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Battery chemistry mix predominantly explains disparities in critical material use for electric passenger vehicles

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Electric Vehicles (EVs) are vital for decarbonization but intensify critical material demand. Existing studies often fall short in precise assessments of material demand and its reduction potential due to overlooking real-world EV characteristics and their inherent spatial, segmental, and technological heterogeneity. To fill this gap, this study adopts a bottom-up multi-dataset fusion approach, providing high-resolution characterizations of segment mix, battery capacity, and battery chemistry mix across five passenger vehicle segments covering China's 31 provinces and 29 EU countries. Results indicate significant shifts of per-EV use of lithium, cobalt, and nickel between 2019 and 2023: −6%, −68%, −41% in China, and +15%, –25%, +29% in the EU, respectively. Battery chemistry mix emerges as a dominant factor, reducing cobalt use by 7.2 kg per vehicle in China and 3.6 kg in the EU, more than offsetting the increases attributable to the other characteristics, and explaining 38%–86% of the material use gaps between the two regions. The findings highlight critical pathways for reducing critical material demand through strategic technological choices and policy design.

Electric vehicles (EVs) are pivotal for decarbonizing transportation and mitigating climate change, with projections indicating their displacement of over 5 million barrels of oil per day by 2030[1]. However, vehicle electrification has triggered a surge in demand for critical battery materials: global EV battery demand reached 950 GWh in 2024, marking a 27% increase from 2023 and driving lithium demand to nearly 170 kt[1,2]. Moreover, the mining and refining of critical materials are highly geographically concentrated, with over 50% of global nickel mined in Indonesia and more than 60% of cobalt in the Democratic Republic of Congo[1]. The concentration raises growing concerns over the stability of critical material supply[3,4] and the adverse social and environmental impacts associated with mining[5]. Major EV markets have responded with measures, such as the European Union's (EU's) Critical Raw Materials Act setting targets for recycled content and limiting import dependence[6], China's qualification standards for battery recycling enterprises[7], and the United States' Inflation Reduction Act which incentivizes sourcing of critical minerals from allied nations[8]. Yet quantifying how much primary material demand can be cut through demand-side *reduction* strategies beyond reuse and recycling, such as avoiding excessive battery capacity and shifting to less material-intensive battery chemistries, is equally essential to enhance supply chain resilience and support sustainable electrification.

China and the European Union (EU) are the two largest EV markets in the world[9–11], consistently representing more than 70% of global EV battery demand[1]. However, their EV market characteristics, which substantially determine critical material use patterns, differ markedly. China has a higher share of affordable, smaller EVs[12] and predominantly uses lithium iron phosphate (LFP) batteries[13,14]. By contrast, the EU market emphasizes larger EVs, especially electric sport utility vehicles (e-SUVs)[15] and tends to adopt lithium nickel-cobalt-manganese oxide (NCM) batteries[13,14,16]. Recognizing these differences is the key to providing reliable critical material use estimates and identifying reduction potentials. Despite this, existing assessments of critical material use[17–19] have largely relied on commonly reported[20,21] aggregate EV characteristics, overlooking segment-level heterogeneity in both battery capacity and chemistry. Although segment-level

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battery capacity has received growing attention recently[1,22], chemistry differences across segments remain underexplored. Even where segment-level chemistry disaggregation has been achieved[23], the analysis remains geographically limited. Moreover, none of these studies quantify how these characteristics contribute to historical trends in material use, limiting the proposition of grounded reduction strategies.

To address this knowledge gap, this study builds upon our previously developed bottom-up multi-dataset fusion approach[24] and extends the high-resolution characterization of electric passenger vehicles in mainland China's 31 provinces (excluding Hong Kong, Macao, and Taiwan) and 29 EU countries (EU27 plus Iceland and Norway) to the period 2019–2023, covering segment mix, battery capacity, and battery chemistry mix across five passenger vehicle segments, dimensions rarely characterized jointly in prior work. Building on this, refined estimates of the lithium, cobalt, and nickel use from electric passenger vehicles are derived. Furthermore, we apply the Logarithmic Mean Divisia Index (LMDI) decomposition approach to systematically quantify how EV characteristics drive differences in material use both spatially and temporally across two major markets. Here we show that China's lithium, cobalt, and nickel use per battery electric vehicle (BEV) decreased by 6, 68, and 41% from 2019 to 2023, and ended up being 26–68% lower than that of the EU, both primarily due to its massive deployment of LFP batteries. At the sub-regional level, differences in critical material use are jointly driven by variations in battery chemistry mix and segment mix.

