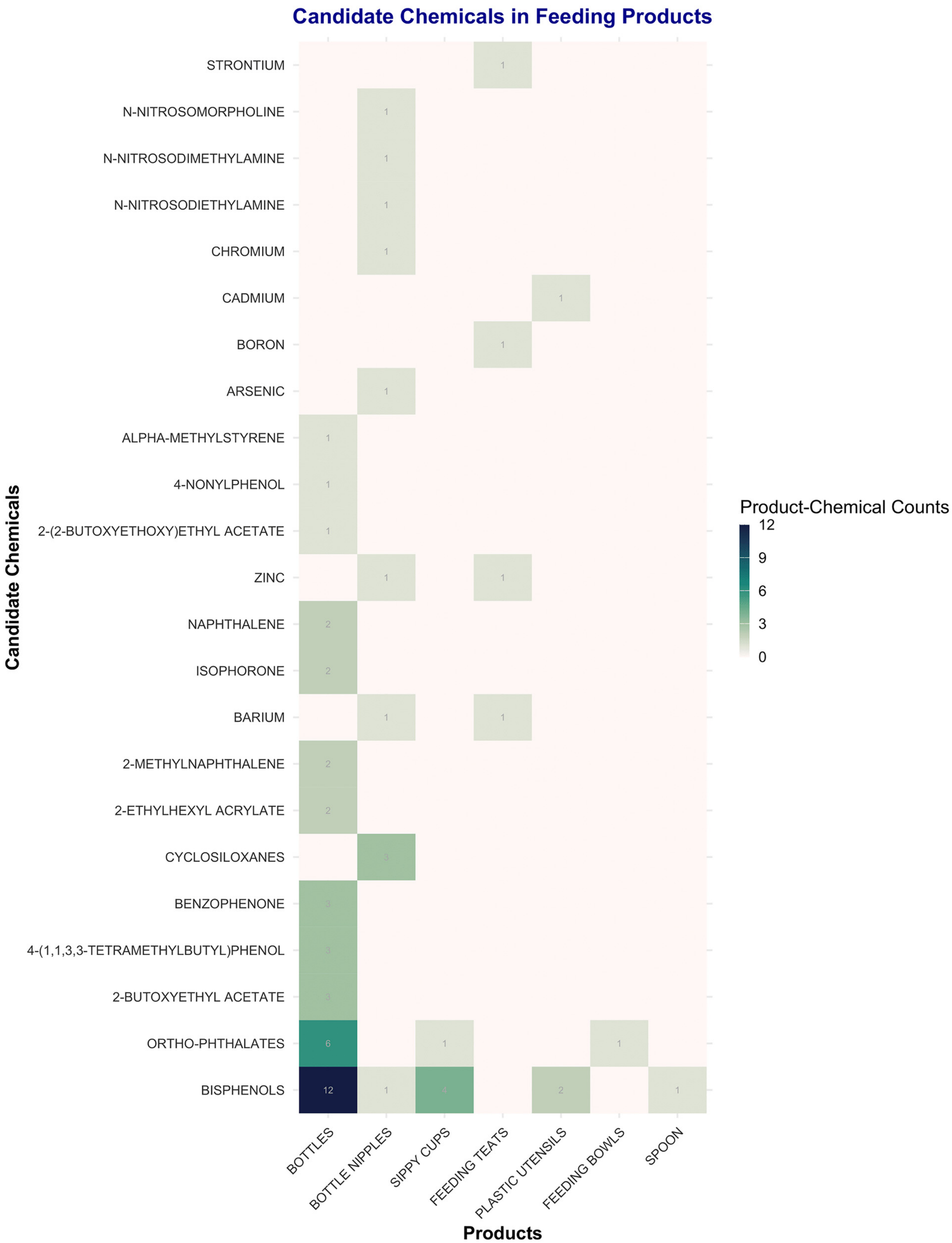

Figure 6. Heat map representing the reported presence of Candidate Chemicals in children's feeding products (generated using Excel Table S2).

Cosmetics and personal care products. From the 35 studies addressing children's cosmetics and personal care products (Figure 2), we identified 141 distinct chemicals, 50 of which were present on the DTSC Candidate Chemicals List[16] (Figure 3). Within this category, the product types with the greatest number of Candidate Chemicals were creams/lotions ($n=22$), shampoos ($n=16$), wipes ($n=16$), makeup ($n=12$), toothpaste ($n=10$), diapers ($n=9$), and sunscreens ($n=9$) (Figure 5).

