systems

MDPI

Review

A Systems Perspective on Material Stocks Research: From Quantification to Sustainability

Tiejun Dai, Zhongchun Yue, Xufeng Zhang * and Yuanying Chi *

College of Economics & Management, Beijing University of Technology, Beijing 100124, China; daitiejun@bjut.edu.cn (T.D.); am_yzc@emails.bjut.edu.cn (Z.Y.)
* Correspondence: xufengzhang@bjut.edu.cn (X.Z.); goodcyy@bjut.edu.cn (Y.C.)

Abstract

Material stocks (MS) serve as essential physical foundations for socio–economic systems, reflecting the accumulation, transformation, and consumption of resources over time and space. Positioned at the intersection of environmental and socio–economic systems, MS are increasingly recognized as leverage points for advancing sustainability. However, there is currently a lack of comprehensive overview, making it difficult to fully capture the latest developments and cutting–edge research. We adopt a systems perspective to conduct a comprehensive bibliometric and thematic review of 602 scholarly publications on MS research. The results showed that MS research encompasses has three development periods: preliminary exploration (before 2007), rapid development (2007–2016), and expansion and deepening (after 2016). MS research continues to deepen, gathering multiple teams and differentiating into diverse topics. MS research has evolved from simple accounting to intersection with socio–economic, resources, and environmental systems, and shifted from relying on statistical data to integrating high–spatio–temporal–resolution geographic big data. MS research is shifting from problem revelation to problem solving, constantly achieving new developments and improvements. In the future, it is still necessary to refine MS spatio–temporal distribution, reveal MS's evolution mechanism, establish standardized databases, strengthen interaction with other systems, enhance problem–solving abilities, and provide powerful guidance for the formulation of dematerialization and decarbonization policies to achieve sustainable development.

Keywords: material stocks (MS); sustainable development; bibliometrics analysis; resource management; spatio–temporal analysis; system interaction

check for updates

Received: 28 May 2025
Revised: 9 July 2025
Accepted: 10 July 2025
Published: 15 July 2025

Citation: Dai, T.; Yue, Z.; Zhang, X.; Chi, Y. A Systems Perspective on Material Stocks Research: From Quantification to Sustainability. *Systems* **2025**, *13*, 587. https://doi.org/10.3390/systems13070587

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Frequent human activities have increased material and energy consumption over the past century, resulting in a series of environmental problems, such as resource shortages, global warming, and a sharp decline in biodiversity, all disrupting ecosystem balance [1,2]. Thus, sustainable development has become the world's long–term vision and urgent goal [2–4], requiring coordinated development of the economy, society, and environment through comprehensive innovation [2,5]. As a critical link between the economy, society, and environment, it is particularly important to conduct in–depth research on the material stocks.

Material stock (MS) refers to materials accumulated over a specific period to support and promote socio–economic development [6]. In a country or region, MS serves as indicators of infrastructure levels, describing the exchange, storage, and conversion of

natural environment and economic system. MS provides essential services for modern society, including housing, transportation, communication, production and manufacturing, entertainment [6,7]. According to the end–use, MS can be divided into buildings (residential buildings, commercial buildings, factories, etc.), infrastructure (roads, pipelines, tracks, pipelines, etc.), and equipment, etc. [8,9].

As a key hub of material metabolism, MS closely links the socio–economic, resource, and environmental systems, carrying the material flow and functional coupling between multiple systems. MS provides tools and venues for socio–economic development, but it also affects shaping urban form, optimizing industrial layout, and population distribution patterns. And it is usually retained for longer periods, which has a strong time– and space–locked effect, influencing long–term planning, hindering transitions toward dematerialization, lightweighting, and energy conservation [7]. In resource systems, MS determines the scale and structural characteristics of resource demand. At the same time, MS also contain valuable reusable resources like metals [10,11] and recycled aggregates [12], representing both accumulated resources in the economy and society and potential for resourcization [13]. Furthermore, as a secondary resource pool, MS can help alleviate the pressure and shortage of resource supply from energy transformation [14,15]. Moreover, MS impacts the environment throughout its entire lifecycle, including raw material extraction, production, maintenance, and disposal, especially in terms of energy consumption and carbon emissions [16]. Clearly, MS is not only the material foundation of socio–economic development, but also the regulator of resource allocation and the instrument of environmental feedback. In systems theory, MS is the physical carrier of the social–resource–environment coupling system. It is important to explore MS's characteristics, dynamics, and interaction mechanisms with various systems to facilitate efficient resource utilization, reduce environmental pressure, and build sustainable societies. As such, MS has gradually become a research hotspot for ecology, human geography, and environmental science.

In recent years, MS's research for resource sustainability and low–carbon transitions has expanded rapidly, yielding a wealth of valuable findings. In this context, a growing number of scholars have undertaken comprehensive reviews to showcase MS's evolution, methodological development, and thematic expansion. Gerst and Graedel reviewed the research status of metal stocks [17]. Müller et al. summarized the application of dynamic material flow analysis in metal stocks [18]. Augiseau and Barles reviewed non–metallic minerals based on 31 studies on built stocks (buildings, roads and pipelines), and summarized research methods and reutilization potential [13]. Lanau et al. reviewed the research status and development prospects of built environment based on 249 documents from 1985 to 2018 [7]. Bao et al. discussed the methods of MS spatial distribution [19]. Grossegger et al. summarized the material composition and quantitative methods of road stocks combined with 86 studies [20]. Fu et al. and Yang et al. reviewed their research progress and development based on bibliometric analysis [21,22].

Previous studies have provided an exhaustive overview of built stocks [7,13], metal stocks [17,18], quantitative methods [7,19,23], evolution and hotspots [21] and resource potential [7]. While MS research increasingly integrates interdisciplinary and multi–thematic approaches, previous reviews focus on exploring and summarizing basic MS research, ignoring the discussion of interaction with other systems like economy, resources, and environment. Nowadays, MS research is gradually shifting from simply exposing problems in socio–economic development, resource management, and ecological environment to exploring solutions. There is an increasing interest in MS's complex relationship with economic development, resource management, and climate change, but existing reviews have not fully covered these emerging issues.

Thus, it is particularly important to provide a comprehensive and detailed overview of the latest developments and cutting–edge explorations in MS research to ensure that we can accurately grasp the latest trends and future development directions. Based on a systems perspective, this study comprehensively integrates 602 studies, to reveal the evolving trend of MS research from "quantitative analysis" to "sustainable transformation". This study summarizes the historical and thematic evolution, tracks cutting–edge dynamics, deeply analyzes its interaction with economic, resource, and environmental systems, and identifies the main challenges and knowledge gaps in the current research. Furthermore, a forward–looking research framework and development path were proposed, aiming to provide forward–looking insights and guidance for future MS research, and to provide a solid knowledge foundation and methodological support for achieving resource efficiency improvement and climate action synergy.

2. Materials and Methods

2.1. Methods

We integrate bibliometric analysis with systematic literature research to conduct a comprehensive and in–depth overview of MS. Bibliometric analysis uses mathematical and statistical methods to quantify information from the literature and evaluate research status and progress [7,19,24]. CiteSpace, a key tool, creates intuitive knowledge maps from massive amounts of literature data, effectively capturing hotspots, cutting–edge and development trends, and overcomes the systemic and accurate limitations of qualitative analysis [21,25]. Thus, we utilized CiteSpace 6.1.6 to extract and visualize the basic information of the literature, and conducted in–depth analysis of MS's theme evolution, extracting the key theme.

We further reviewed the cutting–edge dynamics of key themes through literature review and comprehensively examined MS's role in sustainable development. Further, based on current challenges, future directions will be explored to advance MS research comprehensively and practically, and provide valuable guidance for policy formulation, practical application, and interdisciplinary cooperation.

2.2. Data

To obtain comprehensive and professional data, we have carried out a Topic Search (TS) including title, abstract, author keywords and article keywords in the Web of Science (WoS) core database, known for its global collection of authoritative and high–impact academic journals. As described in the existing research, MS use the following terms: "material stock", "in–use stock", "build environment stock", "built stock", and "anthropological stock". To capture the diversity of terminology and ensure the comprehensiveness and accuracy of the search results, combined with Boolean logic operators (AND, OR, NOT) and wildcards (*), we adopted the retrieval statement: TS = ("material* stock*" OR "in use stock*" OR "build environment stock*" OR "build stock*" OR "anthropologic stock*) from 1900 to 2024 (up to 11 May 2024) and the language limited to "English". After screening and excluding the results (Figure 1), 602 studies were eventually obtained, including Article, Review and Early Access (see Support Information for details).

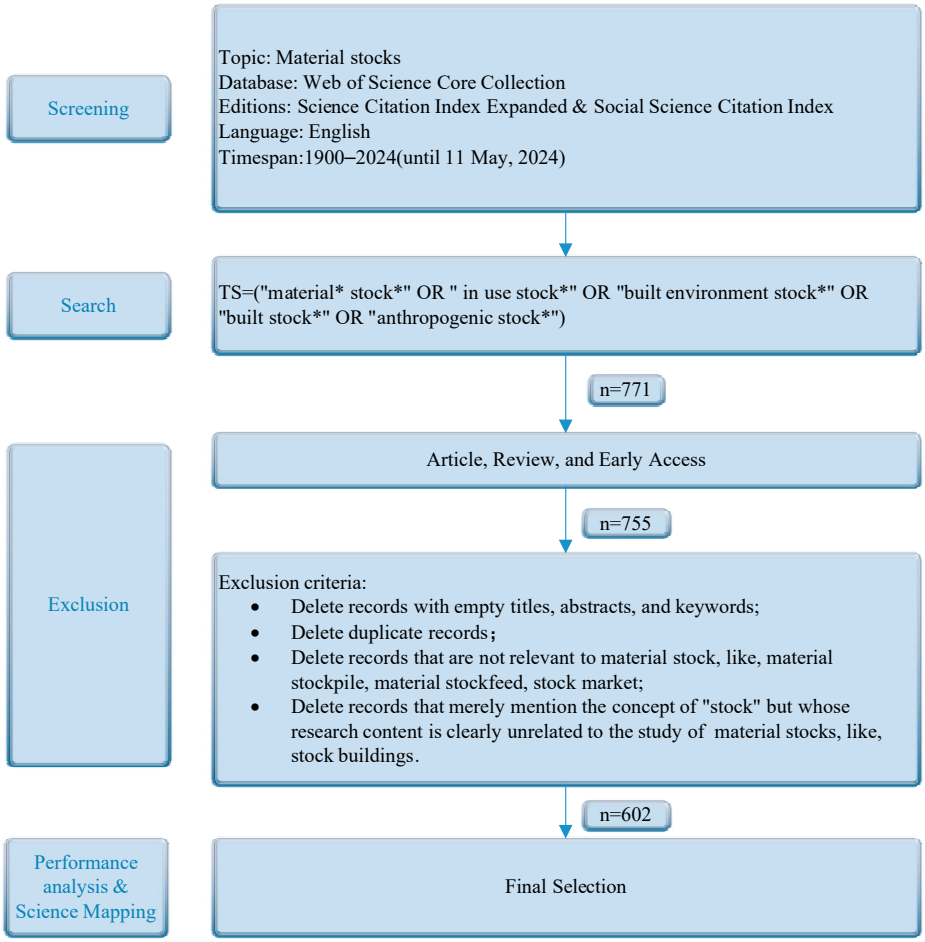


Figure 1. Literature screening process.

3. Publication Analysis

3.1. Publication Trend

Figure 2 demonstrates the yearly publications 94% of all publications have been published since 2006, and the annual publication output has doubled since 2017. It is very clear that MS research has largely gained popularity in academia in recent years (Figure 2).

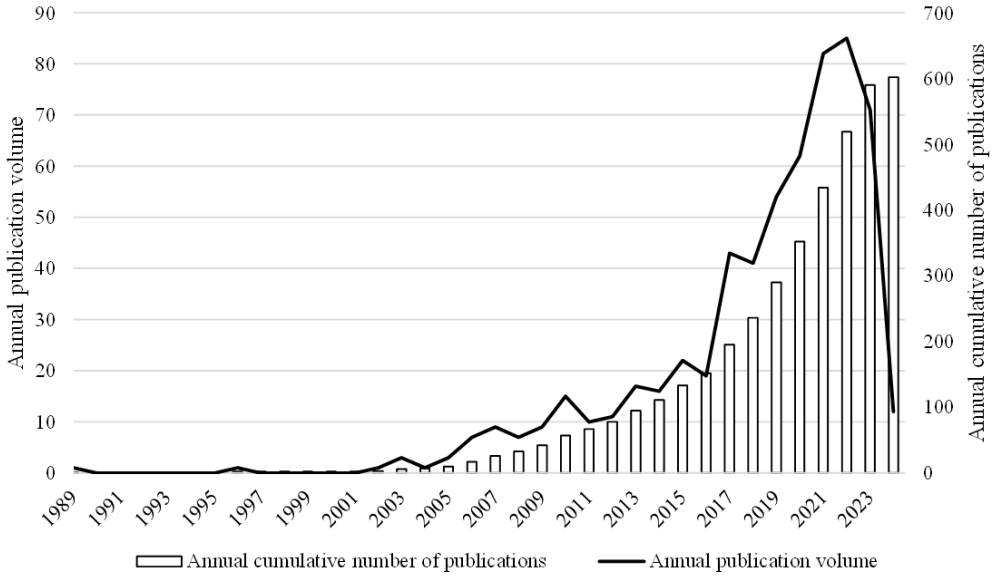


Figure 2. Annual and cumulative publication volume of MS research.

