Review

Soil and Dust Ingestion Rate: Concept, Methodology, Available Data and Knowledge Gaps

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Abstract: Soil and dust particulate matter is a sink of various environmental pollutants, and people are exposed to the pollutants they contain through accidental soil and dust ingestion (SDI). However, up to now, the description of SDI in relevant studies is relatively vague and lacks systematic understanding. Therefore, this review sorts out the definition of SDI, analyzes and summarizes existing research methods, data and relevant influencing factors on the soil and dust ingestion rate (SDIR). The SDI refers to the ingestion of soil and dust particles adhering to hand and object surfaces, primarily through hand-to-mouth and object-to-mouth contact. The main methods for determining SDIR include tracer element methodology (TEM), biokinetic model comparison methodology (BMCM), activity pattern methodology (APM), and dust/soil loading-activity pattern-based parametric formula methodology (LPFM), with the third method being comparatively more accurate. According to the limited available data, the SDIR ranged from 0 to 483 mg/d globally for all populations, and most particles adhering to human hands were below 250 µm. Specifically, in economically underdeveloped areas, the SDIR is relatively higher and tends to increase with increasing in microenvironmental contamination. Comparatively, the SDIR tends to decrease initially and then increase with age. Summer has a higher SDIR compared to other seasons. In addition, this review also provides an outlook on the shortcomings and future directions of existing studies. This review will help to improve the understanding of SDI by scholars in related fields, and will help to adopt the correct methodology and obtain more realistic results in contaminant exposure assessment.

Keywords: soil and dust; hand-to-mouth; ingestion rate; particle size

1. Introduction

Soil and dust are key carriers of various toxic pollutants in the environment, especially for certain pollutants that tend to bind to soil, such as lead, dioxins, and polychlorinated biphenyls (PCBs) [1–6]. The sources of soil and dust pollution are complex and diverse, mainly involving industrial point source emissions, atmospheric dry and wet deposition, the application of agricultural chemicals (including pesticides and fertilizers), as well as migration and transformation processes such as the diffusion of agricultural runoff [7–11]. It is worth noting that contaminated soil and dust are not limited to the outdoor environment. They can migrate to the indoor environment through various channels and thus become an important component of indoor dust [12]. In existing studies, the intake of soil and dust has not always been distinguished. Among them, "soil" refers to the particulate matter that settles outdoors, and "dust" refers to the particulate matter indoors (part of which consists of outdoor particles tracked indoors) [13,14].

In terms of population exposure, children are more likely to be exposed to the pollutants carried by soil and dust due to their physiological and behavioral characteristics, including a long time spent on ground activities, a high frequency of hand/object-to-mouth contact, and a tendency towards pica behavior [3,6,15,16]. This poses potential health risks to their health. The U.S. Environmental Protection Agency (U.S. EPA) has emphasized the importance of being able to quantify children's exposure to soil and dust [17]. Ideally, these should be quantified separately, especially for children living near contaminated sites. Therefore, accurately quantifying the soil and dust ingestion rate (SDIR) is crucial for assessing the relevant human health risks associated with pollutant ingestion. SDIR are influenced by multiple factors, and outdoor soil ingestion rates often differ from indoor dust ingestion rates. Factors such as dust loading on indoor surfaces, soil adhesion characteristics, and the differences in the frequencies of behavioral processes like handwashing and bathing can all affect SDIR [18]. Currently, there are still some ambiguous aspects in people's understanding of the concept of soil and dust ingestion (SDI). However, in fact, there is an association between these two pathways. Early research found that 30–40% of metals in dust originate from soil [19]. In addition, under certain specific circumstances, semi-volatile organic compounds (SVOCs), such as flame retardants (FRs) and phthalates, which usually come from multiple indoor sources including consumer products, building materials, and furniture, have more pollutants present in indoor dust rather than in the soil brought in from outdoors [20–22].

The first study on human SDI using tracer elements was conducted by Binder et al. [23] in 1986. Subsequently, the best tracer method (BTM), biokinetic model comparison methodology (BMCM), activity pattern methodology (APM), and dust/soil loading-activity pattern-based parametric formula methodology (LPFM) have been gradually developed [3,17,24]. However, there is some variation in the determination among the different methods. The SDIR values obtained by the TEM, BMCM, APM and LPFM were 0–483 mg/d, 50–93 mg/d, 3.7–234 mg/d, 19.7–294 mg/d, respectively [25–29]. Despite this progress, studies on SDIR remain limited, mostly focusing on China and some developed countries (e.g., the United States and Canada) [30]. The paucity of research data on SDIR and the unstandardized and inconsistent use of data during calculations can significantly compromise the accuracy of exposure assessment. In most current studies, SDIR for calculating contaminant exposure assessments are chosen from recommended values in the Exposure Factors Handbook published by the U.S. Environmental Protection Agency (EPA) or assumed values from previous studies [21,31,32]. Additionally, Human behavioral habits lead to significant differences in SDIR. Children are more likely to ingest dust from crawling on floors and from frequent hand/object-to-mouth contact among other things [3,6,15,33]. Adults are more likely to ingest soil and dust due to personal habits (e.g., nail biting, smoking) [28]. In addition, some adults are chronically exposed to soil and dust due to their occupations and hobbies, leading to higher SDIR [14].

This review focuses on the problems existing in current research and systematically organizes the concepts, methods, and existing data of SDI. By summarizing the data related to SDIR on a global scale, this paper deeply analyzes various factors affecting SDIR, including geographical, age, gender, and seasonal factors. Meanwhile, this review also elaborates in detail on the limitations of SDIR calculation methods, summarizes the existing patterns in SDIR, and further highlights the gaps in relevant cognitive understanding, aiming to provide guidance and suggestions for future research.