Results

Critical-material-related EV characteristics

Here we decompose critical material use per vehicle into impacts from three characteristics: (1) EV segment mix, (2) battery capacity, and (3) battery chemistry mix. To enable a high-resolution characterization of the three, we adopt a bottom-up approach developed in our previous study[24], in which vehicle trims (the smallest units defined by distinct specifications) are grouped into meta-categories along spatial, segmental, and powertrain dimensions. Trim-level specifications and sales data for BEVs and plug-in hybrid electric vehicles (PHEVs) are collected and aggregated through sales-weighted averaging to derive characteristics for each meta-category and higher-level classifications. To validate the bottom-up estimates, we follow the validation framework established in our previous study, which compares the results with top-down estimates derived from aggregated macro data reported by battery and EV manufacturers, and extend the comparison period to 2019–2023 (see Supplementary Tables S2 and S3). Notably, this study goes beyond the earlier work, which only provided the dataset, by offering a detailed analysis of the 2023 characteristics in the main text (with a summary of key results provided in Supplementary Table S4), while results for other years are presented in the Supplementary Information.

EV market penetration. Although this characteristic does not enter the per-vehicle material use calculation, it is presented to provide a more complete picture of EV development. Our bottom-up results indicate that the overall EV market penetration rates of passenger vehicles in China and the EU reached 34% and 24% in 2023, respectively. China outpaced the EU in both BEV (23% vs. 16%) and PHEV (11% vs. 8%) market penetrations. Contrasting segmental electrification patterns emerged in the two regions: China led electrification in the mini (China 100% vs. EU 19%) and small (China 51% vs. EU 8%) segments, while the EU excelled in the large (China 37% vs. EU 56%) and executive (China 39% vs. EU 46%) segments (Fig. 1a, b).

From a sub-regional perspective (Fig. 1c), Norway (86%), Sweden (61%), and Iceland (60%) were the top three European countries regarding EV market penetration; Croatia (5%), Slovakia (6%), and the Czech Republic (6%) ranked at the bottom. Hainan (54%), Shanghai (51%), and Guangxi (45%) were China's leading provinces, while Tibet (10%), Heilongjiang (13%), and Xinjiang (16%) represented the lowest. The BEV/PHEV (Fig. 1d, e) and small/large EV (Fig. 1f, g) market penetration rates at the sub-regional level generally mirror the overall comparison between China and the EU.

EV segment mix. With a special focus on segment mix, we find a completely different pattern between EVs and internal combustion engine vehicles (ICEVs) in both China and the EU. China exhibited higher shares of both large-end and small-end segments in EVs (52 and 16%) than in ICEVs (44 and 3%), with the medium EV segment squeezed (Fig. 2a). In the EU, large (C4) and executive (C5) segments held a larger share in EVs (52%) than in ICEVs (14%) (Fig. 2b), whereas smaller segments occupied a smaller share in EVs (15%) than in ICEVs (39%). This shows an overall lean towards large-end segments in the EU's EV sales compared to the ICEV sales.

Segment mix differences across sub-regions are particularly pronounced (Fig. 2c–f). In China, Guangxi had the highest share of mini (C1) and small (C2) EVs (44%) and the lowest share of large (C4) and executive (C5) EVs (26%). By contrast, Shanghai recorded the lowest share of mini and small EVs (1%), while Jilin had the highest share of large and executive EVs (81%). In the EU, Romania and Sweden exhibited the highest and lowest shares of mini and small EVs (38% and 2%, respectively), whereas Estonia and Malta had the highest and lowest shares of large and executive EVs (77% and 20%, respectively).

Battery capacity. Regarding sales-weighted average battery capacity, we can observe opposite patterns for BEVs and PHEVs in China and the EU (Fig. 3). The EU's sales-weighted average BEV battery capacity was 67 kWh, larger than that of China (55 kWh). Such distinction is mirrored across all segments, with the EU having 10% (C4)–74% (C1) larger battery capacity than China. For PHEVs, however, the comparison results are reversed: China exhibited higher battery capacities than the EU in all segments, with average capacities of 26 and 16 kWh, respectively. This is largely due to the prevalence of Extended-Range Electric Vehicles (EREVs)—a PHEV sub-category that accounted for 25% of China's PHEV sales but was negligible in the EU[2]. In Fig. 3d, the battery capacity distributions of large (C4) and executive (C5) PHEVs in China show peak sales at 30 and 40 kWh, primarily from EREVs like the AITO M7 and Deepal SL03 in the large segment, and the Li auto L-series in the executive segment (Fig. 3f).