3.2. Source of Publication

There were 602 retrieved publications published from 1900 to 2024 in 95 sources. The topics of these sources are mostly environmental science, green sustainability, and ecology. Among the top ten sources (Figure 3), Resources, Conservation and Recycling (Resour. Conserv. Recycl.), Journal of Industrial Ecology (J. Ind. Ecol.), Environmental Science and Technology (Environ. Sci. Technol.), and Journal of Cleaner Production (J. Clean. Prod.) published approximately 50% of the articles and were the most frequently cited. There is still a relatively "niche" focus to MS research in ecological and environmental research.

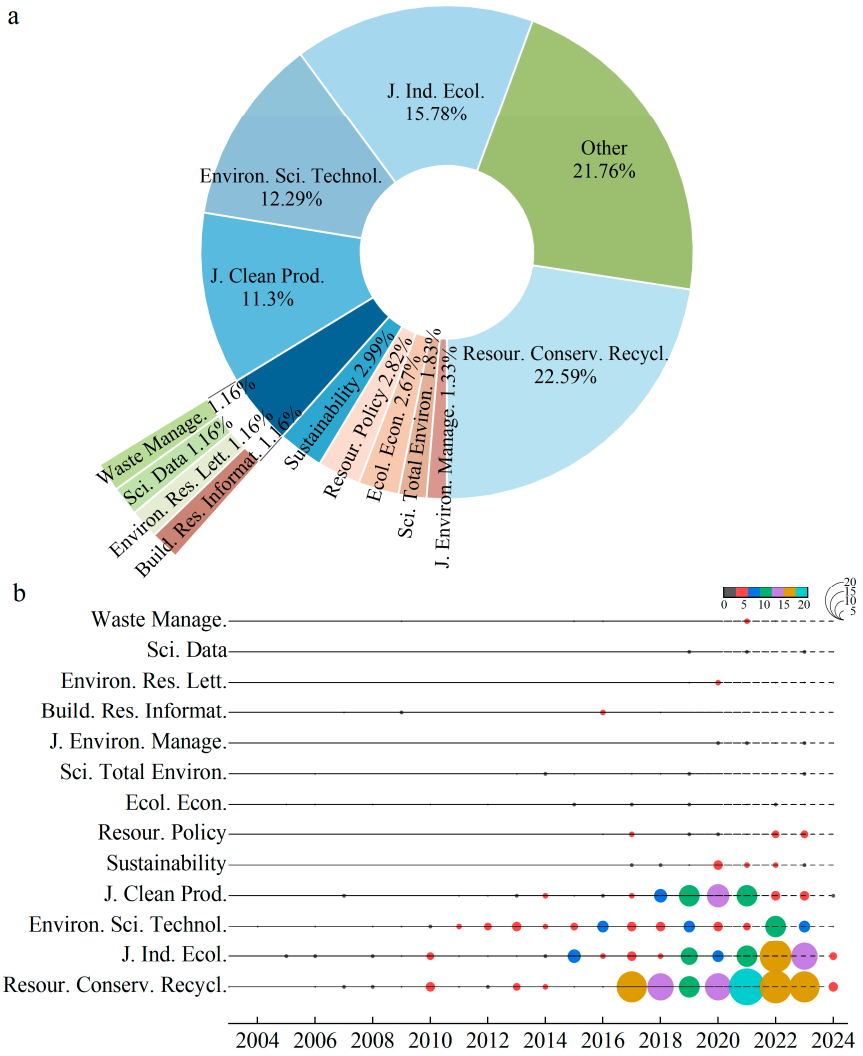


Figure 3. Top 10 sources of publications ((**a**) Proportion of journal distribution; (**b**) annual publication volume of journal).

3.3. Cooperation Network Analysis

The 602 publications originated from 1380 authors at 452 institutions in 46 countries or regions (Figure 4a). China, though not a pioneer, now leads in publication volume, with 215 publications, followed by the USA (117) and Japan (101), which together contribute 71.93% of the global total (Figure 4a). Most of the top 10 publishing countries are developed economies, suggesting a certain correlation between MS research and economic level. In addition, the closest international collaborations are China–USA (Freq = 29), Japan–China (Freq = 22), Japan–USA (Freq = 21), Australia–Japan (Freq = 20) and Denmark–China (Freq = 20) (Figure 4b).

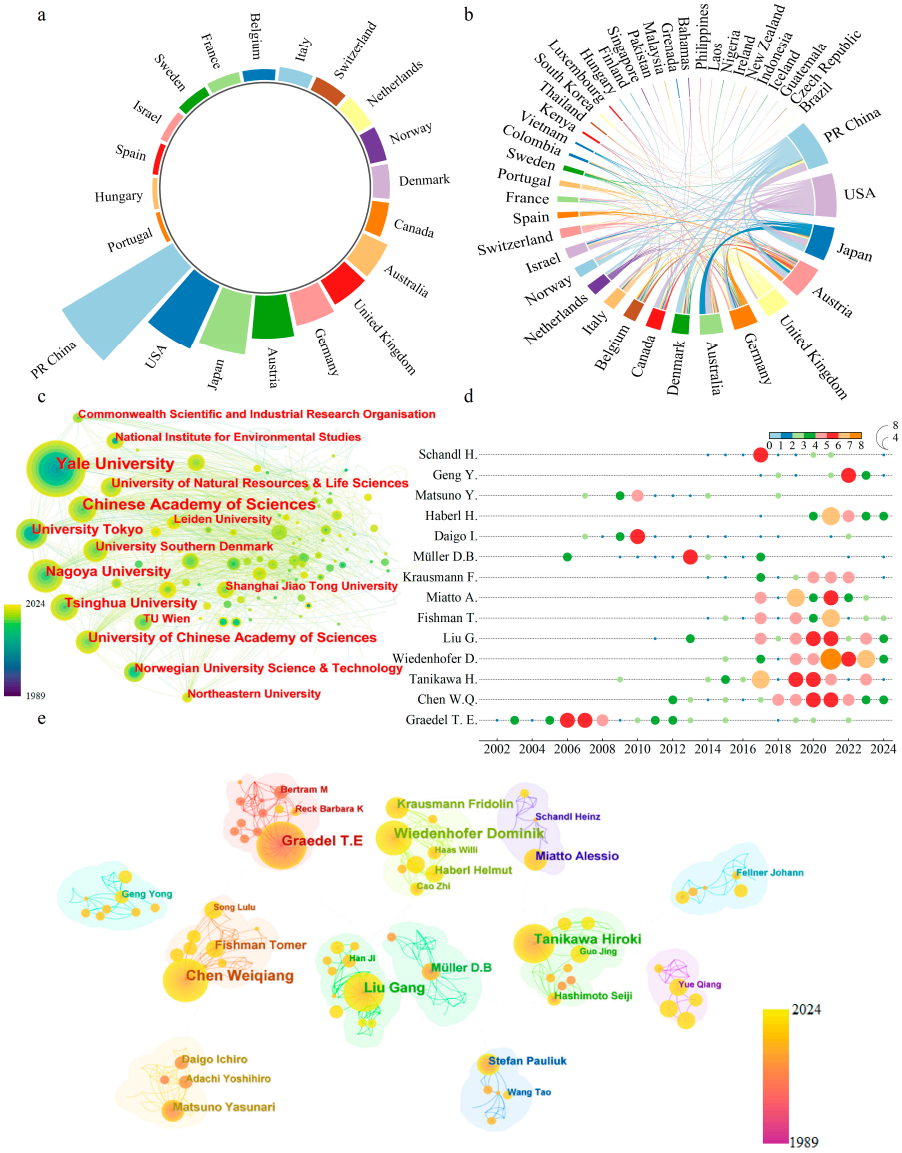


Figure 4. Collaborating networks ((**a**) Top 20 countries of publication volume; (**b**) national cooperation networks; (**c**) institutions cooperation network (Freq $\geq$ 20); (**d**) Top 14 authors by publication volume; (**e**) author collaboration network (Freq $\geq$ 10).

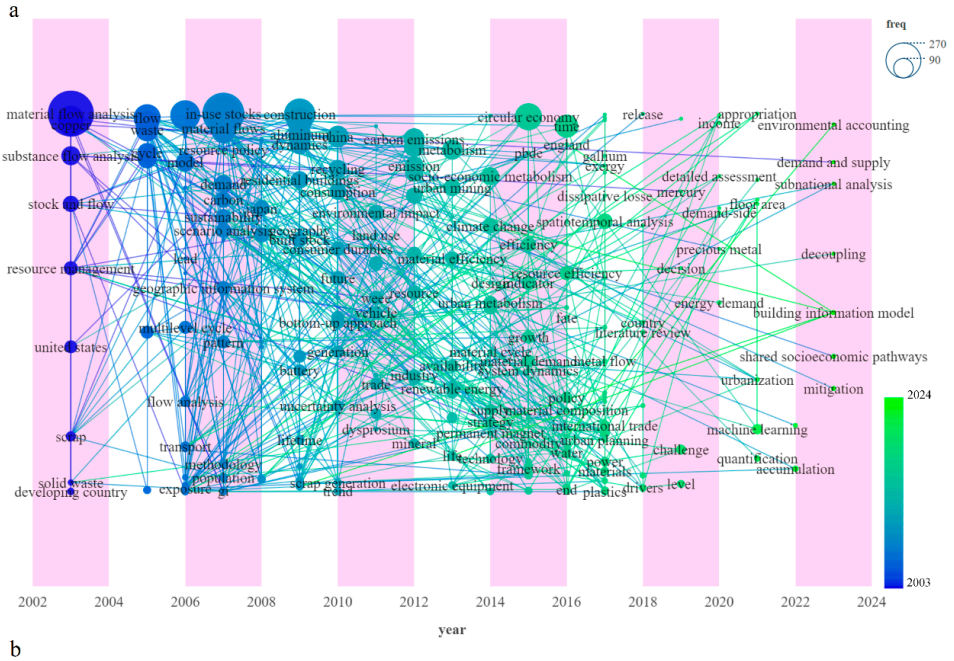
The number of participating institutions is constantly increasing, with universities being the leading force. The top 10 institutions contribute half of all publications with high productivity, with Yale University being the most prolific and productive (78 publications), followed by the Chinese Academy of Sciences (65) and the Nagoya University (41) (Figure 4c). Collaborative ties are concentrated among institutions, especially the Chinese Academy of Sciences (links = 130), Yale University (links = 73), Nagoya University (links = 68) and University of Tokyo (links = 34) (Figure 4c).

As MS research becomes increasingly popular, MS research teams continue to grow (Figure 4d,e). Scholars like Graedel T.E., Adachi Y., Daigo I., Müller D.B., Matsuno Y., and Krausmann F. laid the foundations for MS research, and Chen W.Q., Tanikawa H., Fishman T., and Liu G. push it forward. These authors have formed multiple research teams and engaged in extensive collaboration, especially among top–ranked authors. It has been found that three types of collaborative networks of authors have formed: Graedel T.E. (No. 1, Freq = 42) dominated the static metal stocks research cooperation, focusing on the elements or metal stocks like copper, zinc, lithium, and rare earth elements for resource

management; Chen W.Q. (No. 2, Freq = 39) led the dynamic metal stocks cooperation, studying the spatio–temporal dynamics of metal stocks and preliminarily the relationship between MS and economic development and greenhouse gas emissions; and built stocks (e.g., buildings and infrastructures) research team led by Tanikawa H. (No. 3, Freq = 36), Wiedenhofer D. (No. 4, Freq = 35) and Müller D.B. (No. 9, Freq = 21), etc. Wiedenhofer D.'s team focused on the stock–flow–service nexus; Tanikawa H.'s team explores spatial distribution; Müller D.B.'s team focused on the application of the dynamic stocks analysis method proposed by Müller D.B.; Daigo I. (No. 10, Freq = 20) and Matsuno Y. (No. 12, Freq = 20) mainly examine MS with satellite data. Further, there are many small–scale research collaboration networks that produce representative research.