The most frequently reported Candidate Chemicals in creams and lotions were parabens ($n=8$), ortho-phthalates ($n=5$), and

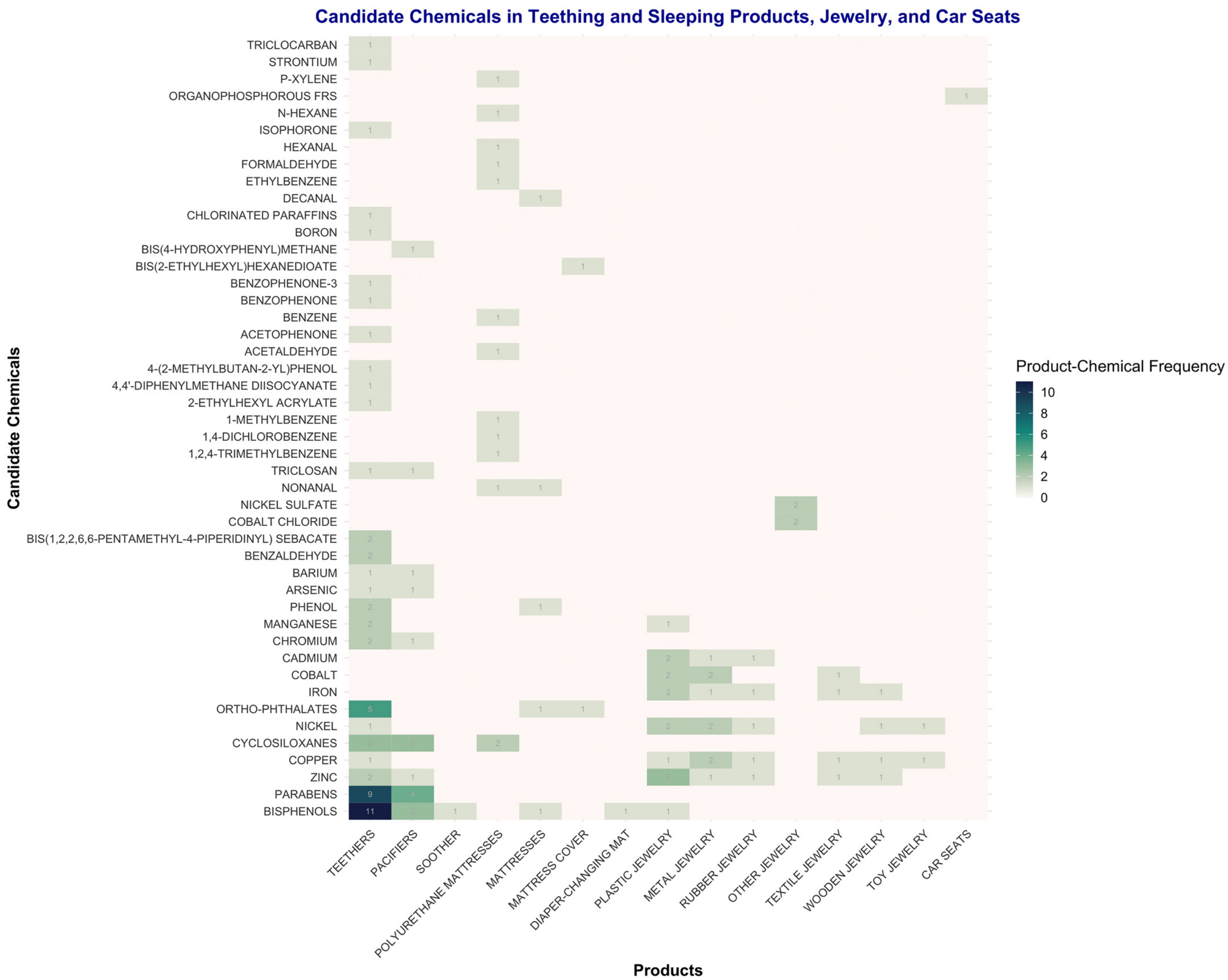

Figure 7. Heat map representing the reported presence of Candidate Chemicals in teething/sucking products, sleeping/relaxation products, jewelry, and car seats (generated using Excel Table S2).

cyclosiloxanes ($n=3$). In shampoos, the most frequently encountered Candidate Chemicals were ortho-phthalates ($n=6$) and cyclosiloxanes ($n=4$), whereas those in wipes were ortho-phthalates ($n=7$), parabens ($n=6$), and 2-(4-tert-butylbenzyl) propionaldehyde ($n=2$), also known as lilial (Figure 5). Other product–chemical combinations of note included toothpastes and body gels containing cyclosiloxanes and diaper creams and children's sunscreens containing parabens. Overall, the five most frequently identified Candidate Chemicals in our dataset among all cosmetic products were parabens ($n=31$), ortho-phthalates ($n=29$), cyclosiloxanes ($n=15$), benzophenone-3 ($n=9$), and 1,4-dioxane ($n=8$).