Battery chemistry mix. In terms of battery chemistry, China and the EU have followed notably divergent paths. Figure 4a, b, shows such divergence by characterizing the market share of vehicles adopting lithium iron phosphate (LFP) batteries in China and the EU. For China, LFP was the predominant battery chemistry, powering 72% of BEVs and 63% of PHEVs in 2023. Although LFP batteries are often seen as best suited for affordable small-end EVs due to their lower cost, technological advancements have enabled LFP batteries to meet the requirements of most EV applications[1,25]—allowing them to increasingly replace NCM batteries in large-end segments: LFP batteries powered 59% of BEVs and 73% of PHEVs in the large (C4) segment, and 42% of BEVs in the executive (C5) segment, outpacing both NCM-M and NCM-H batteries within these categories in China. In contrast, the EU relied heavily on NCM batteries, powering 89% of BEVs and almost 100% of PHEVs (see Supplementary Figs. S49 and S50). The absence of LFP batteries is due to the supply side—EU automakers provided few to no LFP-based EV trims (5% in BEV, almost 0% in PHEV, Fig. 4d, f), leaving consumers with limited options.

Critical material use

Among the reported four EV characteristics, we exclude market penetration and combine only those related to material use (segment mix, battery capacity, and battery chemistry) with the material intensity dataset[26] to calculate the critical material use (lithium, cobalt, and nickel) associated with battery production on a per-vehicle basis. The differences in material use are decomposed using the LMDI decomposition approach into contributions from the aforementioned three characteristics to identify the key driver. Compared with PHEVs, BEVs exhibit higher sales volumes (twofold in both China and the EU) and larger battery capacities (twofold in China and