3.4. Historical and Thematic Evolution

Analysis of publications (Figure 2) and keywords (Figure 5) shows three MS research stages: preliminary exploration (before 2007), rapid development (2007–2016), and expansion and deepening research (after 2016) (Figure 6).



b

Keywords	Year	Strength	Begin	End	1989-2024
substance flow analysis	2003	12.9197	2003	2014	
copper	2003	9.0093	2003	2012	
resource management	2003	8.8562	2003	2013	
scrap	2003	6.6201	2003	2015	
cycle	2005	6.084	2005	2015	
stocks	2005	5.0833	2005	2010	
resource use	2005	3.1834	2005	2009	
multilevel cycle	2006	8.259	2006	2014	
flow analysis	2006	5.1374	2006	2017	
aluminum	2009	3.7856	2009	2014	
lifetime	2009	3.3537	2009	2016	
water	2016	3.8718	2016	2018	
product	2015	3.0756	2017	2019	
china	2010	3.2275	2018	2019	
indicator	2015	3.0408	2018	2019	
management	2012	3.7932	2019	2021	
circular economy	2015	4.8492	2021	2024	
spatiotemporal analysis	2017	4.1754	2021	2024	
machine learning	2021	3.9175	2021	2024	
carbon	2007	3.6675	2022	2024	

Figure 5. Keywords analysis ((**a**). Keyword evolution (Freq ≥ 20); (**b**). Top 20 keywords with the strongest citation bursts).

Before 2007, MS research focused on preliminary methods and theories, published mostly in detailed reports/books, resulting in scarce publications (Figure 1). This period primarily analyzed single material or metal stocks in conjunction with flow (Figures 5a and 6). There is no consensus of MS's origin among academics [17,26,27], with some tracing it back to 1930s metal stock estimations [17,28] and others to 1950s stocks analysis of socio–economic metabolism [22]. But it gradually developed in the 1970s alongside the rise of urban metabolism [29], industrial metabolism [29] and material flow analysis (MFA) [30]. Until the 1990s, MS's concept was clarified and gained attention [31]. As the core dimension of material metabolism research, material flow and MS form a complementary relationship. The former refers to material input, conversion, and output in the system, emphasizing the migration path and conversion rate of substances within the system boundary (input–output), possessing dynamic process analysis. The latter analyzes the state and structural characteristics of matter at particular points in time and space, reflecting time lags and sedimentation. While material flow describes the changes in matter over time, MS describes the accumulation of matter in space. During this period, MS research mainly serves as an auxiliary content for material flow analysis to deepen the understanding of the material metabolism mechanism of the socio–economic system. Meanwhile, the MFA method expanded from simply analyzing material flow to covering material metabolism processes that cover MS, gradually shifting from static to dynamic analysis [32–34]. After 2000, it gradually separated from flow analysis and became an independent research topic due to its prominent role in resource management [35]. Furthermore, the MFA method has gradually shifted from Economy–Wide MFA (EW–MFA) to Substance Flow Analysis (SFA) of specific substances or systems, further promoting MS research at the regional and product levels. The Stock and Flow (STAF) project at Yale University in 2002 spurred more metal stocks research, such as copper [36], steel [18], chromium [37], zinc [38], and lead [39]. Müller D. B. integrated lifestyle with MS [40], further advancing dynamic stock model, encouraging various product stocks research, including buildings [41], roads [41], and consumer durables [42].

From 2007 to 2016, MS research rapidly developed with more publications and a broader research scope (Figures 1, 5a and 6). It covered diverse materials/products like steel, aluminum, chromium, nickel, rare earths, vehicles, and equipment (Figure 6). In addition, it shifted from a single time dimension to incorporating both time and space, with the introduction of geographic information system (GIS) [43–45] and nighttime light (NTL) [46] in 2009. Furthermore, MS research began integrating socio–economic and ecological perspectives to reveal issues like carbon emissions, environmental impact, and urban mining (Figure 5a).

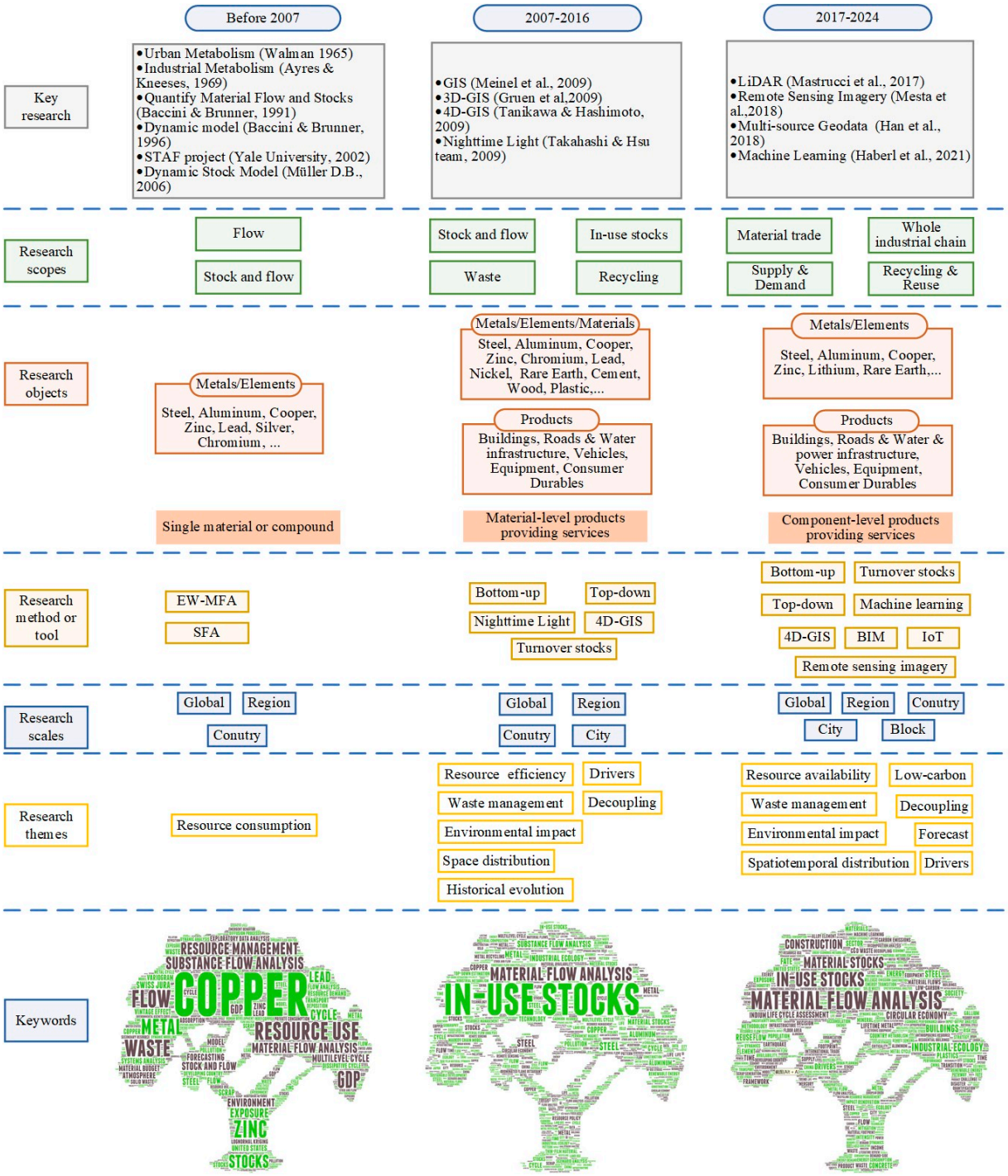


Figure 6. Historical and thematic evolution [29–32,40,43–50].

MS research has expanded and deepened since 2017. With the rapid development of digital and information technology, MS's spatio–temporal analysis has made significant progress [47], and its research are becoming increasingly diversified (Figures 5a and 6). Current hotspots include circular economy, spatio–temporal analysis, machine learning, and carbon, focusing on distribution patterns, socio–economic and environmental issues, and potential solutions (Figures 5b and 6). Various emerging geodata and tools like remote sensing, and artificial intelligence, have infused unprecedented momentum into MS research's precision, e.g., a high resolution of 1 m × 1 m street view map [48], non–residential building classification [51], and urban–rural stock transfer [52]. MS research continues to integrate with socio–economy, resource management, and environment, addressing

challenges like inequality economic development [53], resource supply and demand [14], and climate change [16].

4. Key Themes of MS's Research

MS research has made significant progress, with its focus shifting from simple scale accounting to exploring the essence of socio–economic development and environmental protection issues, ultimately shifting towards seeking solutions. Keyword clustering highlights key themes: the objects, methods, and spatio–temporal distribution of MS (#4, #5, #8, #9, #10, #11), the link between MS and socio–economic activities (#0, #12), sustainable resource management (#1, #2, #3, #7), and MS's environmental impact (#6, #13) (Figure 7a). Thus, MS's research can be summarized into four key themes: quantifying MS accurately, exploring the interaction between MS and socio–economy, resource management, and environment (Figure 7b).

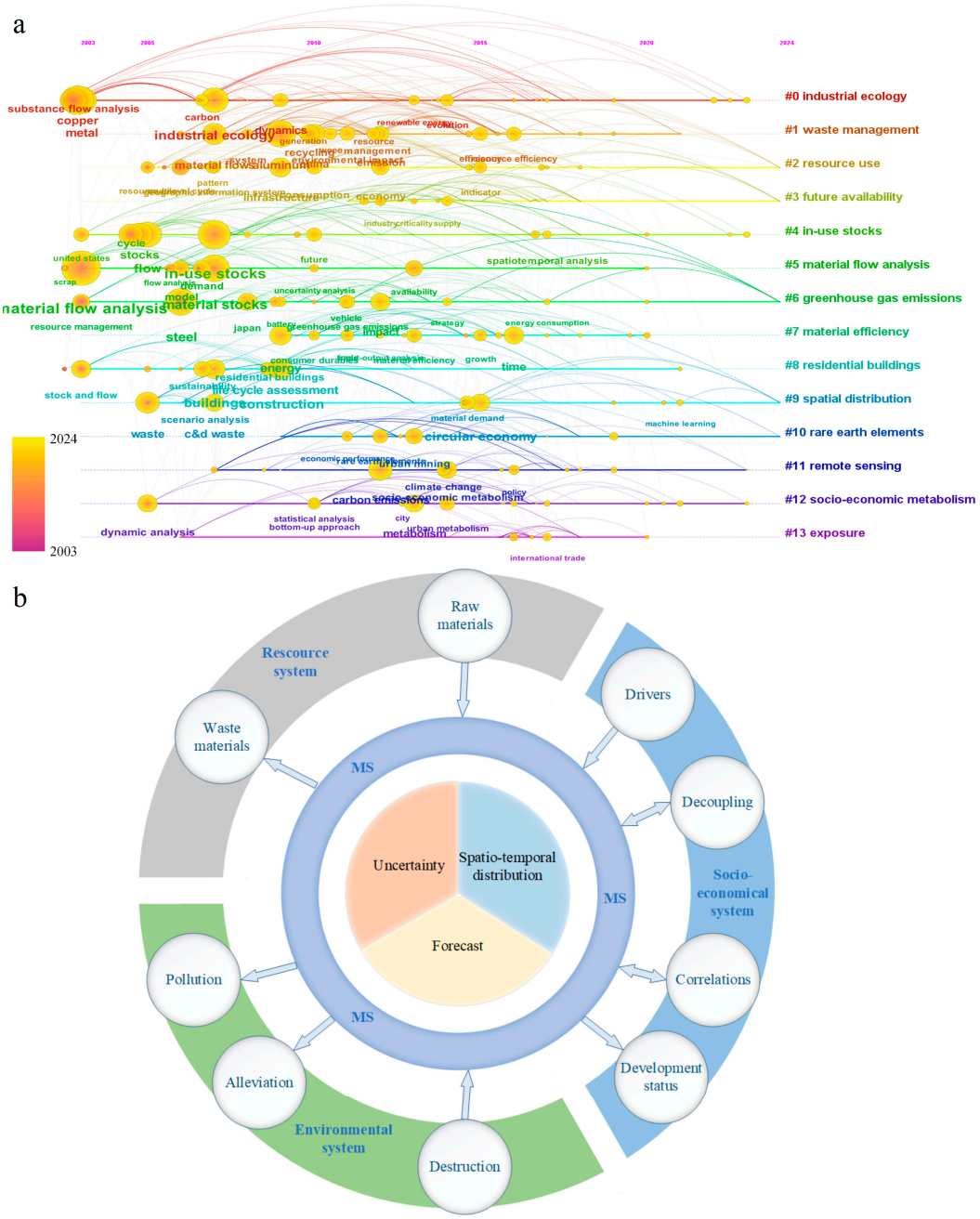


Figure 7. Thematic evolution ((**a**) Keyword timeline; (**b**) key themes).

4.1. MS's Quantification

4.1.1. Spatio–Temporal Analysis

MS's spatial–temporal distribution has made significant progress since the introduction of GIS and NTL. With the advancement of technology, more emerging technologies are being applied. Nowadays, remote sensing and machine learning propel MS research into the high–resolution era [54,55]. Remote sensing technology, as an important means of acquiring geospatial information data, makes use of several professional tools and a variety of channels to acquire images, including high–resolution satellite images [48], drone images [56], and light detection and ranging (LiDAR) images [56]. Machine learning methods provide powerful support for the analysis of remote sensing images, including convolutional neural networks (CNN) [57], deep learning [49], support vector machines (SVM) [58], computer vision [59,60], random forests [49] and gradient boosting decision trees (GBDT) [61,62]. And they can be used to extract spatial and geographic data from remote sensing images for MS's spatial distribution. Significantly, multi–source geodata avoid the limitations of single–source geodata. These methods have been used to account for and analyze built environments at different geographical scales, including country [49,56], city [57,60], block [63].