2. Definition and Pathways of SDI

Soil and dust particles in the environment can potentially expose individuals to pollutants through dietary routes (water, food, fruits, etc.), non-dietary routes (hand-to-mouth contact, object-to-mouth contact), or intentionally (soil pica and geophagy) in their daily lives [34–36]. EPA's Exposure Factors Handbook considers soil ingestion as the consumption of soil, which can occur through, but is not limited to, mouth contact with dirty hands, eating food that reaches the ground, or direct ingestion of soil [17]. However, the current definition of SDI is not clearly articulated, and some studies have partially biased their understanding of its definition. We have summarized the definition of SDI in different studies (Table S1). As shown in Table S1, existing studies have defined SDI around the behavioral process wherein humans (via oral, manual, or other pathways) contact soil/dust-contaminated objects (e.g., toys, utensils) or environments (e.g., gardens, soil), leading to subsequent ingestion of soil and dust particles. As shown in Table S1, most definitions of SDI in existing studies focus on the behavioral process where humans (through oral, manual, or other means) contact soil/dust—contaminated objects (such as toys and utensils) or the environment (such as gardens and soil), and this leads to the subsequent ingestion of soil—dust particles. However, these studies have deficiencies, as they ignore the intake of soil and dust through other pathways. For example, the studies by Li et al. and Moya et al. neglected SDI through the diet [24,37]. In contrast, the expression of SDI in the study by Davis et al. was more comprehensive, but they lacked a delineation of specific ingestion pathways [38].

Therefore, in this review, we have reformulated the concept comprehensive, covering its routes of ingestion as well as different age groups. "Soil" refers to settled outdoor particulate matter, and "dust" refers to indoor dust (including particulate matter carried indoors). Specifically, SDI is defined as the ingestion of soil and dust particles: (1) adsorbed on object surfaces via direct mouth-object contact (e.g., children chewing on toys, adults orally contacting utensils); (2) adhering to human hands (including geophagic and incidental behaviors) via mouth-hand contact (e.g., children sucking fingers, adults biting nails); and (3) contained on the surfaces of food, drink or fruits surfaces via dietary intake (for all age groups). As shown in Table S1, the SDI definition proposed in this review integrates ingestion via multiple pathways (hands, objects, and food surfaces) and covers all age groups, demonstrating broader applicability in scope. However, the amount of SDI varies considerably by different routes. In the study of Özkaynak et al. [39], hand-to-mouth ingestion accounted for approximately 90% of the total SDIR in children aged 3–<6 years, while object-to-mouth ingestion contributed only 10%. In the study by Kwong et al. [40], the proportion of SDI via the hand-to-mouth route was 78%, 52%, 52%, 82%, and 80% for children aged 3–5 months, 6 months–<1 year, 1–<2 years, 2–<3 years, and 3–<4 years, respectively. Another study noted that the proportion of SDI via the hand-to-mouth route was more than 90% for all three exposure behaviors (sedentary, indirect exposure, and direct exposure) in children aged 2–3 years in both the sand and clay groups [41]. Despite the prevalent view that hand-to-mouth contact is the primary ingestion route, Gong et al.'s study demonstrated that for children aged 2–17 years, hand-to-mouth SDIR only accounted for 26.6% of the total SDIR [42]. In the Gong et al. study, they only investigated the hand-to-mouth SDIR of the study participants, and the total SDI values were referred to other literature data. In this process, there are some gaps in intake due to research methodology, region, age, climate, etc., so this data has some bias. Meanwhile, this difference further highlights the need for this study to explore the effects of different research methods and factors on SDIR.

3. Methods for Estimating SDIR

Existing research has used four different methods to estimate the ingestion rate of soil, dust, or soil plus dust, as shown in Figure 1a and Table S2–S5. The studies summarized in Figure 1a predominantly focus on SDIR estimation methodologies (TEM, BMCM, APM, LPFM) rather than specific chemical pollutants. Most of these studies utilize tracer elements (e.g., Al, Si, Ti) as non-specific indicators of soil/dust particles, rather than targeting specific chemicals. As depicted in Figure 1a, the SDIR values calculated by different methods have certain differences.