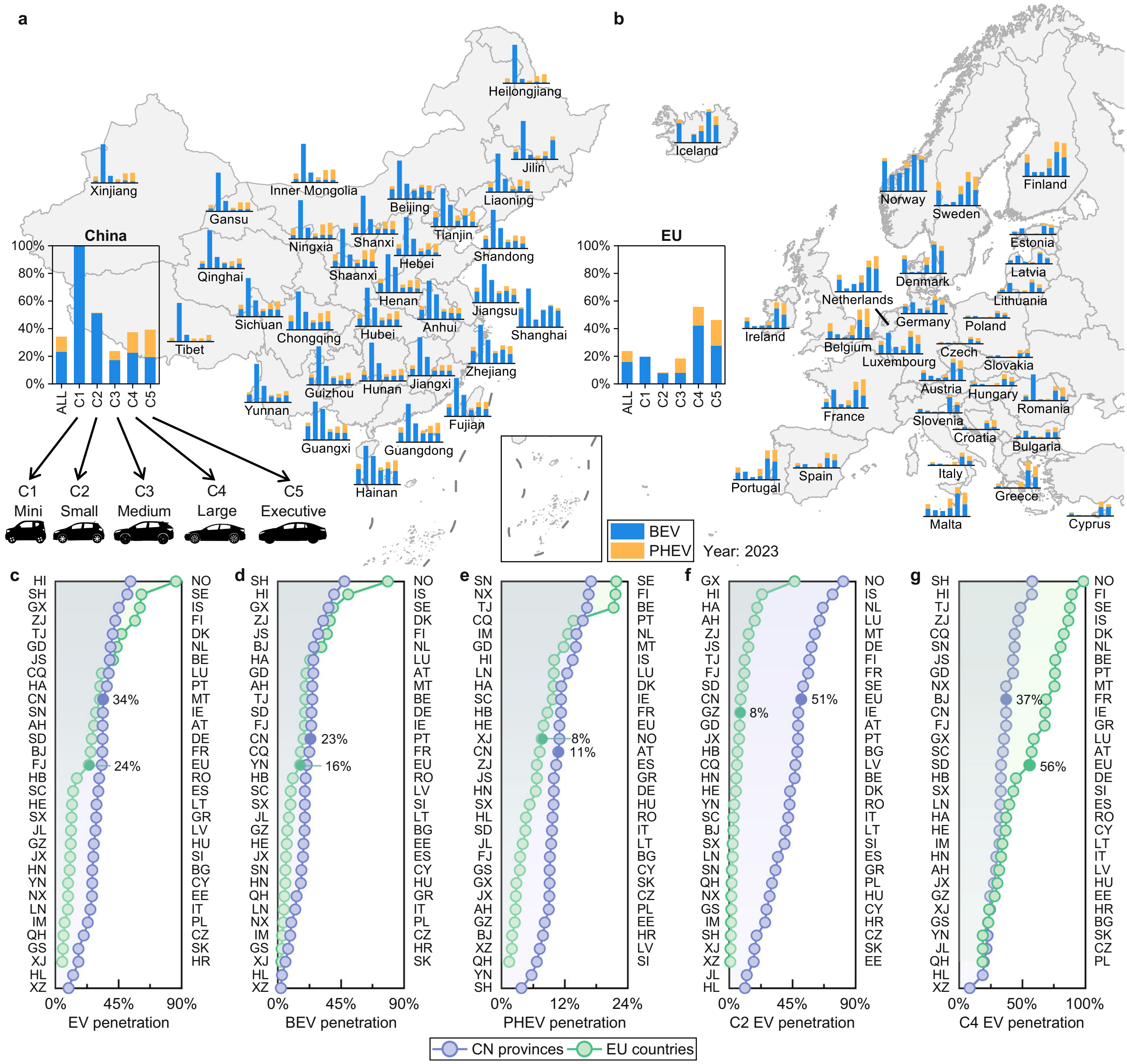


Fig. 1 | EV market penetration overview in China and the EU in 2023. EV market penetration in China (**a**) and the EU (**b**) in 2023; the rankings of overall EV market penetration (**c**), BEV market penetration (**d**), PHEV market penetration (**e**), EV market penetration in the small (C2) segment (**f**), and EV market penetration in the large (C4) segment (**g**). In **a**, **b**, the market penetration rates are characterized at the provincial level for China and the member-state level for the EU, respectively. The market penetration rates are provided for passenger vehicles as a whole and the segments from mini to executive (C1–C5, graphically shown in the lower left corner). The market penetrations of BEVs and PHEVs are separately provided. In **c**–**g**, the two dotted lines are for China (purple) and the EU (green), respectively. The dots on the lines represent sub-regions, specifically provinces for China and member states for the EU. The full names of the abbreviations are shown in Supplementary Table S1. All data presented in this figure are for 2023; specific market penetration rates for these sub-regions during 2019–2022 are provided in Supplementary Figs. S1–S12. The EV market penetration rate of the mini (C1) segment has reached 100% across all provinces in China, with a detailed explanation provided in Supplementary Note S1. EV electric vehicle, BEV battery electric vehicle, PHEV plug-in hybrid electric vehicle.

fourfold in the EU), leading to greater material impacts. In addition, as the primary pathway for full electrification, BEVs have higher charging dependence and stronger infrastructure requirements. Therefore, we focus on BEV in the main text (Figs. 5 and 6) and provide results for PHEV in Supplementary Figs. S62 and S63. For EREVs, which account for a notable share of PHEVs in China, additional results are presented in Supplementary Figs. S61, S76, and S77. Notably, to assess the robustness of the results, uncertainty analyses are conducted to account for uniform material intensity assumptions and data-processing-related uncertainties. Analyses include an extended LMDI decomposition incorporating material intensity differences and Monte Carlo simulations to derive uncertainty ranges of material use and characteristic contributions. Details are provided in the Supplementary Methods, with results shown in Supplementary Figs. S70–S77.