The spatial layout of buildings [60], roads [58,61,62], subway [64], power facilities [65], and home appliances [66] have been explored. Buildings can be classified into 12 types through precise spatial location, surpassing the crude classification of buildings into residential and non–residential categories in the past [51,67]. In addition, cutting–edge research is using these emerging technologies to analyze stocks at the component–level rather than just at the material–level [59,68].

4.1.2. Data Refinement

MS research is data intensive, with accuracy hinging on data quality. The academics increasingly emphasize MS's accurate accounting, focus on reducing data uncertainty, like product data, material composition indices (MCIs), and lifetime distribution, while also evaluated the uncertainty of research results.

Initially, product data mainly derived from statistical yearbooks and official bulletins. Nowadays, with the application of emerging technologies, their accuracy has been greatly improved. By capturing or detecting the spatial location and block of physical entities, detailed information like building features, road length, and household appliance counts can be obtained [54,69]. Combining MCIs, more urban stocks are estimated, like Shanghai [50], Beijing [51], and Lixia District of Jinan [70].

MCIs are crucial for estimating MS and flows, but their accurate acquisition varies and remains challenging. Traditional methods, such as standard manual [71], experts interviews [48], engineering documents [72], and field investigations [73], are time–consuming and uncertain. Nowadays, to overcome these issues, scholars are adopting new strategies: establishing the MCI database through compiling the relevant literature [74], conducting extensive survey [75], or collecting from company [76]; utilizing emerging technologies, like computer vision [59], building information management (BIM) and Internet of Things (IoT) [77,78]; using reinforcement training methods, like Q–reinforcement learning [79], random forest [80], semi–supervised learning [54]) emerged as the times require [76].

Product lifetime affects MS's dynamics, resource recycling, and low–carbon development. Most studies used average or hypothetical lifetimes, leading to uncertainty and error due to product heterogeneity [7]. Building a lifetime database like LiVES database [81,82] or conducting lifetime research on specific products, such as buildings [83,84], vehicles [85,86], consumer durables [85] and electronic devices [87], is used to overcome the uncertainty.

Model and parameter uncertainty affect the accuracy of MS results. Model uncertainty is typically assessed by comparing results from different models [88]. Parameter uncertainty is addressed using methods like pedigree matrix evaluation [88], and statistical approaches like Monte Carlo simulation [6,10], Gaussian error propagation [89], and Fourier Amplitude Sensitivity Test [90]. Some studies use probabilistic models to capture MS's possible range [91]. In machine learning–based MS mapping, statistical errors like mean square error (MSE) and root mean square error (RMSE) are used to evaluate mapping effectiveness [54].

4.1.3. Forecast of Future MS

Predicting MS can reveal resource demand and metabolism, aiding sustainable management, environmental protection, economic development, and social stability. Currently, scholars use methods like growth curves, time series, scenario analysis, and machine learning for such predictions.

Some scholars have predicted MS's future based on their historical characteristics using time series models like Autoregressive Integrated Moving Average (ARIMA) [92] and Autoregressive Non–linear Moving Average [89]. However, these models rarely incorporate external factor dynamic impacts, which limits their ability to capture the impact of socio–economic dynamic changes on MS. To accurately grasp MS's future, socio–economic variables should be considered in more studies. Given resource and environmental limits, MS cannot grow indefinitely. Therefore, some studies have adopted growth curves (such as Logistic [93,94] and Gompertz [95,96]) to explore their future development and saturation with variables like population and GDP [97]. Scenario analysis, widely studied, predicts MS by constructing various socio–economic scenarios [16]. Moreover, emerging tools like machine learning, including GBDT for roads [61], the combination of linear regression (LR), polynomial regression (PR), gradient boosting, and SVM for buildings [98], are also explored for MS prediction.

4.2. MS and Socio–Economic Systems

4.2.1. Drivers of MS

MS has expanded in time and space, prompting scholars to address underlying causes. The complex drivers are being revealed with multidimensional perspectives, interdisciplinary theoretical frameworks, and sophisticated analytical tools.

To systematically understand MS's driving mechanisms, scholars have attempted to identify the drivers. Currently, the methods for exploring MS's drivers are relatively limited, mainly divided into two categories. One uses extended or reformed IPAT model, such as transforming it into regression model [99,100], or decomposing it into specific components [9,10,12]. The other employs statistical methods, including correlation analysis [46,101] and multiple linear regression [102,103].

Based on the above methods, researchers examine MS's drivers from the perspectives of demographics (population, age, household, urbanization) [104,105], economy (industrial structure, Gross Domestic Production (GDP)) [106], and technology [99], with population and economic growth driving expansion, while technology constrains it. In fact, some studies also indicate that other factors like policies [71], consumer attitudes, lifestyles [40], also influence MS's scale, distribution pattern, and material composition [6,71]. However, due to quantification challenges, they are not directly represented in the model but instead manifest their influence through population structure, economic development, and technological progress [6]. There may be some differences in drivers between MS's different categories. For instance, national or regional policies and planning all also affect building stock scales [103] and spatial distribution [70,103]. Sewage pipelines driven by population density and size [105], and consumer durables driven by household size and income [107].

In addition, war significantly impacts metals and in–use stocks due to high demand for weapons and fortifications during wartime, increasing metals demand and supply, and affecting in–use stocks through wartime defenses and post–war renovations, as seen in Austria during World War I [108] and Zurich during World War II [84].

4.2.2. Decoupling and Correlation

MS is essential for economic development, but its expansion has caused numerous environmental problems. Therefore, analyzing their interdependence and decoupling potential is widely research and discussion.

Scholars have measured their dynamic coupling relationship by socio–economic indicators using quantitative methods. Several studies used representative indicators like population [101], GDP [109], urbanization rates [101], infrastructure investment [101], and human development index [110], to explore MS's relationship with socio–economy using curve fitting [102], correlation coefficients [101], and regression analysis [102]. They indicate that the relationship between MS and socio–economic development is closely related and has phased characteristics [102,109], with rapid growth during underdeveloped economies to propel economic growth, slowing down as development progresses, and being restricted when social demands are met [96,111]. They also reveal that MS saturation varies by country, potentially due to unique geographical conditions, different economic development patterns, and urban layout [112].

Correlation analysis indicates decoupling potential between MS and economic development, while decoupling research further examines when, how, and what the current state is [6]. Several studies analyze decoupling of MS and socio–economic using GDP, per capita GDP, and other variables with decoupling models (Tapio, OECD) and elasticity coefficients [6], curve fitting (Environmental Kuznets, Logistic Growth) for inflection points [113], or statistical regression (Logit, Panel) for convergences [102,112]. Combining decoupling with decomposition models delves deeper into decoupling mechanisms [6]. Results show developed countries/regions have achieved relative decoupling but not absolute decoupling [112,113]. Infrastructure expansion and rapid industrialization making decoupling more difficult in developing countries [112,113].

4.2.3. Assessment of Socio–Economic Development

As research continuous deepens and expands, MS's interaction with the socio–economy transcends mere result data for exploring drivers, analyzing correlations, identifying decoupling, and predicting the future. MS now serves as input data for revealing socio–economic development status. It intertwines with population, society, economy, and ecology to reflect new urbanization [114], construction employment [115], urban–material heterogeneous growth [116] and unequal development [117].

4.3. MS and Resources Systems

4.3.1. Waste Management

MS represents not only current resources accumulation, but also potential waste at end–of–life, hence being called "urban mines" or "material banks" [6,60].

Currently, waste management research is increasingly integrated with MS research to predict waste, providing a scientific basis for planning. Using dynamic stock model and product lifetime distribution, they assessed the generation time, scale, composition, and spatial distribution of end–of–life products like buildings [118], roads [8], high–speed railways [119], and power grids [65]. And they explored the materials utilization potential, especially in metals like copper [120] and steel [121].

Rapid tech advancements accelerated the upgrading of electronic products and devices, resulting in three times more electronic waste (WEEE) than municipal solid waste [122].

WEEEs have garnered widespread attention due to their high economic value. Studies analyze waste scale and material composition of televisions [123], mobile phones [124], electric vehicle (EV) batteries [125,126], catalytic converters [57], and photovoltaic panels [127]. The recycling potential of high–value materials in WEEE like rare earth elements [125], platinum–group metals [127], and lithium [125,126] has also been analyzed.

4.3.2. Resource Availability

Resource supply relies on both unextracted reserves and the release capacity of in–use reserves [128]. MS, as a potential resource reserve, is crucial for evaluating overall availability of resources [6,76] by providing what, where, and when secondary resources are available. Current research focuses on strategic materials for high–tech, renewable energy (wind, solar, and tidal), and national defense [14].

Accelerated deployment of renewable energy facilities has surged demand for metals like copper, rare earths, gallium, and indium. Recent studies assess availability and supply risks of these and other materials (e.g., steel, silver, aluminum, nickel, neodymium, praseodymium, and dysprosium) across the entire industry chain, including mining, trade, in–use, end–of–life, and reuse [129]. As the automotive industry electrifies, metal demand for EV batteries rises. Existing research, combined with relevant policies, analyze supply–demand dynamics of metals like nickel [14] and lithium [130]. Additionally, several studies show copper demand will soar from 27 Mt in 2015 to 86–102 Mt in 2050 across power and transportation [131], posing a severe challenge.

4.4. MS and Environment Systems

4.4.1. Environmental Issues

MS accumulation and renewal require significant materials, labor, and production equipment, posing challenges to sustainable development. Mining, processing, and manufacturing of materials exacerbate global warming, harm health, and destroy biodiversity. Thus, academia has conducted extensive and in–depth research on MS's environmental impacts.

Some studies use lifecycle assessment to quantify MS's environmental impacts, including greenhouse gas emissions, energy consumption, water consumption, soil/air pollution and ecological damage. For example, gravel affects non–biological consumption and toxicity; cement impacts global warming and terrestrial ecology; asphalt affects non–biological resource depletion and ozone layer depletion. Fly ash toxicity is similar to asphalt, while materials like gravel, stone chips, lime, and mineral powder have minor impacts. Additionally, studies assess non–biological resource depletion of in–use stocks as resource reserves [132]. As global climate change worsens, more research focuses on MS–related carbon emissions, which account for 11% of global totals [133]. Currently, emissions from buildings [16], infrastructure [71], and vehicles [134] are calculated using carbon emission factors or lifecycle assessment.

Several studies used dynamic material flow analysis (DMFA), probabilistic DMFA, environmental fate modeling, and risk assessment to analyze chemical stocks like polybrominated diphenyl ethers, nanomaterials, and fluorinated polymers [135]. They evaluated exposure risks, accumulation, release, impacts, and concentration fluctuations in soil, water, and air throughout the product lifecycle [136].

4.4.2. Mitigating Climate Change

MS connects socio–economic and environmental systems, and its optimal allocation is crucial for sustainable development. Amid global challenges of low–carbon transformation and climate change, MS scientific management is vital strategy. Existing research explores two aspects: the Service–MS–Carbon Nexus, aiming to understand how various socio–

economic service affect carbon emissions through MS utilization efficiency and patterns, and the Energy–MS–Carbon Nexus, exploring how flows and stocks transition in the energy system affect carbon emissions.

Research on Service–MS–Carbon Nexus explores emission reduction in services through MS optimization, proposing circular economy strategies like design optimization, lifetime extension, process improvement, sharing–economy, energy–saving materials, and reuse/recycle. They have explored the reduction potential of these strategies in areas in buildings, vehicles, and infrastructure at the global [137], national [96], and city [16] scales.

Research on Energy–MS–Carbon Nexus highlights cleaner energy as a key to reducing carbon emissions [14,138]. Many countries are pursuing energy transformation through renewable energy and EVs. Studies on EV batteries [139], wind–power, and photovoltaics [138] offer insights into carbon mitigation, though not directly exploring their emission reduction potential.

4.4.3. The Impact of Environmental Degradation

Extreme weather events significantly affects MS development. MS in earthquake zones is highly vulnerable [140,141]. For instance, the Fukushima earthquake reduced Japan's building and road stocks by 31.80 Mt and 2.10 Mt, respectively [141]. Hurricanes and sea–level rise also impact coastal MS [142,143]. Per capita timber stocks grew by 172% and metals by 103% after Hurricane Ivan I in Grenada, and building stocks decreased by 135–216 Kt after Ivan II [143]. In Fiji, sea–level rise will submerge 4.5% of buildings by 2050 and 6.2% by 2100, resulting in an average annual loss of 26 Gg of concrete, 1.7 Gg of wood, and 1 Gg of steel [142].