Feeding products. From the 25 publications reporting chemical composition information for children's feeding products (Figure 2), we identified 125 distinct chemicals, 38 of which were on the DTSC Candidate Chemicals List[16] (Figure 3A). Sixty percent of the products within this product category containing Candidate Chemicals were baby bottles ($n=38$); the remainder included bottle nipples, sippy cups, children's utensils, and feeding bowls. The most frequently encountered Candidate Chemicals in feeding products were bisphenols ($n=20$) and ortho-phthalates ($n=8$). Bisphenols and ortho-phthalates were also the most prevalent Candidate Chemicals in baby bottles (Figure 6). Several other Candidate Chemicals were detected in feeding products other than baby bottles: bisphenols ($n=8$), ortho-phthalates ($n=2$), and barium ($n=2$).

Teething/sucking products. From the 17 studies that reported data on teething/sucking products (Figure 2), we identified only 3 product types with Candidate Chemicals: 56 teethers, 16 pacifiers, and 1 soother. In total, 109 distinct chemicals were identified (Figure 3A), 42 of which were Candidate Chemicals[16] in 58 distinct product–chemical combinations. The most prevalent Candidate Chemicals identified were bisphenols ($n=15$), parabens ($n=13$), and cyclosiloxanes ($n=6$).

Sleeping/relaxation products. From the seven studies that analyzed products used to facilitate the sleeping or relaxation of a child (Figure 2), we identified five product types containing Candidate Chemicals (polyurethane mattresses, unspecified mattresses, mattress covers, and a diaper-changing mat) and 21 distinct product–chemical combinations (Figure 3B). Of the 38 distinct chemicals identified, 21 were on the DTSC Candidate Chemicals List[16] (Figure 3A). Cyclosiloxanes, bisphenols, ortho-phthalates, and nonanaldehyde appeared twice in our dataset, whereas the other 13 Candidate Chemicals appeared only once.

The full list of product–chemical combinations identified can be found in Table S2.

Children's jewelry. From the six studies pertaining to children's jewelry (Figure 2), we identified seven types of products: plastic jewelry, metal jewelry, rubber jewelry, textile jewelry, wooden jewelry, and toy jewelry, as well as other unspecified jewelry. In total, we identified 31 product–chemical combinations (Figure 3A). All 10 chemicals reported in these products were on the DTSC Candidate Chemicals List: various heavy metals and their salts, as well as bisphenols[16] (Figure 7).

Car seats. We identified only two studies that reported product–chemical combinations in children's car seats (Figure 2). One found at least one organophosphorus flame retardant in 73% ($n=72$) of all car seat samples ($n=98$).[28] Tris(1,3-dichloro-2-propyl)phosphate (TDCIPP), tris(1-chloro-2-propyl) phosphate (TCPP), 2,2-bis(chloromethyl)-propane-1,3-diyltetrakis (2-chloroethyl) bisphosphate (V6), and FireMaster 550 (a mixture of four chemicals; see Table S3) were identified in 50% ($n=49$), 27% ($n=26$), 4% ($n=4$), and 3% ($n=3$) of all car seat samples, respectively.[28]

Discussion

Informing Future Work

Systematic evidence mapping provides an evidence-based approach to search for, screen, and synthesize all available data. It uses systematic review methodologies for literature searching and screening but also provides improved flexibility in how the data are mined from literature and how this information is communicated (i.e., via visualizations enabled by data mapping). Systematic evidence mapping is rapidly gaining popularity in the environmental health field for evaluating the health risks of environmental chemical exposures[29,30] due to its ability to minimize biases that may occur during literature acquisition and synthesis in comparison with traditional literature reviews. Several working groups in chemical policy have used systematic evidence mapping for evidence surveillance exercises.[31–33] These mapping efforts allow us to visualize emerging trends in the available evidence for any research inquiry. Further, systematic evidence mapping provides a reproducible and organized approach for updating databases to reflect the constantly evolving nature of the environmental health landscape.

We developed this adapted systematic evidence mapping protocol to provide a structured approach to identifying and prioritizing product–chemical combinations in children's products based on available scientific literature. This approach helps to focus attention and resources on those combinations that are well studied and may pose health risks. Our systematic evidence mapping methodology used publicly available literature to construct a novel dataset of chemicals of potential concern present in several categories of children's products. By revealing both what is known and where the gaps are, our evidence map can be used to inform further exploratory analyses of children's products, set the direction for future hazard characterization and exposure assessment, and prioritize potential regulatory action aimed at protecting children's health.