Our results indicate that in 2023, electric passenger vehicle batteries in China consumed a total of 36.3 kt of lithium, 16.9 kt of cobalt, and 89.0 kt of nickel, and those in the EU consumed 15.6, 15.9, and 78.4 kt, respectively. On a per-vehicle basis, the average lithium, cobalt, and nickel use per BEV was 6.1, 2.8, and 13.7 kg in China, 8.2, 7.9, and 42.6 kg in the EU. The major reason behind the per-vehicle difference is battery chemistry, in particular, accounting for 86% and 83% of the differences in cobalt and nickel use, respectively. Even when accounting for uncertainties in material intensity,

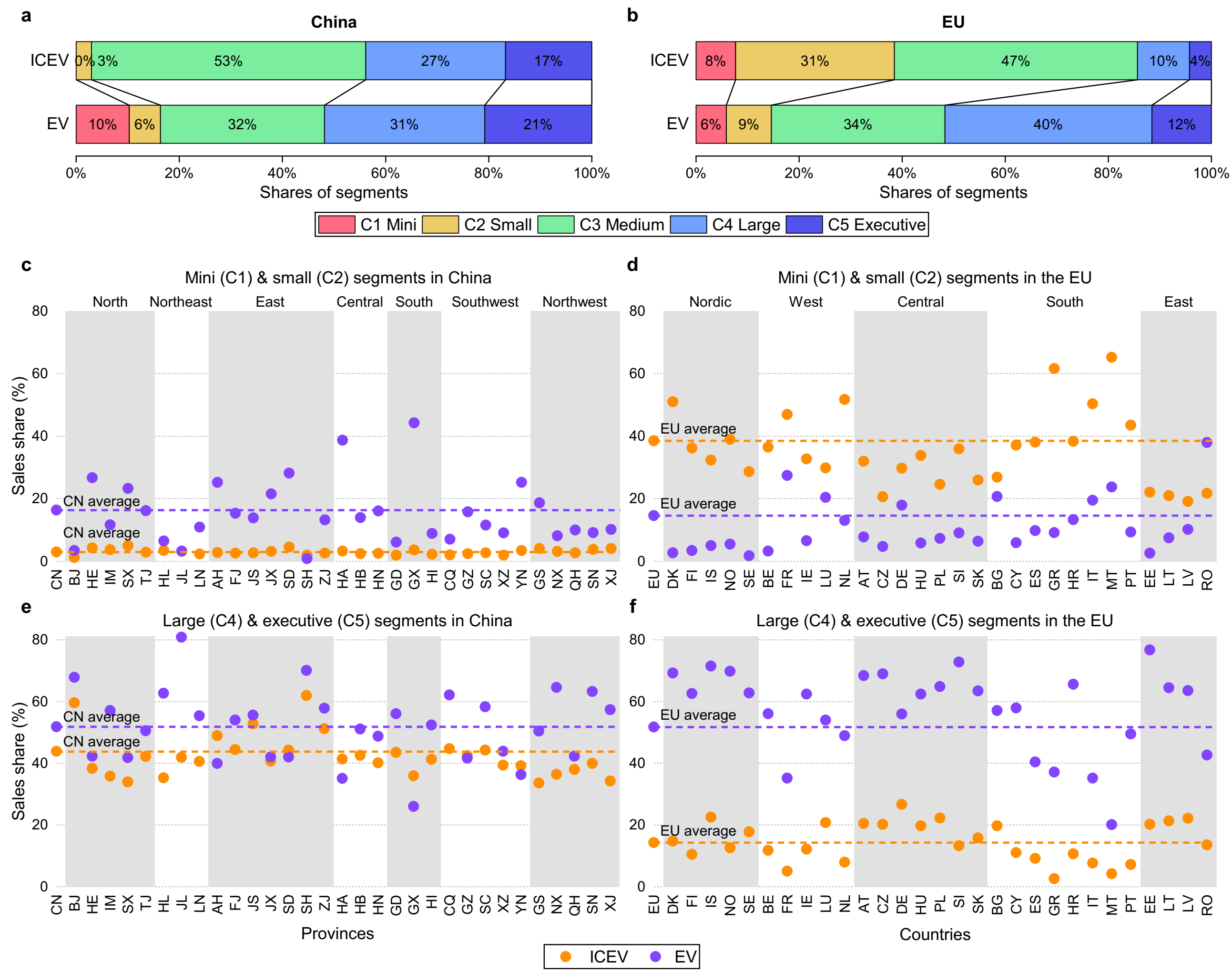


Fig. 2 | Breakdown of ICEV and EV sales by vehicle segments in China and the EU in 2023. Vehicle sales breakdown by segments (segment mix) for ICEVs and EVs in China (**a**) and the EU (**b**), 2023; market share of mini (C1) and small (C2) segments in ICEVs and EVs in China (**c**) and the EU (**d**); market share of large (C4) and executive (C5) segments in ICEVs and EVs in China (**e**) and the EU (**f**). In **c**–**f**, Chinese provinces and EU countries are divided into 7 and 5 groups by geographical proximity. The dashed lines indicate the average market shares in China and the EU. All data presented in this figure are for 2023; segment mixes for China, the EU, and their sub-regions during 2019–2022 are provided in Supplementary Figs. S13–S28. ICEV internal combustion engine vehicle, EV electric vehicle.