5. Future Trends in MS Research

5.1. More Refined Spatio–Temporal Analysis

Currently, emerging technologies like big data, remote sensing, and machine learning, have accurately quantified MS's spatial distribution, significantly improving research resolution and data accuracy. However, there are still two main limitations to existing research. Firstly, because of data availability and ease of manipulation, most studies focus on buildings' spatio–temporal evolution, with few addressing power infrastructure and consumer durables. Secondly, research on product stocks has primarily focused on the material–level rather than the component–level [59,144]. Therefore, it is necessary to conduct more refined research by integrating emerging technologies.

In terms of spatial dimension, it is urgent to integrate high–resolution images with multi–source geodata to expand the spatial distribution of more types, such as photovoltaic and consumer durables, which is helpful in understanding what, where, and when secondary resources are available, thereby reducing supply risks and facilitating rational layout and trade of renewable resources. In terms of research object dimension, further focus should be placed on the component–level. On the one hand, reusing components is often more economical and environmentally friendly than reusing elementary materials, as it requires less energy [145]. In particular, more building components will be used in the future as the use of prefabrication technology rises [16]. On the other hand, components have shorter lifespans than products, requiring replacement or repair during the product's lifespan [77,144]. Therefore, emerging technologies like IoT and smart cities are being integrated to monitor dynamic changes in maintenance, updates, and recycling, extending product lifespan, alleviating climate pressure and promoting sustainability.

Thus, refined spatio–temporal analysis is essential to inform the formulation of circular economy policies and guide the optimization of resource management.

5.2. Building a Comparable Global Data Platform

As global climate change intensifies, there is an urgent need to strengthen cross–national cooperation and exchanges to effectively promote sustainability. To this end, sharing data, experiences, and research results is essential for deepening global MS studies, to addressing global climate challenges.

Academics have explored extensively, creating various MS databases like YSTAFDB [146], PMSFD [147], UPBIMS [148], and the MCIs database of China [55] and Dutch [76]. However, due to diverse purposes, data sources, methods, and material types, these databases lack unified standards and comparability, which directly limits cross regional comparisons and the construction of global material metabolism maps. While Myers et al. proposed the Unified Materials Information System (UMIS) [149], it is mainly based on Yale's research and has not been widely adopted.

Therefore, a comparable and widely recognized data–sharing platform is necessary. Standardization of data collection and accounting methods should be encouraged, as well as unifying the classification of materials. Further, developing a secure and open collaboration mechanism, encouraging research institutions from different countries to participate deeply, and improving data coverage and timeliness are also crucial. Building a global data platform not only enhances the systematic and refined level of MS research, but also supports global climate governance and sustainable policy–making.

5.3. Exploration of Evolution Mechanism

As accelerate economic transformation to tackle increasingly severe climate challenges and achieve sustainable development, with the rise of the 15–min city [150,151], it's crucial to adjust material composition and layout to adapt new development patterns. Thus, revealing MS's evolution mechanism is key to understanding its response to socio–economic and environmental dynamic changes.

Although existing studies have focused on the interaction between MS and socio–economic indicators [9,99,103], their analytical frameworks face two major limitations. First, many studies rely on constant coefficients or linear models to reveal the phased relationships with MS and socio–economy [102,109], ignoring intrinsic, nonlinear, and time–varying responses. Second, the fragmentation between systems limits a comprehensive understanding of complex interconnections between MS and other domains such as the economy, resources, and the environment. In reality, MS evolution is highly coupled across systems and involves feedback among multiple stakeholders. Moreover, interactions also occur across different types of stocks. For instance, building layout may influence roads [51], increases in building floor area can drive demand for durable goods, and changes in subway networks may shift transportation choices [103]. However, existing research only combines a few key indicators and simple models, failing to capture the nonlinear coupling and complex structural changes.

Thus, it is necessary to take a systematic perspective and comprehensively consider multidimensional factors to reveal MS's complex evolution. On the one hand, introduce dynamic and nonlinear modeling methods, such as system dynamics, to capture the dynamic characteristics of MS evolution over time, and combine spatial econometric techniques to analyze its spatio–temporal correlation with different development stages. On the other hand, construct a multi–system coupling analysis framework that comprehensively considers economic development indicators, resource constraints, and environmental pressures, and uses complex network models to identify key nodes and feedback mechanisms that drive MS evolution. Accurately capturing MS dynamic evolution can provide a scientific basis for formulating policies that are both time sensitive and system oriented.

5.4. Management of the Whole Industry Chain

MS connects upstream and downstream of the industrial chain, encompassing material extraction and processing, product's production and maintenance, and waste's recycling and treatment, with each activity affecting MS's scale and development. However, current research often focuses on isolated aspects within the industrial chain to addressing specific issues, such as waste management, environmental impacts or low–carbon materials, neglecting the entire chain or all stakeholders. For example, green–buildings promote eco–friendly materials [152], EVs drive lithium consumption, and reducing material loss improves efficiency [2]. Therefore, it is essential to systematically integrate the entire industrial chain, from consumer market dynamics to all stages of product lifecycle, until recycling and reuse, for optimal deployment and management.

Consequently, it is urgent to establish a systematic management mechanism that fully integrates MS's dynamic characteristics with the overall industrial chain operation process. Specifically, a dynamic monitoring system for MS can be constructed to achieve real–time tracking throughout the entire lifecycle, from raw material extraction to end–of–life product recycling. In parallel, an integrated information–sharing platform across the industrial chain should be established to promote coordination among upstream and downstream actors and to improve the efficiency of resource allocation. Moreover, MS–related indicators can be incorporated into the green performance evaluation framework, providing a quantitative basis for assessing resource utilization efficiency and associated environmental pressures. Realize the paradigm shift of MS management from "link control" to "whole–chain optimization", providing systematic support for solving resource constraints, climate crisis, and industrial upgrading problems.

5.5. Enhancing Action on Climate Change

MS, as a significant carbon emitter, has its management efficacy directly shaping the attainment of climate mitigation objectives. Some studies focus on emission reduction potential of building and infrastructure through material efficiency or circular economy strategies [16,139]. While renewable energy facilities like wind power, photovoltaics, and energy storage systems can reduce carbon emissions, their effectiveness in alleviating climate pressure remains uncertain. Currently, most research on renewable energy focuses on resource supply risks [14] and carbon emissions [148,153], lacking in–depth evaluation of their overall effectiveness on climate mitigation [98]. Therefore, future research should focus on evaluating the reduction potential of renewable energy facilities, especially in the context of global energy transition, and optimizing their deployment and synergizing efforts for global low–carbon goals.

To enhance MS's ability to respond to climate change, it is necessary to conduct a entire lifecycle climate benefit assessment and quantify the carbon emissions from construction to disposal. In particular, research on new energy facilities should be revised to ensure their net emission reduction contribution is authentic. Develop a comprehensive climate action framework that spans MS's entire lifecycle, including source control (material selection and design optimization), process optimization (enhancing operational efficiency), and end–of–life recycling (recovery and reuse of scrap), to support global energy transition and climate pressure mitigation.

5.6. Promoting Research on Two–Way Interaction with Other Systems

MS involves not only resource consumption but also is closely tied to socio–economic, resource, and environmental systems. Existing research focuses on the unidirectional relationship between MS and these systems, such as resource consumption, environmental impacts, and drivers, neglecting its socio–economic insights, resource management

support, and environmental response. MS indicates socio–economic issues like urban expansion [116], industrial layout, labor demand [115], and inequality [117]. It's also the supply and demand of resources, requiring raw materials and providing abundant secondary resources [6,60]. As global resources become scarce and unevenly distributed, the challenge is to allocate and utilize them efficiently. Additionally, socio–economic development relies heavily on MS's services, but MS has an effect on climate change at all stages of its lifecycle, including generation, maintenance, and disposal. A better understanding of how MS interacts with socio–economic, resource, and environmental systems will enable MS to be utilized and reduced effectively. Thus, future work should explore MS' bidirectional interaction with these systems to promote sustainable development, alleviate climate pressure, and ensure harmony between socio–economy and environment.

To achieve this goal, it may be necessary to break through the static and linear analysis limitations to explore the bidirectional interaction between MS and other systems. Developing a dynamic analysis framework that integrates MS with socio–economic, resource, and environmental systems can be combined with system dynamics and multi–agent modeling methods to simulate complex feedback relationships between different factors. In addition, the bidirectional effects of climate change and MS can also be explored using relevant economic models of climate change. Identifying MS's bidirectional interactions with the systems can enable systematic solutions to global challenges such as resource scarcity and climate change.

6. Conclusions

Based on 602 MS publications retrieved from the WoS database, this study comprehensively summarizes publication information, including volume, institution, journal, and collaboration network, and provides a comprehensive picture of the history, theme evolution, and future research directions. MS research has gained attention since the 2000s, evolving into a systematic and independent field with cross–fertilization of multiple themes, rich and diverse methods, and continuous expansion of contents. With the introduction of emerging technologies such as remote sensing and big data, MS research is rapidly evolving towards multi–scale and high resolution. From identifying resource and environmental problems associated with socio–economic development to actively seeking solutions to climate change, resource recycling, and low–carbon transformations, MS research has gradually evolved from identifying problems to solving them. However, MS research still faces many key challenges, including the need for finer research with higher spatio–temporal resolution, an in–depth revelation of the dynamic evolution mechanism, systematic elucidation of the complex feedback between MS and socio–economic environmental systems, and the establishment of a unified analytical framework across scales and regions. Thus, we have tentatively proposed potential directions for future MS research, aiming to transform MS research from knowledge accumulation to decision support, to enhance its capabilities in formulating sustainable development policies and promoting circular economy strategies, and to provide more support for global sustainable transformation.

This study has some limitations, excluding research in other languages or forms (e.g., early reports and books) due to search criteria that focused on English articles. However, by reviewing citations, we traced many historically significant and foundational studies, constructing a more complete research framework and thematic evolution, ensuring research depth and breadth. Future research can further broaden the scope of retrieval by exploring multilingual retrieval and incorporating more publication types for more comprehensive perspective.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/systems13070587/s1.

Author Contributions: Conceptualization, T.D. and Z.Y.; methodology, Z.Y.; software, Z.Y.; validation, X.Z., Y.C. and Z.Y.; formal analysis, Z.Y.; data curation, Z.Y.; writing—original draft preparation, Z.Y.; writing—review and editing, T.D. and Z.Y.; visualization, Z.Y.; supervision, T.D., X.Z. and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Humanities and Social Sciences Planning Fund Project of the Ministry of Education (21YJA790009), the China Postdoctoral Science Foundation (2023M730151), the Beijing Postdoctoral Research Foundation (2023-zz-157) and the National Natural Science Foundation of China Youth Program (No. 72304026).