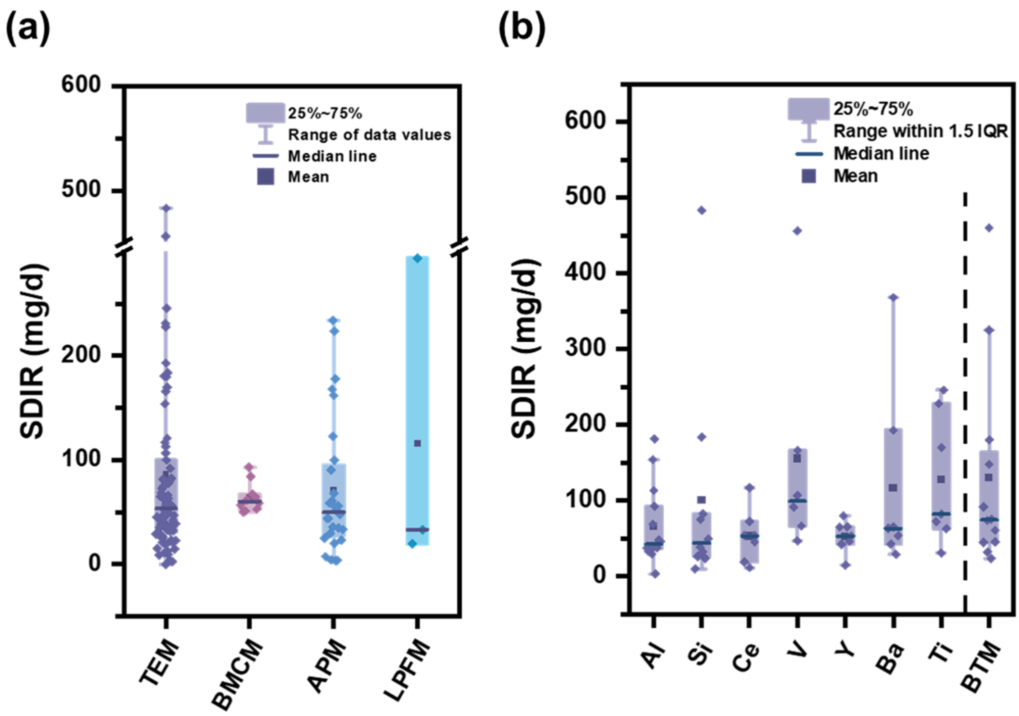

Figure 1. (**a**) Soil and dust ingestion rate (SDIR) determined by different methods (TEM: Tracer Element Methodology, BMCM: Biokinetic Model Comparison Methodology, APM: Activity Pattern Methodology, LPFM: dust/soil loading-activity pattern-based parametric formula methodology), and (**b**) The soil and dust ingestion rate (SDIR) determined in the literature using different tracer elements the best tracer method (BTM). Reproduced with permission. Copyright 2006, Nature Publishing [38]; 2022, Nature Publishing [43]; 2011, Wiley Publishing [39]; 2012, Wiley Publishing [44]; 2016, NIEHS Publishing [27]; 1986, Routledge Publishing [23]; 1989, Academic Press, Inc Publishing [26]; 1990, Routledge Publishing [45] ;1995, NIEHS Publishing [46]; 1997, Academic Press Publishing [47]; 2012, Elsevier B.V. Publishing [35]; 2014, Elsevier B.V. Publishing [48]; 2015, Nature Publishing [49]; 2017, NIEHS Publishing [50]; 2022, Springer Publishing [42]; 2019, Springer Nature Publishing [40]; 2019, ACS Publishing [30]; 2018, Taylor and Francis Group, LLC Publishing [51]; 2018, Elsevier Ltd. Publishing [52]; 2022, MDPI Publishing [53].

3.1. Tracer Element Methodology

The first method for the determination of SDIR is the TEM. This method quantifies SDIR of the study subjects based on Equation (1) by analyzing the weight of feces and urine excreted, the weight of nonsoil or dust ingested, and the concentrations of tracer elements (which are generally not metabolized by the human body or absorbed by the gastrointestinal tract) contained in the feces, urine and nonsoil or dust of the study subjects [44]. Table S2 summarizes the values of SDIR determined by TEM in earlier studies.

$$\mathrm{SDIR} = \frac{(\mathrm{W_{fe}} \times \mathrm{C_{fe}} + \mathrm{V_u} \times \mathrm{C_u}) - \mathrm{W_n} \times \mathrm{C_n}}{\mathrm{C_{sd}}} \tag{1}$$

where: SDIR is the daily soil or dust ingestion rate (mg/d), W_{fe} is the daily dry weight of feces (kg/day), C_{fe} is the concentration of tracer elements in feces (mg/kg), V_u is the urine volume (mL/day), C_u is the concentration of tracer elements in urine (μg/mL), W_n is the weight of nonsoil or dust (e.g., food, water, medicine) (kg/day), C_n is the concentration of tracer elements in nonsoil or dust (mg/kg), C_{sd} is the concentration of tracer elements in soil and dust (mg/kg).

As shown in Figure 1b, the SDIR varied considerably with different choices of tracer elements during the study. In the earlier study by Binder et al. [23], the mean values of SDIR calculated based on elements Al and Si were 181 and 184 mg/d, respectively. In another study, Calabrese et al. [26] calculated the SDIR not only selected Al and Ti, but also added the elements Ba, Mn, V, Y, and Zr, however, only the SDIR calculated based on Al and Ti (154 and 170 mg/d, respectively) are similar to the results of Binder et al. [23].

Reliance on a solitary tracer element is inadequate for securing reliable results. Therefore, in subsequent studies, selecting elements with a relatively low food-to-soil (F/S) ratio and low coefficient of variation (CV, %) as tracers is considered the best method for determining the ingestion rate (i.e., BTM) [47,53]. The SDIR was estimated in subjects over 20 years old in a Canadian wilderness area by selecting Al, Ce, La, and Si as the BTMs, and the results showed a mean value of 75.0 mg/d [35]. However in the study by Irvine et al. [48] the same tracer elements were chosen to study adult volunteers in a rural area of Canada, and the mean SDIR was 32.0 mg/d. In a study by Wang et al. [51], based on the elements Al, Ce, Sc, V, and Y, the mean SDIR for children aged 2.5 to <6 years and 6 to <12 years in three regions of China (Guangdong, Hubei, and Gansu), were estimated to be 60.8 and 91.6 mg/d, respectively. In another study, the mean values for adolescents aged 12 to 16.5 years in Hubei were 45.2 mg/d based on Al, Ce, Sc, V, Y [52]. However, in an e-waste dismantling area in South China, based on the elements Al, Ce, Sc, Ti, and Y, the mean values for children aged 3 to 17 years were estimated to be 148 mg/d [53]. These research findings reveal significant cross-study variability in the estimated values of SDIR, suggesting that in addition to methodological differences, exposure factors such as geography, age, and behavior may also play a significant role.

3.2. Biokinetic Model Comparison Methodology

The BMCM compares measured biomarker levels in human urine or blood with predicted values from a model to estimate ingested soil or dust levels [24], and it was calculated by Equation (2):

$$\begin{aligned}\mathrm{SDIR} = 1000 \times \{\mathrm{UP_{SD}} / [(\mathrm{C_d} \times \mathrm{PT_d} \times \mathrm{ABS_d}) + (\mathrm{C_{ys}} \times \mathrm{PT_{ys}} \times \mathrm{ABS_{ys}}) \\ + (\mathrm{C_{cs}} \times \mathrm{PT_{cs}} \times \mathrm{ABS_{cs}}) + (\mathrm{C_{ns}} \times \mathrm{PT_{ns}} \times \mathrm{ABS_{ns}})]\}\end{aligned} \tag{2}$$

where: UP_{sd} is the uptake of biomarker in soil and dust (μg/d). C_d, C_{ys}, and C_{ns} are the concentration of dust, yard soil, and neighborhood soil (mg/kg), respectively. PT is the partition coefficient for different soil and dust sources. ABS is the absolute bioavailability of different soil and dust sources.

Von Lindern et al. [27] analyzed children's blood lead samples, as well as total lead in indoor dust, yard soil, and quality control samples at the Bunker Hill Superfund Site in Idaho, USA, and modeled lead uptake in age-specific children through the U.S. EPA Integrated Exposure Uptake Biokinetic (IEUBK) Model, and to calculate children's total lead intake and SDIR according to Equation (2) (the results is available in Table S3). In that study, the average SDIR for children aged 0.5 to 9 years was calculated to be 66.0 mg/d according to the source partitioning scenario of 50% house dust/25% yard soil/10% neighborhood soil/15% community soil. The mean SDIR values were 86.0–94.0 mg/d for children aged 0.5 to 2 years and 51.0–67.0 mg/d for children aged 2 to 9 years, with the mean value peaking at 94.0 mg/d in the 1 to <2 years stage. And children's SDIR increased with age, reached a peak and then began to decline. This pattern may be related to the child's own physical behavior and lifestyle habits. Research has shown that infants and toddlers aged 6 months to 2 years are unable to control some behaviors on their own, and spend more time sucking on non-food objects such as hands, toys, and clothing [54]. Children older than 2 years, except for those with soil pica, have a sense of autonomy over some behaviors, and there is a substantial relative decrease in non-food sucking activities. Although older children spent more time in activity areas such as playgrounds, their hand/object-to-mouth activities were negatively correlated with age, so the latter had relatively lower SDIR in both age groups [55].