the contribution of battery chemistry to the China–EU differences remains substantial, with a lower bound of 3.5 kg for cobalt and 21 kg for nickel, still exceeding the maximum combined contribution of other characteristics (1.9 and 10 kg, respectively, see Supplementary Fig. S70). China's predominant use of LFP batteries, which are cobalt- and nickel-free, largely eliminates the reliance on these critical materials.

Sub-regional disparities in material use are also pronounced. For example, the Chinese provinces with the lowest and highest lithium use are Henan (4.2 kg) and Shanghai (7.8 kg), −31% and +28% compared to the national average. In the EU, the range is −22% to +16%, with Romania (6.4 kg) and Estonia (9.5 kg) representing the lowest and highest. Segment mix is the primary driver: mini and small segments accounted for 56% of all BEV sales in Henan, while only 1% in Shanghai and 54% in Romania, versus 4% in Estonia (see Supplementary Figs. S17 and S25). The battery chemistry mix also played a key role: France recorded the lowest cobalt use per BEV in the EU (6.3 kg, −20% compared to the EU average), with 75% of the difference attributable to its battery chemistry mix: a 15% adoption rate of LFP batteries—the highest among EU countries (see Supplementary Fig. S51). Notably, sub-regions with high material use per BEV, like Shanghai and Norway, are leading the regional electrification progress (Fig. 2). Given their higher market penetration rates, they usually serve as exemplary models for other sub-regions to follow. It is crucial for these leaders to manage their material impacts to show more positive guidance.

For the temporal changes in critical material use (Fig. 6), in China, the average lithium use per BEV decreased from 6.4 kg in 2019 to 5.6 kg in 2021, followed by a steady increase to 6.1 kg in 2023, mainly driven by changes in segment mix. In the EU, lithium use per BEV rose steadily from 7.1 kg in 2020 to 8.2 kg in 2023, primarily influenced by changes in battery capacity. Both China and the EU saw a downward trend in cobalt use per BEV from 2019 to 2023, falling from 8.8 to 2.8 kg (−68%) and from 10.6 to 7.9 kg (−25%), respectively. This decline was mainly attributed to changes in battery chemistry mix, which reduced cobalt use by 7.2 and 3.6 kg per vehicle in China and the EU, respectively, substantially outweighing the combined increases of 1.1 and 0.9 kg attributable to the other characteristics. The faster cobalt reduction in China resulted from a shift from NCM-M to LFP batteries (Supplementary Fig. S37), whereas the EU's shift toward NCM-H batteries (Supplementary Fig. S49) led to a slower decline.

The move toward LFP batteries and, alternatively, toward nickel-rich NCM batteries represents two distinct cobalt-reduction strategies, each affecting nickel use differently. In China, the transition to LFP batteries led to simultaneous reductions in both nickel and cobalt, with average nickel use