Product categories that deserve further research and regulatory scrutiny include toys, cosmetics, and products used for feeding and teething, because of their numerous known chemical constituents (Figure 3A). Toys were the most heavily represented product category within our constructed dataset, due to several previous research efforts.[15,34–36] The children's toy industry is notoriously plastic intensive[37] and a well-known user of a multitude of chemicals, many of which have robust evidence of toxicity.[37]

The most common product–Candidate Chemical combinations in our dataset were polymer toys containing ortho-phthalates, baby bottles and teethers containing bisphenols, and children's creams and lotions containing parabens. Parabens, ortho-phthalates, and bisphenols are EDCs[38] and known to be associated with reproductive toxicity,[39] developmental neurotoxicity,[40,41] as well as metabolic disorders and various types of cancer.[42] The presence of these chemical groups in several different product categories suggests the potential for aggregate exposure to these chemicals.

Other notable product–chemical combinations include children's jewelry containing heavy metals and car seats containing organophosphorus flame retardants. These chemicals have been linked to neurodevelopmental[43] and endocrine adverse effects.[44] In addition, cyclosiloxanes (e.g., D4, D5, D6) are well represented in our dataset due to recent reporting on their widespread usage in consumer products.[45–47]

The bioavailability of these particular chemicals varies depending on molecular characteristics, such as high molecular weight or volatility (which may diminish likelihood of oral and/or dermal absorption).[48,49] These chemical properties, along with the product type and use case, may also impact the internal dose, meaning the amount of the chemical absorbed across the exchange boundaries, such as the skin, lung, or gastrointestinal tract.[50]

Although the intent of the systematic evidence map is not to model or prioritize exposure risks across product types, systematic evidence mapping offers a tool to monitor the range of chemicals of potential concern in consumer products. Future updates to this mapping exercise may allow us to see shifts in the chemical landscape as alternatives replace known chemicals of concern. For example, hazardous ortho-phthalates may be phased out and replaced with lesser-known members of the same class, or with other viable alternatives that might not necessarily be less toxic.

This evidence map also highlights where further research or regulatory action may be needed, such as better characterizing the presence of cyclosiloxanes in children's toothpaste and parabens in diaper cream. One study identified through our literature search reported trace levels of siloxanes in children's toothpastes (with a mean concentration of 0.23 μg/g), suggesting that this product is likely a minor source of exposure.[51] Select parabens, however, were detected at a mean concentration of 5.91 μg/g (methylparaben) and 211 μg/g (propylparaben) in a study sampling diaper cream formulations ($n=3$).[52] Another study reported that parabens (nonspecified) were detected in 10 out of a total of 41 diaper-prep formulations (no concentrations nor limits of detection were provided).[53]

An important finding is that some of the Candidate Chemicals identified in our dataset have the potential to cause adverse health effects even at low concentrations, especially those with endocrine-disrupting properties (e.g., ortho-phthalates, bisphenols, parabens).[39,54] The map highlights that these product–chemical combinations are documented in the literature. Additional research efforts may be warranted to clarify whether chemical presence is brand-specific and whether these products are marketed and sold in the state of California and to determine where regulatory interventions may be needed.

Our systematic evidence mapping approach presents a case study as to how the literature can be used to identify research gaps and support regulatory action on chemicals of concern. We acknowledge that although environmental health literature is a crucial resource, it may reflect a bias toward frequently studied substances of concern and certain product categories (e.g., children's toys) due to policy needs, public pressure, and challenges in identifying new substances of concern.[55] For example, limited published literature exists regarding the chemical constituency of children's products used to facilitate sleeping/relaxing, presenting an opportunity for investigative research and illustrating a need for increased manufacturer transparency. On the other hand, there is an abundance of literature on the presence of ortho-phthalates in polymer toys, parabens in children's creams and lotions, and bisphenols in teethers. Though this literature review is not necessarily a reflection of the California market, these observations may be useful in encouraging potential regulation or further investigation of parabens in cosmetics products beyond solely isobutyl- and isopropylparaben[56] and for all bisphenol analogs beyond solely BPA in children's bottles.[57]

Study Limitations

The results of this study are not a complete reflection of the children's products chemosphere. Although a systematic review is designed to capture large amounts of relevant data, the strength of conclusions drawn is relative to the degree of available information. Our dataset is based on current and publicly available research. Substances in consumer products that have attracted more interest and investigation are more frequently analyzed in the literature. On the other hand, we can conclude little to nothing about products and chemicals that were not targeted or tested in studies published between 1 January 2012 and 1 June 2024.