3.3. Activity Pattern Methodology

The APM is used to obtain information on hand/object-to-mouth behavior, environmental data, and basic data needed to run the model through video recordings, questionnaires, and real-time recordings to obtain SDIR [17]. The advantage of this method lies in the fact that the SDIR can be estimated independently, enabling us to determine the respective contributions of soil and dust to the total ingestion [24]. Table S4 summarizes SDIR estimated by this method in published studies.

In a study estimating the SDIR of children aged 3 to 6 in the United States, Özkaynak et al. utilized the Stochastic Human Exposure and Dose Simulation Model (SHEDS Model), which was introduced by the U.S. Environmental Protection Agency and is one of the types within the APM [39]. This model focuses on the child population and quantifies the adhesion and removal process of soil/dust on hands (such as the transfer amount during handwashing) and the behavioral parameters of direct ingestion of dust-containing objects by integrating the Comprehensive Human Activity Database (CHAD) of the U.S. Environmental Protection Agency and random interview data. The study ultimately concluded that the soil ingestion rates via hand-to-mouth, dust ingestion rates via hand-to-mouth and object-to-mouth were 41.0, 20.0 and 7.0 mg/d respectively for children, and verified the practicality of the SHEDS model [39].

As researchers further studied the SHEDS model, its reliability for estimating SDIR in children aged 3 to <6 years was demonstrated, e.g., Ross Wilson et al. used the model to learn that the mean SDIR for children aged 7 months to < 4 years was 61 mg/d; Wang et al. showed that the SDIR of sand and clay by 2 to 3 years old were 90.7 and 29.8 mg/d, respectively [28,41,43]. The study by Özkaynak et al. [43], activity data from birth to 21 years of age of the study subjects were provided. The results showed that the SDIR value of infants and young children (aged 0–11 years old) was approximately 35–60 mg/d, which was significantly higher than that of adolescents aged 16–21 years old, which was 20 mg/d. In addition, the usage of pacifiers and the dust attachment amount on carpets are the key factors affecting the exposure levels of infants and young children to dust and soil.

3.4. Dust/Soil Loading-Activity Pattern-Based Parametric Formula Methodology

Recent literature proposes a new method for calculating SDIR, namely the LPFM [3]. The method is based on a new mouthing-mediated ingestion model proposed in a recent study [37]. Based on the calculation method in the study of Wang et al. [56], the soil and dust loads on the hands of the study subjects were quantified by establishing standard curves, and the oral-mediated intake module of the model was used to obtain the $SDIR_{hm/total}$ values for different ages, which led to the calculation of the hand-to-mouth and total SDIR for different study subjects according to Equations (3) and (4).

$$SDIR_{hm} = M \times TE \times SAC \times EF \tag{3}$$

$$SDIR_{total} = SDIR_{hm} / SDIR_{hm/total} \tag{4}$$

where: $SDIR_{hm}$ is the soil and dust ingestion through hand-to-mouth contact (mg/d), $SDIR_{total}$ is the total daily ingestion of soil and dust (mg/d), M is the load of hand soil and dust (mg), TE is the transfer efficiency of soil and dust (%), SAC is the proportion of hand area per contact with the mouth (%), EF is the frequency of exposure during a day (d^{-1}), $SDIR_{hm/total}$ is the ratio of soil and dust ingested through hand-to-mouth contact to total soil and dust ingestion.

Only in the study by Li et al. [3], was this method applied to calculate the exposure levels for the general population. The total SDIR for preschoolers (1–12 years old), college students (18–22 years old), and security guards (>45 years old) were 245, 19.7, and 33.1 mg/d, respectively; and the hand-to-mouth SDIR were 142, 9.5, and 13.6 mg/d, respectively [3].

4. Factors Effect on SDIR Based on the Available Data

People ingest adhered soil and dust particles through incidental hand/object-to-mouth contact. Currently available data indicate a wide range of SDIR in global populations. In this process, the SDIR is influenced by multiple factors, primarily including geographical environment, age differences, gender characteristics, and seasonal variations. Economic levels, climatic conditions, hygiene practices, and lifestyles in different regions lead to significant variations in SDIR; age influences the frequency of soil/dust contact through behavioral patterns and activity levels; gender differences are reflected in activity types and physiological characteristics; and seasons indirectly regulate SDIR by altering outdoor activity duration and environmental conditions. In addition, this review analyzed four factors that affect SDIR values, but it should be acknowledged that current research has limitations: specifically, direct comparative studies on SDIR calculations across the four methods under standardized conditions (e.g., identical age and gender) are scarce. Moreover, the limited data coverage has hindered cross-method validation of influencing factors on SDIR values, including geographical location, age stratification, gender, and season.

4.1. Geographic Effects on SDIR

Different countries and regions have unique climatic conditions (e.g., humidity), ethnic traditions (e.g., traditional hunting activities of aboriginal people living in wilderness areas), lifestyles (e.g., food, clothing, housing, transportation), as well as hygiene practices (e.g., brushing of teeth, bathing), and consequently, the SDIR in a particular region may not be globally representative [35,38,50,57].

Based on the available data collected, SDIR varied considerably between different regions. The ranges of SDIR for children in China, Bangladesh, and Congo were 9.60–245, 162–234, and 180–460 mg/d, respectively, and in the United States over the last two decades the SDIR ranged from 4.00–93.0 mg/d [3,27,29,30,44,49]. As shown in Figure 2a, some countries (Bangladesh, Congo) with less developed economic levels have relatively high SDIR. In low-income countries, especially in some rural areas, the floors of houses and village roads are usually made of soil [29]. Most children living in these areas play directly on bare ground, relatively frequently hand/object-to-mouth contact, may even ingest soil and dust directly [58]. Furthermore, the relatively low education attainment of the population, poor living conditions, and the lack of emphasis on hygienic practices in most households, contribute to the likelihood of some children coming into direct contact with highly contaminated objects [40,59]. In addition, fruits and vegetables consumed in some rural households may not be fully washed, thus increasing the rate of dust and soil ingestion by children [30].