Data Availability Statement: The data presented in this study are available within this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. International Energy Agency. *Global Energy and Climate Model*; International Energy Agency: Paris, France, 2022.
2. I.P.R. *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future*; United Nations Environment Programme: Nairobi, Kenya, 2020.
3. Pauliuk, S.; Heeren, N.; Berrill, P.; Fishman, T.; Nistad, A.; Tu, Q.; Wolfram, P.; Hertwich, E.G. Global Scenarios of Resource and Emission Savings from Material Efficiency in Residential Buildings and Cars. *Nat. Commun.* **2021**, *12*, 5097. [CrossRef] [PubMed]
4. Zhang, X.; Sun, J.; Zhang, X.; Fenglai, W. Statistical Characteristics and Scenario Analysis of Embodied Carbon Emissions of Multi-Story Residential Buildings in China. *Sustain. Prod. Consum.* **2024**, *46*, 629–640. [CrossRef]
5. Regona, M.; Yigitcanlar, T.; Hon, C.; Teo, M. Artificial Intelligence and Sustainable Development Goals: Systematic Literature Review of the Construction Industry. *Sustain. Cities Soc.* **2024**, *108*, 105499. [CrossRef]
6. Dai, T.; Yue, Z. The Evolution and Decoupling of In-Use Stocks in Beijing. *Ecol. Econ.* **2023**, *203*, 107606. [CrossRef]
7. Lanau, M.; Liu, G.; Kral, U.; Wiedenhofer, D.; Keijzer, E.; Yu, C.; Ehlert, C. Taking Stock of Built Environment Stock Studies: Progress and Prospects. *Environ. Sci. Technol.* **2019**, *53*, 8499–8515. [CrossRef] [PubMed]
8. Kloostra, B.; Makarchuk, B.; Saxe, S. Bottom-up Estimation of Material Stocks and Flows in Toronto's Road Network. *J. Ind. Ecol.* **2022**, *26*, 875–890. [CrossRef]
9. Deng, T.; Fu, C.; Zhang, Y. What Is the Connection of Urban Material Stock and Socioeconomic Factors? A Case Study in Chinese Cities. *Resour. Conserv. Recycl.* **2022**, *185*, 106494. [CrossRef]
10. Liu, Q.; Cao, Z.; Liu, X.; Liu, L.; Dai, T.; Han, J.; Duan, H.; Wang, C.; Wang, H.; Liu, J.; et al. Product and Metal Stocks Accumulation of China's Megacities: Patterns, Drivers, and Implications. *Environ. Sci. Technol.* **2019**, *53*, 4128–4139. [CrossRef] [PubMed]
11. Pfaff, M.; Glöser-Chahoud, S.; Chrubasik, L.; Walz, R. Resource Efficiency in the German Copper Cycle: Analysis of Stock and Flow Dynamics Resulting from Different Efficiency Measures. *Resour. Conserv. Recycl.* **2018**, *139*, 205–218. [CrossRef]
12. Ren, Z.; Jiang, M.; Chen, D.; Yu, Y.; Li, F.; Xu, M.; Bringezu, S.; Zhu, B. Stocks and Flows of Sand, Gravel, and Crushed Stone in China (1978–2018): Evidence of the Peaking and Structural Transformation of Supply and Demand. *Resour. Conserv. Recycl.* **2022**, *180*, 106173. [CrossRef]
13. Augiseau, V.; Barles, S. Studying Construction Materials Flows and Stock: A Review. *Resour. Conserv. Recycl.* **2017**, *123*, 153–164. [CrossRef]
14. Basuhi, R.; Bhuwalka, K.; Moore, E.A.; Diersen, I.; Malik, R.H.; Young, E.; Billy, R.G.; Stoner, R.; Ceder, G.; Müller, D.B.; et al. Clean energy demand must secure sustainable nickel supply. *Joule* **2024**, *8*, 2960–2973. [CrossRef]
15. Desing, H.; Widmer, R.; Bardi, U.; Beylot, A.; Billy, R.G.; Gasser, M.; Gauch, M.; Monfort, D.; Müller, D.B.; Raugei, M.; et al. Mobilizing Materials to Enable a Fast Energy Transition: A Conceptual Framework. *Resour. Conserv. Recycl.* **2024**, *200*, 107314. [CrossRef]
16. Yue, Z.; Dai, T. Circular Economy Strategies Research for Beijing Buildings in a Low-Carbon Future. *Sustain. Cities Soc.* **2024**, *116*, 105894. [CrossRef]
17. Gerst, M.D.; Graedel, T.E. In-Use Stocks of Metals: Status and Implications. *Environ. Sci. Technol.* **2008**, *42*, 7038–7045. [CrossRef] [PubMed]
18. Müller, E.; Hilty, L.M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **2014**, *48*, 2102–2113. [CrossRef] [PubMed]
19. Bao, Y.; Huang, Z.; Guo, Q.; Liu, Y. Spatial Calculation of Urban Built Environment Stock: Progress and Prospects. National Remote Sens. *Bulletin* **2022**, *26*, 1909–1919. [CrossRef]

20. Grossegger, D.; MacAskill, K.; Al-Tabbaa, A. A Critical Review of Road Network Material Stocks and Flows: Current Progress and What We Can Learn from It. *Resour. Conserv. Recycl.* **2024**, *205*, 107584. [CrossRef]
21. Fu, C.; Zhang, Y.; Deng, T.; Daigo, I. The Evolution of Material Stock Research: From Exploring to Rising to Hot Studies. *J. Ind. Ecol.* **2022**, *26*, 462–476. [CrossRef]
22. Yang, D.; Liu, J.; Li, Y.; Jia, Y.; Shi, F. A Review of Urban Building Stock Analysis for the Urban Management. *Chinese J. Environ. Manag.* **2019**, *11*, 88–93. [CrossRef]
23. Nasir, U.; Chang, R.; Omrany, H. Calculation Methods for Construction Material Stocks: A Systematic Review. *Appl. Sci.* **2021**, *11*, 6612. [CrossRef]
24. Chen, C.; Song, M. Visualizing a Field of Research: A Methodology of Systematic Scientometric Reviews. *PLoS ONE* **2019**, *14*, 223994. [CrossRef] [PubMed]
25. Chen, C.; Ibekwe-SanJuan, F.; Hou, J. The Structure and Dynamics of Cocitation Clusters: A Multiple-Perspective Cocitation Analysis. *J. Am. Soc. Info. Sci. Technol.* **2010**, *61*, 1386–1409. [CrossRef]
26. Fischer-Kowalski, M.; Hüttler, W. Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part I, 1860–1970. *J. Ind. Ecol.* **1998**, *2*, 61–78. [CrossRef]
27. Fischer-Kowalski, M.; Hüttler, W. Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part II, 1970–1998. *J. Ind. Ecol.* **1998**, *2*, 107–136. [CrossRef]
28. Bain, H.F. *The Rise of Scrap Metals. Mineral Economics*; Lectures under the Auspices of the Brooking Institution; McGraw-Hill: New York, NY, USA; London, UK, 1932.
29. Wolman, A. The Metabolism of Cities. *Sci. Am.* **1965**, *213*, 178–193. Available online: http://www.jstor.org/stable/24931120 (accessed on 9 July 2025). [CrossRef]
30. Ayres, R.U.; Kneese, A.V. Production, Consumption, and Externalities. *Am. Econ. Rev.* **1969**, *59*, 282–297.
31. Baccini, P.; Brunner, P.H. *Metabolism of the Anthroposphere*; Springer eBooks: Berlin/Heidelberg, Germany, 1991.
32. Baccini, P.; Brunner, P.H. *Regionaler Stoffhaushalt*; Spektrum Akademischer Verlag: Berlin/Heidelberg, Germany; Oxford, UK, 1996.
33. Voet, E.; Heijungs, R.; Mulder, P.; Huele, R.; Kleijn, R.; Oers, L. Substance Flows through the Economy and Environment of a Region Part Ii: Modelling. *Environ. Sci. Pollut. Res.* **1995**, *2*, 137–144. [CrossRef] [PubMed]
34. Voet, E.; Kleijn, R.; Oers, L.; Heijungs, R.; Huele, R.; Mulder, P. Substance Flows through the Economy and Environment of a Region Part i: Systems Definition. *Environ. Sci. Pollut. Res.* **1995**, *2*, 90–96. [CrossRef] [PubMed]
35. Voet, E.; Kleijn, R.; Huele, R.; Ishikawa, M.; Verkuijlen, E. Predicting Future Emissions Based on Characteristics of Stocks. *Ecol. Econ.* **2002**, *41*, 223–234. [CrossRef]
36. Graedel, T.E. The Contemporary European Copper Cycle: Introduction. *Ecol. Econ.* **2002**, *42*, 5–7. [CrossRef]
37. Johnson, J.; Schewel, L.; Graedel, T.E. The Contemporary Anthropogenic Chromium Cycle. *Environ. Sci. Technol.* **2006**, *40*, 7060–7069. [CrossRef] [PubMed]
38. Spatari, S.; Bertram, M.; Fuse, K.; Graedel, T.E.; Shelov, E. The Contemporary European Zinc Cycle: 1-Year Stocks and Flows. *Resour. Conserv. Recycl.* **2003**, *39*, 137–160. [CrossRef]
39. Elshkaki, A.; Voet, E.; Holderbeke, M.; Timmermans, V. The Environmental and Economic Consequences of the Developments of Lead Stocks in the Dutch Economic System. *Resour. Conserv. Recycl.* **2004**, *42*, 133–154. [CrossRef]
40. Müller, D.B. Stock Dynamics for Forecasting Material Flows—Case Study for Housing in the Netherlands. *Ecol. Econ.* **2006**, *59*, 142–156. [CrossRef]
41. Schiller, G. Urban Infrastructure: Challenges for Resource Efficiency in the Building Stock. *Build. Res. Inf.* **2007**, *35*, 399–411. [CrossRef]
42. Oguchi, M.; Kameya, T.; Yagi, S.; Urano, K. Product Flow Analysis of Various Consumer Durables in Japan. *Resour. Conserv. Recycl.* **2008**, *52*, 463–480. [CrossRef]
43. Meinel, G.; Hecht, R.; Herold, H. Analyzing Building Stock Using Topographic Maps and GIS. *Build. Res. Inf.* **2009**, *37*, 468–482. [CrossRef]
44. Gruen, A.; Behnisch, M.; Kohler, N. Perspectives in the Reality-Based Generation, Nd Modelling, and Operation of Buildings and Building Stocks. *Build. Res. Inf.* **2009**, *37*, 503–519. [CrossRef]
45. Tanikawa, H.; Hashimoto, S. Urban Stock over Time: Spatial Material Stock Analysis Using 4d-Gis. *Build. Res. Inf.* **2009**, *37*, 483–502. [CrossRef]
46. Takahashi, K.I.; Terakado, R.; Nakamura, J.; Adachi, Y.; Elvidge, C.D.; Matsuno, Y. In-Use Stock Analysis Using Satellite Nighttime Light Observation Data. *Resour. Conserv. Recycl.* **2009**, *55*, 196–200. [CrossRef]
47. Mastrucci, A.; Marvuglia, A.; Popovici, E.; Leopold, U.; Benetto, E. Geospatial Characterization of Building Material Stocks for the Life Cycle Assessment of End-of-Life Scenarios at the Urban Scale. *Resour. Conserv. Recycl.* **2017**, *123*, 54–66. [CrossRef]
48. Mesta, C.; Kahhat, R.; Santa Cruz, S. Geospatial Characterization of Material Stock in the Residential Sector of a Latin-american City. *J. Ind. Ecol.* **2018**, *23*, 280–291. [CrossRef]

49. Haberl, H.; Wiedenhofer, D.; Schug, F.; Frantz, D.; Virág, D.; Plutzar, C.; Gruhler, K.; Lederer, J.; Schiller, G.; Fishman, T.; et al. High-Resolution Maps of Material Stocks in Buildings and Infrastructures in Austria and Germany. *Environ. Sci. Technol.* **2021**, *55*, 3368–3379. [CrossRef] [PubMed]
50. Han, J.; Chen, W.; Zhang, L.; Liu, G. Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis. *Environ. Sci. Technol.* **2018**, *52*, 12122–12132. [CrossRef] [PubMed]
51. Mao, R.; Bao, Y.; Huang, Z.; Liu, Q.; Liu, G. High-Resolution Mapping of the Urban Built Environment Stocks in Beijing. *Environ. Sci. Technol.* **2020**, *54*, 5345–5355. [CrossRef] [PubMed]
52. Gao, X.; Nakatani, J.; Zhang, Q.; Huang, B.; Wang, T.; Moriguchi, Y. Dynamic Material Flow and Stock Analysis of Residential Buildings by Integrating Rural–Urban Land Transition: A Case of Shanghai. *J. Clean. Prod.* **2020**, *253*, 119941. [CrossRef]
53. Watari, T.; Yokoi, R. International Inequality in In-Use Metal Stocks: What It Portends for the Future. *Resour. Policy* **2021**, *70*, 101968. [CrossRef]
54. Yuan, L.; Lu, W.; Xue, F.; Li, M. Building Feature-based Machine Learning Regression to Quantify Urban Material Stocks: A Hong Kong Study. *J. Ind. Ecol.* **2023**, *27*, 336–349. [CrossRef]
55. Bao, Y.; Huang, Z.; Mao, R.; Liu, G.; Wang, H.; Yin, G. High-Resolution Mapping of Material Stocks in the Built Environment across 50 Chinese Cities. *Resour. Conserv. Recycl.* **2023**, *199*, 107232. [CrossRef]
56. Schug, F.; Frantz, D.; Wiedenhofer, D.; Haberl, H.; Virág, D.; Linden, S.; Hostert, P. High-resolution Mapping of 33 Years of Material Stock and Population Growth in Germany Using Earth Observation Data. *J. Ind. Ecol.* **2023**, *27*, 110–124. [CrossRef]
57. Liu, Z.; Saito, R.; Guo, J.; Hirai, C.; Haga, C.; Matsui, T.; Shirakawa, H.; Tanikawa, H. Does Deep Learning Enhance the Estimation for Spatially Explicit Built Environment Stocks through Nighttime Light Data Set? Evidence from Japanese Metropolitans. *Environ. Sci. Technol.* **2023**, *57*, 3971–3979. [CrossRef] [PubMed]
58. Yu, B.; Li, L.; Tian, X.; Yu, Q.; Liu, J.; Wang, Q. Material Stock Quantification and Environmental Impact Analysis of Urban Road Systems. *Transp. Res. Part D Transp. Environ.* **2021**, *93*, 102756. [CrossRef]
59. Dai, M.; Jurczyk, J.; Arbabi, H.; Mao, R.; Ward, W.; Mayfield, M.; Liu, G.; Tingley, D.D. Component-Level Residential Building Material Stock Characterization Using Computer Vision Techniques. *Environ. Sci. Technol.* **2024**, *58*, 3224–3234. [CrossRef] [PubMed]
60. Raghu, D.; Bucher, M.J.J.; Wolf, C. Towards a 'Resource Cadastre' for a Circular Economy—Urban-Scale Building Material Detection Using Street View Imagery and Computer Vision. *Resour. Conserv. Recycl.* **2023**, *198*, 107140. [CrossRef]
61. Yu, B.; Chen, Q.; Li, N.; Wang, Y.; Li, L.; Cai, M.; Zhang, W.; Gu, T.; Zhu, R.; Zeng, H.; et al. Life Cycle Assessment of Urban Road Networks: Quantifying Carbon Footprints and Forecasting Future Material Stocks. *Constr. Build. Mater.* **2024**, *428*, 136280. [CrossRef]
62. Wang, Z.; Wiedenhofer, D.; Stephan, A.; Perrotti, D.; Bergh, W.; Cao, Z. High-Resolution Mapping of Material Stocks in Belgian Road Infrastructure: Material Efficiency Patterns, Material Recycling Potentials, and Greenhouse Gas Emissions Reduction Opportunities. *Environ. Sci. Technol.* **2023**, *57*, 12674–12688. [CrossRef] [PubMed]
63. Guo, J.; Fishman, T.; Wang, Y.; Miatto, A.; Wuyts, W.; Zheng, L.; Wang, H.; Tanikawa, H. Urban Development and Sustainability Challenges Chronicled by a Century of Construction Material Flows and Stocks in Tiexi, China. *J. Ind. Ecol.* **2021**, *25*, 162–175. [CrossRef]
64. Mao, R.; Bao, Y.; Duan, H.; Liu, G. Global Urban Subway Development, Construction Material Stocks, and Embodied Carbon Emissions. *Humanit. Soc. Sci. Commun.* **2021**, *8*, 83. [CrossRef]
65. Li, S.; Wang, P.; Zhang, Q.; Li, J.; Cao, Z.; Li, W.; Chen, W. Monitoring China's Solar Power Plant in-Use Stocks and Material Recycling Potentials Using Multi-Source Geographical Data. *Resour. Conserv. Recycl.* **2025**, *212*, 107920. [CrossRef]
66. Liu, Y.; Song, L.; Wang, W.; Jian, X.; Chen, W. Developing a Gis-Based Model to Quantify Spatiotemporal Pattern of Home Appliances and e-Waste Generation—A Case Study in Xiamen, China. *Waste Manag.* **2022**, *137*, 150–157. [CrossRef] [PubMed]
67. Huang, Z.; Bao, Y.; Mao, R.; Wang, H.; Yin, G.; Wan, L.; Qi, H.; Li, Q.; Tang, H.; Liu, Q.; et al. Big Geodata Reveals Spatial Patterns of Built Environment Stocks across and within Cities in China. *Engineering* **2024**, *34*, 143–153. [CrossRef]
68. Heisel, F.; Mcgranahan, J.; Ferdinando, J.; Dogan, T. High-Resolution Combined Building Stock and Building Energy Modeling to Evaluate Whole-Life Carbon Emissions and Saving Potentials at the Building and Urban Scale. *Resour. Conserv. Recycl.* **2022**, *177*, 106000. [CrossRef]
69. Arehart, J.H.; Pomponi, F.; D'Amico, B.; Srubar, W.V. A New Estimate of Building Floor Space in North America. *Environ. Sci. Technol.* **2021**, *55*, 5161–5170. [CrossRef] [PubMed]
70. Yang, D.; Dang, M.; Guo, J.; Sun, L.; Zhang, R.; Han, F.; Shi, F.; Liu, Q.; Tanikawa, H. Spatial–Temporal Dynamics of the Built Environment toward Sustainability: A Material Stock and Flow Analysis in Chinese New and Old Urban Areas. *J. Ind. Ecol.* **2023**, *27*, 84–95. [CrossRef]
71. Shi, F.; Huang, T.; Tanikawa, H.; Han, J.; Hashimoto, S.; Moriguchi, Y. Toward a Low Carbon-Dematerialization Society. *J. Ind. Ecol.* **2012**, *16*, 493–505. [CrossRef]