In addition, the way chemicals are referred to in publications is not standardized. It is important to note that we recorded the chemical identity mined from each publication as reported by the respective study authors, but different studies often used different names for the same chemicals. As described in the "Methods" section, we used the US EPA CompTox Dashboard batch search[27] to identify missing chemical CAS RNs. Chemicals for which CAS RNs were not identified or identified incorrectly were resolved manually by sourcing the most currently accepted CAS RNs from PubChem or US EPA CompTox Dashboard. Because this was done using our team's best judgment, this process may be subject to human error.

The frequency of occurrence of specific chemicals in products reported in the dataset does not necessarily correspond to a hierarchy of concern (i.e., some products and chemicals were studied more than others but not necessarily because they are more harmful to children's health). Numerous factors inform research prioritization, including human and ecological health concerns and the potential for exposure. Similarly, regulatory needs, financial interests, and research and development efforts also drive prioritization for market-ready chemicals.[58]

It is important to acknowledge that the outcomes of this research solely indicate the presence or absence of specific chemicals. Although caution should be taken when attempting to prioritize actions based solely on these data, availability of information is a critical factor in regulators' decision-making processes. As such, systematic evidence mapping to synthesize the literature landscape is important because policymakers are more likely to prioritize actions on chemicals with more comprehensive and accessible data.

Aggregating of data from different research methodologies naturally produces limitations that may affect conclusions. Publications included in this review used different analytical techniques, resulting in potential variations that may affect the perceived prevalence of chemicals because the frequency results are directly linked to the analytical methods used in the studies. Many studies were excluded from our results because the methodologies did not directly detect chemical presence in the products. For example, one publication ascertained contents of products via ingredient labels rather than laboratory detection methods.[59] We excluded this study because it was the only study in our dataset that used ingredient labels instead of analytical results. Another publication was excluded because presence of ortho-phthalates in baby care products was only linked to urine metabolite detections.[60] Finally, another publication collected products with unknown market originations from childcare centers. As a result, the publication was excluded because we could not determine whether the products were on the market within our set time bounds.[61]

This project was conceptualized with a focus on California and the United States, which is reflected in its conclusions. Our definition of "children's products" aligns with California's SCP Program,[17] our research focused on chemicals on the DTSC Candidate Chemicals List, and our methodology excluded product–chemical combinations subject to current regulatory restrictions in California. However, although we aimed to inform a prioritization strategy for chemicals of concern in California, this literature review included products tested globally. Only 23% of all articles in scope reported on products purchased from the US market. The remaining articles investigated products/medical cases in the European Union (12%), China (12%), and other countries (53%). Given the complexity of the global market and regulations, it is difficult to accurately estimate which products are sold in California and the relevance of these data to the California market. For example, in California, the revision of state flammability standards in 2013 (TB 117-2013) and expanded restrictions on flame retardants in juvenile products and furniture in 2020 (AB 2998) has been shown to markedly reduce flame retardant concentrations in consumer products after the regulations were instituted.[62]

Conversely, the generalizability of our results to other regions beyond California, including those beyond the United States, may be constrained by geographical, cultural, and market differences. Global trade and country-specific regulations directly influence the production and distribution of children's products, underscoring the need to consider international contexts, market dynamics, and development of new regulations in the analysis.

Conclusions

Children's vulnerability to toxicant exposures underscores the critical need for a comprehensive understanding of the chemical composition of products designed for and marketed toward them. Our modified literature acquisition and synthesis methods offer objectivity and transparency in collecting and synthesizing vast scientific evidence on chemicals in consumer products[19] and can be applied for informed decision-making by policymakers. Derived from a robust methodology that emphasizes objectivity and transparency, our findings highlight the presence of chemicals of potential concern in a wide range of children's products beyond just toys. Our dataset may allow researchers and regulators to understand the diversity of potential exposures sustained during a child's day and prioritize protective actions. An important result of using this methodology was that endocrine-disrupting ortho-phthalates, parabens, and bisphenols were found in multiple types of products geared toward infants and children, especially in plastic toys, children's creams and lotions, baby bottles, and teethers. This finding raises concerns for aggregate exposures and evidence gaps in regulatory protections for this sensitive subpopulation. With a focus on the chemicals listed on the California DTSC Candidate Chemicals List, our study illustrates how systematic evidence mapping protocols can be adapted to develop a transparent, reproducible method for evaluating the available scientific evidence with minimal time and effort to inform regulatory decision-making in the context of chemicals in consumer products.

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