Within the same country, different geographic and climatic conditions can also lead to differences in SDIR. In the study by Wang et al. [51] SDIR were estimated for children in three Chinese cities (Lanzhou, Wuhan, Shenzhen), and among them, Lanzhou is located in northwestern China, running through the Yellow River and surrounded by a large number of canyons and basins, a unique geographic environment conducive to the formation of sandstorms and dust storms; Shenzhen is located in a seaside city in southern China, with a humid climate and a high frequency of land vegetation cover, hand washing and bathing, and house cleaning [42]. Therefore, in that study, the average SDIR of children in Lanzhou was 117.4 mg/d, which was much higher than that of Wuhan (63.0 mg/d) and Shenzhen (47.5 mg/d).

Even in the same region, there were some differences in the SDIR among the study subjects in different exposed microenvironments. In a study by Li et al. [3], it was noted that preschoolers in Xinxiang City, China, experienced a sequential increase in dust loads on commercial, residential, and bare ground surfaces. Commercial areas have less soil and dust due to more comprehensive cleaning and disinfection measures, and although children have frequent hand-to-mouth contact in this environment, their SDIR is relatively low due to their low hand soil and dust loads. Similarly, the results of the model simulation by Li et al. research indicates that lower cleaning frequencies lead to increased dust accumulation on indoor surfaces, which in turn causes more chemicals to transfer to hands and mouth during each contact. In dirtier environments, the hand-to-mouth dust SDIR of 3-year-olds and 25-year-olds increases by 172 mg/d and 41.8 mg/d, respectively [37].

For some special ethnic groups, they have distinctive ways of life, and different customs can also affect SDIR. For examples, the SDIR for adult residents from a First Nations community located in the Nemiah Valley of British Columbia, western Canada, was 75.0 mg/d [35]; another study, using a more simplified, direct, and mechanistic approach, showed that the average SDIR of Canadian adults was 4.20 mg/d [28]; however, SDIR measured on adult volunteers near Cold Lake in Alberta, Canada, were 32.0 mg/d [48]. Residents of First Nations communities represent the daily living conditions of those who live in rural or wilderness areas. During the study period, they were engaged in numerous “moderate exposure” activities to soil and dust, such as daily collection and felling of trees, hunting, and fishing [35]. Indeed, their daily lives are characterized by activities that involve direct contact with the soil and dust, such as collecting herbs and spices and participating in rodeos, and most of their food consists of a number of large game and fish traditional foods obtained by smoking, drying, freezing, and other methods [57]. As a result, their SDIR are slightly higher than those of adults in urban areas in the same age range, but lower than those of real-life Aboriginal people. In the study of Irvine et al. [48], the SDIR was lower than the results of Doyle et al. [35], possibly because the subjects did not provide fecal samples for the duration of the study, which left a portion of the tracer elemental content data excreted out of the body missing.

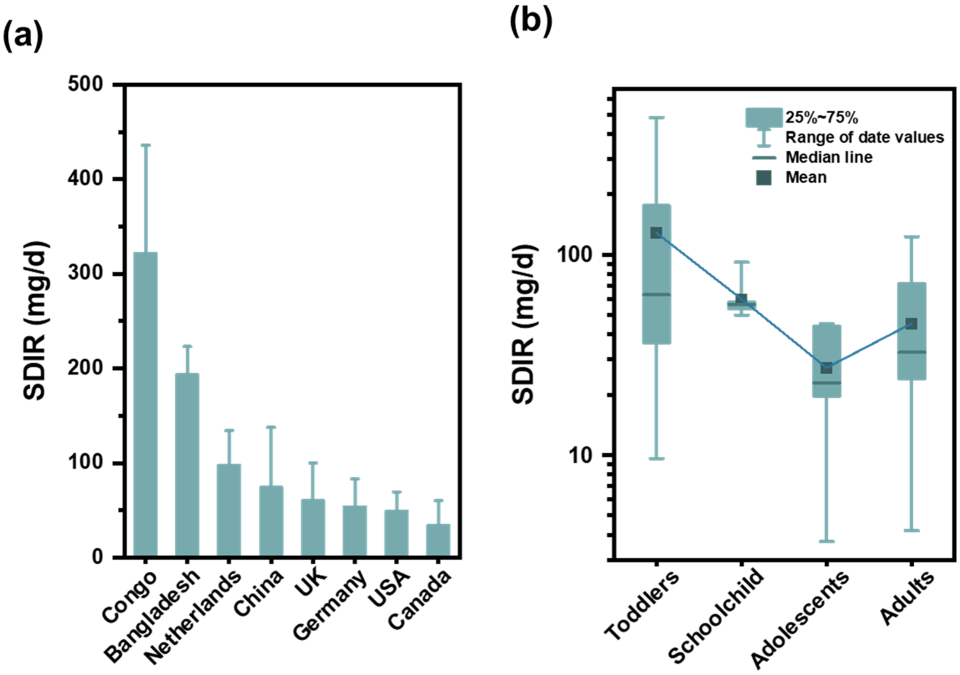

Figure 2. (**a**) The soil and dust ingestion rate (SDIR) in different countries, and (**b**) Comparison of SDIR of study subjects of different ages (infants: 0–6 years, preschoolars:6–12 years, teens:12–24 years, adults:24–60 years). Reproduced with permission. Copyright 1975, Nature Publishing, [60]; 1977, Elsevier Scientific Publishing, [61]; 1987, Springer Verlag Publishing, [62]; 1989, Academic Press, Inc Publishing [26]; 1990, Routledge Publishing [45]; 1990, Academic Press, Inc Publishing [25]; 1995, NIEHS Publishing [46]; 2004, VKTA Publishing [63]; 2006, Nature Publishing [38]; 2011, Wiley Publishing [39]; 2012, Wiley Publishing [44]; 2012, Elsevier B.V. Publishing [35]; 2013, Taylor and Francis Publishing [28]; 2014, Elsevier B.V. Publishing [48]; 2015, Nature Publishing [49]; 2016, NIEHS Publishing [27]; 2017, NIEHS Publishing [50]; 2018, Taylor and Francis Group, LLC Publishing [51]; 2018, Elsevier Ltd. Publishing [52]; 2019, Springer Nature Publishing [29]; 2019, ACS Publishing [30]; 2021, ACS Publishing [41]; 2022, Elsevier B.V. Publishing [14]; 2022, Nature Publishing [43]; 2022, Springer Publishing [42]; 2022, MDPI Publishing [53]; 2023, Springer Publishing [3].