72. Kleemann, F.; Lederer, J.; Rechberger, H.; Fellner, J. GIS-Based Analysis of Vienna's Material Stock in Buildings. *J. Ind. Ecol.* **2017**, *21*, 368–380. [CrossRef]
73. Guo, Z.; Hu, D.; Zhang, F.; Huang, G.; Xiao, Q. An Integrated Material Metabolism Model for Stocks of Urban Road System in Beijing, China. *Resour. Conserv. Recycl.* **2014**, *146*, 45–54. [CrossRef]
74. Heeren, N.; Fishman, T. A Database Seed for a Community-Driven Material Intensity Research Platform. *Sci. Data* **2019**, *6*, 23. [CrossRef] [PubMed]
75. Yang, D.; Guo, J.; Sun, L.; Shi, F.; Liu, J.; Tanikawa, H. Urban Buildings Material Intensity in China from 1949 to 2015. *Resour. Conserv. Recycl.* **2020**, *159*, 104824. [CrossRef]
76. Sprecher, B.; Verhagen, T.J.; Sauer, M.L.; Baars, M.; Heintz, J.; Fishman, T. Material Intensity Database for the Dutch Building Stock: Towards Big Data in Material Stock Analysis. *J. Ind. Ecol.* **2022**, *26*, 272–280. [CrossRef]
77. Dai, M.; Ward, W.O.C.; Arbabi, H.; Densley Tingley, D.; Mayfield, M. Scalable Residential Building Geometry Characterisation Using Vehicle-Mounted Camera System. *Energies* **2022**, *15*, 6090. [CrossRef]
78. Hu, S.; Zhang, Y.; Yang, Z.; Yan, D.; Jiang, Y. Challenges and Opportunities for Carbon Neutrality in China's Building Sector—Modelling and Data. *Build. Simul.* **2022**, *15*, 1899–1921. [CrossRef]
79. Renard, S.; Corbett, B.; Swei, O. Minimizing the Global Warming Impact of Pavement Infrastructure through Reinforcement Learning. *Resour. Conserv. Recycl.* **2020**, *167*, 105240. [CrossRef]
80. Zhang, R.; Guo, J.; Yang, D.; Shirakawa, H.; Shi, F.; Tanikawa, H. What Matters Most to the Material Intensity Coefficient of Buildings? Random Forest-based Evidence from China. *J. Ind. Ecol.* **2022**, *26*, 1809–1823. [CrossRef]
81. Murakami, S.; Oguchi, M.; Tasaki, T.; Daigo, I.; Hashimoto, S. Lifespan of Commodities, Part I. *J. Ind. Ecol.* **2010**, *14*, 598–612. [CrossRef]
82. Oguchi, M.; Murakami, S.; Tasaki, T.; Daigo, I.; Hashimoto, S. Lifespan of Commodities, Part II. *J. Ind. Ecol.* **2010**, *14*, 613–626. [CrossRef]
83. Cao, Z.; Liu, G.; Duan, H.; Xi, F.; Liu, G.; Yang, W. Unravelling the Mystery of Chinese Building Lifetime: A Calibration and Verification Based on Dynamic Material Flow Analysis. *Appl. Energy* **2019**, *238*, 442–452. [CrossRef]
84. Aksözen, M.; Hassler, U.; Kohler, N. Reconstitution of the Dynamics of an Urban Building Stock. *Build. Res. Inf.* **2017**, *45*, 239–258. [CrossRef]
85. Dunant, C.F.; Shah, T.; Drewniok, M.P.; Craglia, M.; Cullen, J.M. A New Method to Estimate the Lifetime of Long-Life Product Categories. *J. Ind. Ecol.* **2020**, *25*, 321–332. [CrossRef]
86. Held, M.; Rosat, N.; Georges, G.; Pengg, H.; Boulouchos, K. Lifespans of Passenger Cars in Europe: Empirical Modelling of Fleet Turnover Dynamics. *Eur. Transp. Res. Rev.* **2021**, *13*, 9. [CrossRef] [PubMed]
87. Zhilyaev, D.; Cimpan, C.; Cao, Z.; Liu, G.; Askegaard, S.; Wenzel, H. The Living, the Dead, and the Obsolete: A Characterization of Lifetime and Stock of Ict Products in Denmark. *Resour. Conserv. Recycl.* **2021**, *164*, 105117. [CrossRef]
88. Schiller, G.; Müller, F.; Ortlepp, R. Mapping the Anthropogenic Stock in Germany: Metabolic Evidence for a Circular Economy. *Resour. Conserv. Recycl.* **2017**, *123*, 93–107. [CrossRef]
89. Wiedenhofer, D.; Fishman, T.; Plank, B.; Miatto, A.; Lauk, C.; Haas, W.; Haberl, H.; Krausmann, F. Prospects for a Saturation of Humanity's Resource Use? An Analysis of Material Stocks and Flows in Nine World Regions from 1900 to 2035. *Glob. Environ. Change* **2021**, *71*, 102410. [CrossRef]
90. Mcmillan, C.A.; Moore, M.R.; Keoleian, G.A.; Bulkley, J.W. Quantifying U.S. Aluminum in-Use Stocks and Their Relationship with Economic Output. *Ecol. Econ.* **2010**, *69*, 2606–2613. [CrossRef]
91. Cao, Z.; Shen, L.; Zhong, S.; Liu, L.; Kong, H.; Sun, Y. A Probabilistic Dynamic Material Flow Analysis Model for Chinese Urban Housing Stock. *J. Ind. Ecol.* **2018**, *22*, 377–391. [CrossRef]
92. Fishman, T.; Schandl, H.; Tanikawa, H. Stochastic Analysis and Forecasts of the Patterns of Speed, Acceleration, and Levels of Material Stock Accumulation in Society. *Environ. Sci. Technol.* **2016**, *50*, 3729–3737. [CrossRef] [PubMed]
93. Müller, D.B.; Wang, T.; Duval, B. Patterns of Iron Use in Societal Evolution. *Environ. Sci. Technol.* **2011**, *45*, 182–188. [CrossRef] [PubMed]
94. Zhang, L.; Yuan, Z.; Bi, J. Predicting Future Quantities of Obsolete Household Appliances in Nanjing by a Stock-Based Model. *Resour. Conserv. Recycl.* **2011**, *55*, 1087–1094. [CrossRef]
95. Pauliuk, S.; Wang, T.; Müller, D.B. Moving toward the Circular Economy: The Role of Stocks in the Chinese Steel Cycle. *Environ. Sci. Technol.* **2012**, *46*, 148–154. [CrossRef] [PubMed]
96. Song, L.; Ewijk, S.; Masanet, E.; Watari, T.; Meng, F.; Cullen, J.M.; Cao, Z.; Chen, W. China's Bulk Material Loops Can Be Closed but Deep Decarbonization Requires Demand Reduction. *Nat. Clim. Change* **2023**, *13*, 1136–1143. [CrossRef]
97. Yokoi, R.; Nakatani, J.; Hatayama, H.; Moriguchi, Y. Dynamic Analysis of In-Use Copper Stocks by the Final Product and End-Use Sector in Japan with Implication for Future Demand Forecasts. *Resour. Conserv. Recycl.* **2022**, *180*, 106153. [CrossRef]
98. Wang, L.; Qiu, T.; Zhang, M.; Cao, Q.; Qin, W.; Wang, S.; Wang, L.; Chen, D.; Wild, M. Carbon Emissions and Reduction Performance of Photovoltaic Systems in China. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114603. [CrossRef]