4.2. Age Effects on SDIR

The frequency of hand/object-to-mouth contact varies among children across age groups due to their different activities, exposure, and environmental conditions, and therefore the SDIR of children of different ages also varies. Studies have shown that age is one of the most important factors influencing SDIR by children, and that the frequency and duration of hand/object-to-mouth contact and SDI by children indoors and outdoors are significantly correlated with age [42,49,53,64,65]. It is worth noting that the influence of particle size on SDIR varies with age. The smaller the particle size, the larger the specific surface area, the higher the concentration of pollutants, and the more likely the particles are to adhere to the hands [66,67]. Among them, particles smaller than 100 μm account for more than 90% [3]. Compared with adults, the skin characteristics of children aged 1 to 12 and their habits of frequently grasping the ground, toys, etc., result in a significantly larger number of fine particles smaller than 4.7 μm adhering to their hands [3]. Coupled with their frequent hand-to-mouth and object-to-mouth contact behaviors, the influence of particle size on SDIR is further amplified.

As shown in Figure 2b, the SDIR of the study subjects showed a trend of decreasing and then increasing with age. The SDIR of toddlers (0–6 years) is the highest in this age division interval, which may be greatly related to their habits and physiological behaviors. Sucking is a natural developmental behavior for toddlers, who can’t help but suck on pacifiers, their own hands, the hands of caregivers, clothing, and anything else they can touch as they grow [68]. Children at this stage of life stay mostly indoors, spending a lot of time crawling and playing on the ground and having more exposure to soil and dust [42,49]. Concurrently, they will show a higher frequency of hand/object-to-mouth contact and ingesting dust on clothing, toys, blankets, etc., through hand/object-to-mouth contact [43,65]. As they get older, their range of motion begins to gradually expand. Although they are basically accompanied by their parents at play, and the frequency and duration of contact between objects and their mouths are reduced due to parental intervention, they have greater mobility than newborn infants, and the time they spend playing in parks, plazas, amusement parks, and other recreational facilities is gradually lengthening [65]. These areas are relatively more exposed to soil and dust particles, and the higher moisture content of toddlers hands makes it easier for particles to adhere to their hands, thus increasing their intake [1,69]. As a result, toddlers have higher SDIR.

Schoolchild (6–12 years) are in elementary school, and although the frequency of hand/object-to-mouth contact is reduced, their schooling is relatively easy compared to that of middle and high school students, they play outdoors for longer periods, and their activity level is strong, and they are exposed to higher levels of soil/dust content [52,56]. Especially for boys, are more active, enjoying and indulging in a number of outdoor activities such as playing basketball, soccer, and running [70]. For these reasons, this leads to higher SDIR in preschoolers as well.

Adolescents (12–24 years), face a lot of homework and pressure to go to school, and although they are more active, their outdoor time is significantly reduced compared to preschoolers. Additionally, children in this age group are in their adolescence, they gradually begin to care about their self-image, focus on cleanliness and tidiness, seldom come into direct contact with soil and dust, and tend to stay in relatively clean environments, so they have a relatively low SDIR [3,42].

As for adults (24–60 years), their SDIR may be related to their residential environment, as well as their occupation, and their food, clothing, and shelter. Some of the research subjects collected in the study were aboriginal people in a certain area. Their habits, exposure, activities, and diets differed significantly from those of the general population (excluding people engaged in or involved in activities or jobs that involve prolonged exposure to soil and dust, such as construction workers, landscapers, and agricultural practitioners). Alao their frequency of exposure to soil and dust was relatively high [35,48]. There is also a proportion of subjects who work in contact with soil and dust, which also increases their intake [38]. Thus, the SDIR for adults counted in this paper is high overall. In addition, we compared the SDIR of four methods at the same age group and analyzed the relevant influencing factors. For the 2–18 years age group, the SDIR values of TEM, BMBC, APM and LPFM were 73.5, 51–67, 35–59 and 245 mg/d, respectively [3,27,43,50]. This substantial discrepancy may be attributed to the fact that TEM calculations did not take into account the intake of tracer elements through toothpaste and other materials, BMCM failed to consider all relevant sources of chemical tracers, APM lacked data on soil and dust ingestion via food, and the parameter selection affecting the derivation of total SDIR in LPFM through hand-to-mouth intake remained unknown.

4.3. Gender Effects on SDIR

In general, there is a positive correlation between the amount of soil/dust loading on the hand and its SDIR., while the amount of soil/dust on the hands of the study subjects differed between genders. Most studies have showed that boys have higher loading of soil and dust on their hands than girls [42,56,70]. There are significant differences in the type and frequency of activities between boys and girls [68]. Boys are more active than girls and tend to jump, run, climb, and play ball outdoors, which in turn increase their risk of exposure to soil and dust [71]. The girls, on the other hand, enjoy singing, watching TV, and other activities that have relatively little contact with soil and dust. It has been pointed out that sebum content is an important parameter influencing the adhesion of soil and dust to the hands, and that men tend to have a higher sebum content than women [3,72]. In the study of Li et al. [3], soil and dust loads on the hands of male college students and preschoolers were 2 and 1.7 times higher than those of females, respectively. However, in Gansu and Guangdong Province in China, the mean hand soil and dust loads for boys were 119.48 and 34.64 mg, respectively, which were lower than those for girls (150.5 and 38.51 mg) [42].

As shown in Figure 3, in the study by Wang et al. [51], the mean and median SDIR of men were 69.2 and 45.5 mg/d, respectively, which were lower than those of women (78.0 and 59.8 mg/d). In another study, the determination of SDIR of both parents in the same family based on the element Al showed that mothers ingested more than fathers, while the opposite was true for the determination based on element Si [38]. Analysis of the collected data showed that although there were differences between the SDIR of the different sexes of the study subjects, they were not statistically significant [38,44,47,49,51]. The existence of differences may be more related to socio-economic level, geographical conditions, family income, health habits, education level, behavioral patterns and so on [3,51].

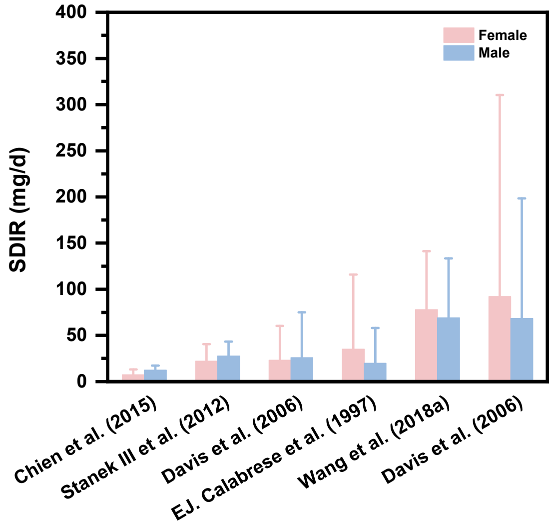

Figure 3. Comparison of soil and dust ingestion rate (SDIR) of males and females in different literatures.

4.4. Season Effects on SDIR

The SDIR can also be affected by the seasons, with people spending less time outdoors during cold periods, which may result in lower ingested soil content [24]. In the studies of Özkaynak et al. [43] and Hubbard et al. [14], the SDIR of the study subjects was predicted according to four different periods (March to May; June to August; September to November; December to February). SDIR was much higher in the summer than in the other three seasons (Figure 4a). High outdoor temperatures in the summer, which make the body prone to sweating, increasing the adhesive properties of soil and dust on the hand, thus increasing the SDIR [14]. As shown in Figure 4b, the proportion of soil ingested by the study subjects during the summer months increased with age. Most people spend more time outdoors in the summer than in the winter, raising the risk of exposure to outdoor soil [43]. Frequent activity increases hand-to-mouth and object-to-mouth contact, resulting in relatively high dust ingestion as well as total SDI during the summer months. As shown in Figure S1, the percentage of the respective intake of dust and soil in spring and fall was consistent among different age groups, i.e., most of the population had a higher intake of dust than soil. In winter, when the temperature is lower and most people tend to stay indoors, they will be exposed to more dust, which in turn leads to a greater percentage of dust ingestion. For persons over 21 years of age, who have their own work and school commitments, the seasons do not have a great impact on them. Children under the age of one are relatively physically weak and have limited mobility, spending most of their time indoors. Therefore, their SDIR fluctuates little throughout the year, and the substances they ingest are mainly indoor dust.

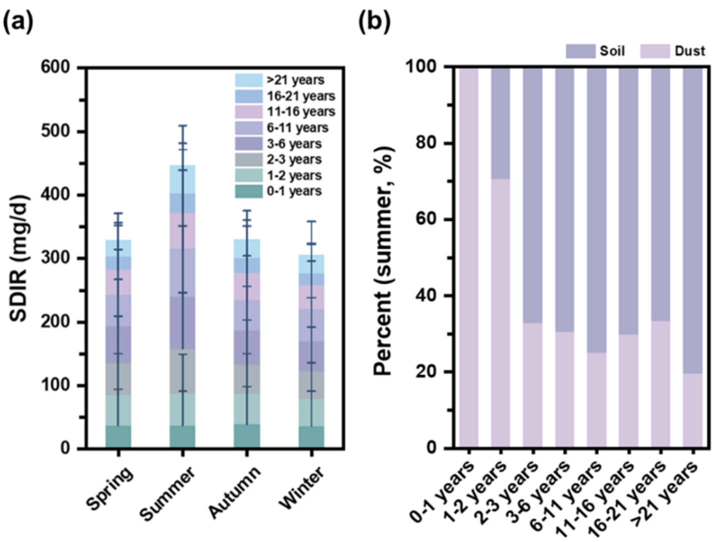

Figure 4. (**a**) Seasonal changes in soil and dust ingestion rate (SDIR) in different age groups predicted from the SHEDS model, and (**b**) Percentage of respective SDIR in different age groups during summer months. Reproduced with permission. Copyright 2022, Elsevier B.V. Publishing [14] and 2022, Nature Publishing [43].

5. Knowledge Gaps and Perspectives

5.1. Limitations of Existing Research Methods

The SDIR obtained by the different study methods varied considerably, which may be due to the limitations of the methods (Table S6). The elemental tracer method calculates SDIR mainly by mass balance, so the choice of tracer elements as well as measurement errors in the process, source errors and transit time misalignment can cause differences in the results [41,50,73]. If the estimated values of tracer elements in food and drugs are higher than those contained in feces and urine samples, and the weight of food and drugs is greater than that of feces and urine, the SDIR will be negatively biased if elemental ingest is ignored for the food and drug portions of the mass balance process [17]. Failure to fully account for non-dietary tracer ingestion (e.g., dermal absorption, inhalation, toothpaste ingestion) or tracer excretion via sweat and tears can bias results [3,24,41,52,73]. Meanwhile, the uncertainty of the transit time of the tracer element in the body can cause errors. Some studies considered a 24-h transit time for the tracer, which led to the collection of fecal samples and the calculation of soil and dust uptake [48]. However, the bioavailability of tracer elements in one day may not fully represent their metabolism in the body over a long period [52]. A short period of tracking does not establish that the intake of the tracer element is comparable to the excretion [48]. In general, extending the duration of the study improves the balance between tracer input and output and reduces the effects produced by transit time [52,73]. However, as the duration of the study increases, the collection of samples can face great difficulties [52].

The BMCM to determine SDIR in children involves dermal absorption, inhalation, and other routes of exposure to contaminants, and some important sources of lead exposure may not be accounted for, which could lead to underestimation of blood lead levels in the model [17,24]. Moreover, the long duration of exposure in this model and the sources of biomarkers, if not fully considered, can also underestimate blood lead concentrations in children, which can lead to an overestimation of SDIR [3]. In addition, it has been demonstrated that children's blood lead levels tend to increase in the fall, which may lead to corresponding changes in children's SDIR. However the BMCM has been studied over a long period of time and has not paid attention to the effect of season on SDIR [2]. Also, the education and intervention of the family and the gender of the children have an effect on their blood lead levels, which can lead to changes in SDIR [17,74]. There are also limitations in the application of TEM and BMCM methods. Ethical approval is required for chemicals with adverse health outcomes. At the same time, the use of high doses of these undesirable chemicals may cause environmental hazards.