99. Chu, J.; Zhou, Y.; Cai, Y.; Wang, X.; Li, C.; Liu, Q. Flow and Stock Accumulation of Plastics in China: Patterns and Drivers. *Sci. Total Environ.* **2022**, *852*, 158513. [CrossRef] [PubMed]
100. Fishman, T.; Schandl, H.; Tanikawa, H. The Socio-Economic Drivers of Material Stock Accumulation in Japan's Prefectures. *Ecol. Econ.* **2015**, *113*, 76–84. [CrossRef]
101. Fu, C.; Zhang, Y.; Yu, X. How Has Beijing's Urban Weight and Composition Changed with Socioeconomic Development? *Sci. Total Environ.* **2019**, *675*, 98–109. [CrossRef] [PubMed]
102. Ding, Y.; Geng, X.; Wang, P.; Chen, W. How Material Stocks Sustain Economic Growth: Evidence from Provincial Steel Use in China. *Resour. Conserv. Recycl.* **2021**, *171*, 105635. [CrossRef]
103. Shen, L.; Yang, Q.; Yan, H. Spatial Characterization Analysis of Residential Material Stock and Its Driving Factors: A Case Study of Xi'an. *Buildings* **2023**, *13*, 581. [CrossRef]
104. Gontia, P.; Thuvander, L.; Wallbaum, H. Spatiotemporal Characteristics of Residential Material Stocks and Flows in Urban, Commuter, and Rural Settlements. *J. Clean. Prod.* **2020**, *251*, 119435. [CrossRef]
105. Lwin, C.M.; Dente, S.M.R.; Wang, T.; Shimizu, T.; Hashimoto, S. Material Stock Disparity and Factors Affecting Stocked Material Use Efficiency of Sewer Pipelines in Japan. *Resour. Conserv. Recycl.* **2017**, *123*, 135–142. [CrossRef]
106. Augiseau, V.; Kim, E. Inflows and Outflows from Material Stocks of Buildings and Networks and Their Space-Differentiated Drivers: The Case Study of the Paris Region. *Sustainability* **2021**, *13*, 1376. [CrossRef]
107. Dombi, M.; Karcagi-Kováts, A.; Tóth-Szita, K.; Kuti, I. The Structure of Socio-Economic Metabolism and Its Drivers on Household Level in Hungary. *J. Clean. Prod.* **2018**, *172*, 758–767. [CrossRef]
108. Klinglmair, M.; Fellner, J. Historical Iron and Steel Recovery in Times of Raw Material Shortage: The Case of Austria during World War i. *Ecol. Econ.* **2011**, *72*, 179–187. [CrossRef]
109. Zhang, C.; Chen, W.; Liu, G.; Zhu, D. Economic Growth and the Evolution of Material Cycles: An Analytical Framework Integrating Material Flow and Stock Indicators. *Ecol. Econ.* **2017**, *140*, 265–274. [CrossRef]
110. Lin, C.; Liu, G.; Müller, D.B. Characterizing the Role of Built Environment Stocks in Human Development and Emission Growth. *Resour. Conserv. Recycl.* **2017**, *123*, 67–72. [CrossRef]
111. Dombi, M.; Harazin, P.; Karcagi-Kováts, A.; Aldebei, F.; Cao, Z. Perspectives on the Material Dynamic Efficiency Transition in Decelerating the Material Stock Accumulation. *J. Environ. Manag.* **2023**, *335*, 117568. [CrossRef] [PubMed]
112. Ding, Y.; Geng, X.; Liu, X.; Zhang, C.; Chen, W. Material Resource Decoupling Dilemma: Convergence and Traps of in-Use Stock Productivity in National Economy Development. *J. Environ. Manag.* **2024**, *351*, 119617. [CrossRef] [PubMed]
113. Yang, X.; Zhang, C.; Li, X.; Cao, Z.; Wang, P.; Wang, H.; Liu, G.; Xia, Z.; Zhu, D.; Chen, W. Multinational Dynamic Steel Cycle Analysis Reveals Sequential Decoupling between Material Use and Economic Growth. *Ecol. Econ.* **2024**, *217*, 108092. [CrossRef]
114. Song, L.; Zhang, C.; Han, J.; Chen, W. In-Use Product and Steel Stocks Sustaining the Urbanization of Xiamen, China. *Ecosyst. Health Sustain.* **2019**, *5*, 110–123. [CrossRef]
115. Liu, Q.; Liu, L.; Liu, X.; Li, S.; Liu, G. Building Stock Dynamics and the Impact of Construction Bubble and Bust on Employment in China. *J. Ind. Ecol.* **2021**, *25*, 1631–1643. [CrossRef]
116. Yang, M.; Liu, N.; Li, Y.; Zhang, Y.; Wang, X.; Zhang, J. Using Material Flow and Stock Indicators to Evaluate Urban Allometry: Evidence from the Beijing–Tianjin–Hebei Region. *Ecosyst. Health Sustain.* **2023**, *9*, 84. [CrossRef]
117. Yang, N.; Gao, J.; Han, F.; Sun, M.; Yang, D.; Shi, F.; Zhang, L. The Material Stock Inequality in Chinese Rural Households. *Sustain. Prod. Consum.* **2023**, *41*, 179–186. [CrossRef]
118. Arora, M.; Raspall, F.; Cheah, L.; Silva, A. Buildings and the Circular Economy: Estimating Urban Mining, Recovery and Reuse Potential of Building Components. *Resour. Conserv. Recycl.* **2020**, *154*, 104581. [CrossRef]
119. Mao, R.; Wu, Y.; Chen, J.; Chen, P.; Li, X. Development Patterns, Material Metabolism, and Greenhouse Gas Emissions of High-Speed Railway in China. *Commun. Earth Environ.* **2023**, *4*, 312. [CrossRef]
120. Soulier, M.; Pfaff, M.; Goldmann, D.; Walz, R.; Geng, Y.; Zhang, L.; Tercero Espinoza, L.A. The Chinese Copper Cycle: Tracing Copper through the Economy with Dynamic Substance Flow and Input-Output Analysis. *J. Clean. Prod.* **2018**, *195*, 435–447. [CrossRef]
121. Wang, T.; Tian, X.; Hashimoto, S.; Tanikawa, H. Concrete Transformation of Buildings in China and Implications for the Steel Cycle. *Resour. Conserv. Recycl.* **2015**, *103*, 205–215. [CrossRef]
122. Islam, M.T.; Huda, N. E-Waste in Australia: Generation Estimation and Untapped Material Recovery and Revenue Potential. *J. Clean. Prod.* **2019**, *237*, 117787. [CrossRef]
123. Habib, K.; Mohammadi, E.; Vihanga Withanage, S. A First Comprehensive Estimate of Electronic Waste in Canada. *J. Hazard. Mater.* **2023**, *448*, 130865. [CrossRef] [PubMed]
124. München, D.D.; Stein, R.T.; Veit, H.M. Rare Earth Elements Recycling Potential Estimate Based on End-of-Life NdFeB Permanent Magnets from Mobile Phones and Hard Disk Drives in Brazil. *Minerals* **2021**, *11*, 1190. [CrossRef]
125. Hu, X.; Yan, X. Estimation of Critical Metal Consumption in Household Electrical and Electronic Equipment in the Uk, 2011–2020. *Resour. Conserv. Recycl.* **2023**, *197*, 107084. [CrossRef]

126. Schuster, V.; Ciacci, L.; Passarini, F. Mining the In-Use Stock of Energy-Transition Materials for Closed-Loop e-Mobility. *Resour. Policy* **2023**, *86*, 104155. [CrossRef]
127. Xun, D.; Hao, H.; Sun, X.; Liu, Z.; Zhao, F. End-of-Life Recycling Rates of Platinum Group Metals in the Automotive Industry: Insight into Regional Disparities. *J. Clean. Prod.* **2020**, *266*, 121942. [CrossRef]
128. Fishman, T.; Myers, R.; Rios, O.; Graedel, T.E.; Oak Ridge National Laboratory Ornl, O.R.T.U. Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States. *Resources* **2018**, *7*, 9. [CrossRef]
129. Deetman, S.; Boer, H.S.; Engelenburg, M.; Voet, E.; Vuuren, D.P. Projected Material Requirements for the Global Electricity Infrastructure-Generation, Transmission and Storage. *Resour. Conserv. Recycl.* **2021**, *164*, 105200. [CrossRef]
130. Sun, T.Y.; Bornhöft, N.A.; Hungerbühler, K.; Nowack, B. Dynamic Probabilistic Modeling of Environmental Emissions of Engineered Nanomaterials. *Environ. Sci. Technol.* **2016**, *50*, 4701–4711. [CrossRef] [PubMed]
131. Seck, G.S.; Hache, E.; Bonnet, C.; Simoën, M.; Carcanague, S. Copper at the Crossroads: Assessment of the Interactions between Low-Carbon Energy Transition and Supply Limitations. *Resour. Conserv. Recycl.* **2020**, *163*, 105072. [CrossRef] [PubMed]
132. Schneider, L.; Berger, M.; Finkbeiner, M. Anthropogenic Stock Extended Abiotic Depletion Potential (Aadp) as a New Parameterisation to Model the Depletion of Abiotic Resources. *Int. J. Life Cycle Assess.* **2011**, *16*, 929–936. [CrossRef]
133. United Nations Environment Programme. *Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2022.
134. Nakamoto, Y.; Nishijima, D.; Kagawa, S. The Role of Vehicle Lifetime Extensions of Countries on Global CO2 Emissions. *J. Clean. Prod.* **2019**, *207*, 1040–1046. [CrossRef]
135. Dien, N.T.; Hirai, Y.; Sakai, S. In-Use Polybrominated Diphenyl Ether (Pbde) Stocks and Atmospheric Emissions in Japan. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 1342–1350. [CrossRef]
136. Li, L.; Liu, O.; Hu, J.; Wania, F. Degradation of Fluorotelomer-Based Polymers Contributes to the Global Occurrence of Fluorotelomer Alcohol and Perfluoroalkyl Carboxylates: A Combined Dynamic Substance Flow and Environmental Fate Modeling Analysis. *Environ. Sci. Technol.* **2017**, *51*, 4461–4470. [CrossRef] [PubMed]
137. Zhong, X.; Hu, M.; Deetman, S.; Steubing, B.; Lin, H.X.; Hernandez, G.A.; Harpprecht, C.; Zhang, C.; Tukker, A.; Behrens, P. Global Greenhouse Gas Emissions from Residential and Commercial Building Materials and Mitigation Strategies to 2060. *Nat. Commun.* **2021**, *12*, 6126. [CrossRef] [PubMed]
138. Li, D.; Shen, L.; Zhong, S.; Elshkaki, A.; Li, X. Spatial and Temporal Evolution Patterns of Material, Energy and Carbon Emission Nexus for Power Generation Infrastructure in China. *Resour. Conserv. Recycl.* **2023**, *190*, 106775. [CrossRef]
139. Istrate, R.; Mas-Fons, A.; Beylot, A.; Northey, S.; Vaidya, K.; Sonnemann, G.; Kleijn, R.; Steubing, B. Decarbonizing Lithium-Ion Battery Primary Raw Materials Supply Chain. *Joule* **2024**, *8*, 2992–3016. [CrossRef]
140. Xin, G.U.; Yihan, C.H.; Lixiao, Z.H.; Yan, H.A. Urban Material Flow in Earthquake and Post-Disaster Reconstruction. *J. Beijing Norm. Univ. (Nat. Sci.)* **2021**, *57*, 555–562. [CrossRef]
141. Tanikawa, H.; Managi, S.; Lwin, C.M. Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami. *J. Ind. Ecol.* **2014**, *18*, 421–431. [CrossRef]
142. Merschroth, S.; Miatto, A.; Weyand, S.; Tanikawa, H.; Schebek, L. Lost Material Stock in Buildings Due to Sea Level Rise from Global Warming: The Case of Fiji Islands. *Sustainability* **2020**, *12*, 834. [CrossRef]
143. Symmes, R.; Fishman, T.; Telesford, J.N.; Singh, S.J.; Tan, S.Y.; Kroon, K. The Weight of Islands: Leveraging Grenada's Material Stocks to Adapt to Climate Change. *J. Ind. Ecol.* **2020**, *24*, 369–382. [CrossRef]
144. Arbabi, H.; Lanau, M.; Li, X.; Meyers, G.; Dai, M.; Mayfield, M.; Tingley, D.D. A Scalable Data Collection, Characterization, and Accounting Framework for Urban Material Stocks. *J. Ind. Ecol.* **2022**, *26*, 58–71. [CrossRef]
145. Arora, M.; Raspall, F.; Cheah, L.; Silva, A. Residential Building Material Stocks and Component-Level Circularity: The Case of Singapore. *J. Clean. Prod.* **2019**, *216*, 239–248. [CrossRef]
146. Myers, R.J.; Reck, B.K.; Graedel, T.E. YSTAFDB, a Unified Database of Material Stocks and Flows for Sustainability Science. *Sci. Data* **2019**, *6*, 84. [CrossRef] [PubMed]
147. Song, L.; Han, J.; Li, N.; Huang, Y.; Hao, M.; Dai, M.; Chen, W. China Material Stocks and Flows Account for 1978–2018. *Sci. Data* **2021**, *8*, 303. [CrossRef] [PubMed]
148. Li, X.; Song, L.; Liu, Q.; Ouyang, X.; Mao, T.; Lu, H.; Liu, L.; Liu, X.; Chen, W.; Liu, G. Product, Building, and Infrastructure Material Stocks Dataset for 337 Chinese Cities between 1978 and 2020. *Sci. Data* **2023**, *10*, 228. [CrossRef] [PubMed]
149. Myers, R.J.; Fishman, T.; Reck, B.K.; Graedel, T.E. Unified Materials Information System (UMIS): An Integrated Material Stocks and Flows Data Structure. *J. Ind. Ecol.* **2019**, *23*, 222–240. [CrossRef]
150. Abbiasov, T.; Heine, C.; Sabouri, S.; Salazar-Miranda, A.; Santi, P.; Glaeser, E.; Ratti, C. The 15-Minute City Quantified Using Human Mobility Data. *Nat. Hum. Behav.* **2024**, *8*, 445–455. [CrossRef] [PubMed]
151. Barbieri, L.; D'Autilia, R.; Marrone, P.; Montella, I. Graph Representation of the 15-Minute City: A Comparison between Rome, London, and Paris. *Sustainability* **2023**, *15*, 3772. [CrossRef]

152. Zuo, J.; Zhao, Z. Green Building Research-Current Status and Future Agenda: A Review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 271–281. [CrossRef]
153. Lei, Y.; Xu, X.; Li, J.; Wang, H.; Yue, Q.; Chen, W. Material Flows and Embodied Carbon Emissions of Aluminum Used in China's Photovoltaic Industry from 2000 to 2020. *Resour. Conserv. Recycl.* **2024**, *215*, 108055. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.