The LPFM method mainly relies on a large amount of data to obtain reference values of the calculated parameters for different populations (the variation of M or TE for different population may lead to uncertainty of SDIR). Whereas the APM may produce insufficient and missing information in the process of data collection. In the process of filling out the information in the questionnaire and the oral interviews, the inaccuracy of the data collected can be caused by the inability of the research subjects to remember clearly and their misunderstanding of the questions, which can lead to a certain amount of bias [24]. Videotaping eliminates memory bias but faces data gaps, particularly for young children whose high-frequency mouthing behaviors often move them outside camera coverage, resulting in incomplete data [54]. For adults, their activities are more complex and difficult to capture fully by the camera [14,17] In addition, the model is based on a large amount of data, and insufficient data on the study population, uncertainty and possible fallibility of the inputs can produce errors [14,41,43]. In summary, the uncertainty of calculation/modeling parameters in LPFM and APM methods can affect SDIR, leading to positive or negative biases. Additionally, applying these methods requires significant effort and time to observe or measure specific populations.

5.2. Suggestions and Perspectives

Therefore, in the course of subsequent studies, researchers should try to overcome the limitations of the research methodology to obtain more accurate data on SDIR, which will lead to an accurate assessment of the risk of human exposure. We have the following suggestions and outlook for the calculation methods of SDIR:

(1) Correctly understand the concept of ingestion. The hand-to-mouth ingestion and object-to-mouth ingestion are both SDI and should not be confused with each other. Accurate calculation of SDIR allows for appropriate risk assessment of contaminant exposure during ingestion.

(2) Distinguish between ingested soil and dust. There are some differences in the types of contaminants contained in soil and dust. In the future, appropriate methods should be chosen to measure the respective SDIR separately, such as the APM. Alternatively, 4-Dodecylbenzenesulfonic acid (DBSA) and tripropyl citrate proposed in the study of Ogunbiyi et al. [34] should be chosen as unique tracers to calculate the SDIR respectively.

(3) Use more reasonable exposure parameters. When estimating SDIR using the LPFM, based on the data from the literature, we suggest that in subsequent studies based on an exposure time of 12 h a day, the exposure frequency was 15, 7, 5, 3, and 2 d^{-1} for 3–<6, 6–<11, 11–<16, 16–<21, and ≥21 years of age, respectively; and the transfer efficiency of soil/dust and the proportion of hand area per contact with the mouth were 50% and 10%, respectively.

(4) Calculations of SDIR should take into account the effects of different regions, ages and particle sizes. In some economically underdeveloped areas, they often tend to ingest large amounts of soil and dust. We should pay more attention to the impact of SDIR on the health of people in these areas. Adults whose occupations have regular contact with soil and dust, have a high risk of exposure to chemicals in soil and dust particles. Elderly people, whose bodies are as weak as those of children, are also more susceptible to the effects of soil and dust particles. There is a need to expand the age range of the study participants and to study their SDIR in depth. In addition, the concentration of contaminants in soil and dust particles of different particle sizes varies, and ingested particle sizes also need to be analyzed for better exposure risk assessment.

(5) Identification of major ingestion pathways. The majority of current research suggests that the primary route of SDI in children is through hand-to-mouth contact, but there are also different opinions. Therefore, the main pathway SDI need to be explored in subsequent studies in order to take appropriate measures to reduce ingest.

(6) Criteria for choosing methodologies based on study goals. For total ingestion quantification (e.g., mass balance), TEM or BMCM are employed, using biomarkers (e.g., Al, Si, blood lead) to track intake and excretion. For pathway-specific analysis (e.g., hand-to-mouth vs. object-to-mouth), APM or LPFM are chosen, requiring behavioral data (e.g., mouthing frequency, dust loading). For children, APM and LPFM are prioritized, which focus on hand-to-mouth behaviors (e.g., crawling, sucking); conversely, for adults or occupational groups, TEM and BMCM are selected, relying on biomarkers or long-term exposure modeling. APM and LPFM are suitable for differentiating indoor dust and outdoor soil (e.g., via the SHEDS model), and methods can be combined—such as using TEM for total SDIR analysis and APM for pathway analysis—to enhance accuracy in complex scenarios.

6. Conclusions

Soil and dust particles contain a variety of contaminants, posing potential health risks, primarily through the route of SDI. This paper reviews the current literature and provides a brief data analysis of available SDIR. Although variations in researcher's directions focused on, SDI is an important indicator for evaluating exposure risk. In addition, factors such as geography, age, gender, and season are all potential factors influencing the SDIR. Geography and age were the main factors causing differences in ingestion. Seasons have an impact on the proportion of soil uptake in SDIR, with soil uptake in summer being much higher than in other seasons. Under the influence of living habits and other conditions, gender does not lead to significant differences in SDIR. Hand-to-mouth ingestion is the main SDI pathway considered in the current study. However, the insufficient data available on SDIR, necessitates further analysis of influencing factors (e.g., economic level, educational attainment) and subsequent in-depth studies. Given the potential hazards to diverse populations, particularly infants and young children, protective measures such as reducing crawling on the ground and contact between contaminated hand/object-to-mouth contact are vital to mitigate the impact of pollutants on human health.

Supplementary Materials: The following supporting information can be downloaded at: https://media.sciltp.com/articles/others/2506270947457582/GES-1150-Supplementary-Materials.pdf, Table S1: Definition of soil and dust ingestion (SDI) in different studies; Table S2: Summary of soil and dust ingestion rate (SDIR) from prior studies using the tracer element methodology; Table S3: Summary of SDIR from prior studies using the biokinetic model comparison methodology; Table S4: Summary of SDIR from prior studies using the activity pattern methodology; Table S5: Summary of SDIR from prior studies using the dust/soil loading-activity pattern-based parametric formula methodology; Table S6: Impact of different research methods on SDIR; Figure S1: (a) Percentage of respective SDIR in different age groups during spring months, (b) Percentage of respective SDIR in different age groups during autumn months, and (c) Percentage of respective SDIR in different age groups during winter months.

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