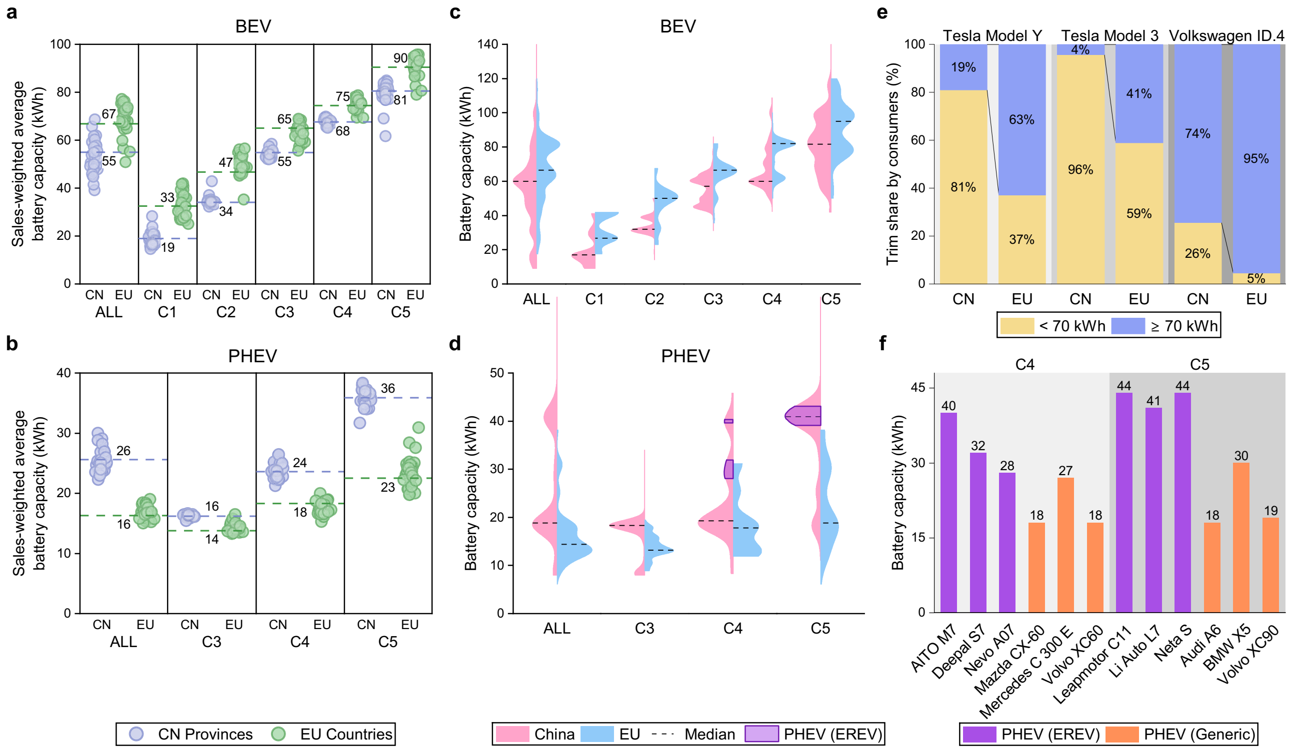


Fig. 3 | Sales-weighted average battery capacity by segment and trim-level battery capacity distribution and comparison in China and the EU in 2023. Sales-weighted average battery capacity of BEV (**a**) and PHEV (**b**), 2023; battery capacity distribution of BEV (**c**) and PHEV (**d**) trims; market share of trims with different battery capacities for three representative BEV models sold in both China and the EU (**e**); comparison of battery capacity between representative EREVs and generic PHEVs (**f**). In **a**, **b**, the dots denote China's provinces (purple) and the EU's member states (green). Dots are jittered to avoid overlap. The dashed purple and green lines depict the sales-weighted average battery capacity in China and the EU, respectively. In **c**, **d**, the half violins on the left and right represent the battery capacity distribution of trims in China and the EU, respectively. The half violins only cover trims with sales exceeding one thousand. In **d** the range of battery capacity that EREV predominantly occupies is highlighted in purple. In **e**, trims of the same model with different capacities are categorized according to whether the capacity size is less than 70 kWh. In **f**, the battery capacities of representative PHEV trims are displayed, labeled by their model names for clarity. All data presented in this figure are for 2023; sales-weighted average battery capacities for sub-regions during 2019–2022 are provided in Supplementary Figs. S29–S36. BEV battery electric vehicle, PHEV plug-in hybrid electric vehicle, EREV extended-range electric vehicle.

per BEV dropping from 23.3 kg in 2019 to 13.7 kg in 2023 (−41%). In contrast, the EU's cobalt reduction came at the cost of rising nickel use, driven by both battery chemistry mix (2019–2022) and segment mix (from 2020), reaching 40.7 kg in 2022. However, between 2022 and 2023, the EU's partial shift toward LFP batteries (4–9%, Supplementary Fig. S49) moderated the increase, with battery chemistry mix changes contributing for the first time to suppressing further nickel increases.

On average per PHEV, China exhibited a higher lithium and nickel use (2.8 and 9.4 kg) compared to the EU (2.2 and 8.8 kg; Supplementary Fig. S62), primarily due to its stronger preference for large-end segments (Supplementary Figs. S14 and S22) and higher average battery capacity (Supplementary Figs. S30 and S34). However, for cobalt, the EU's advantage in segment mix and battery capacity was outweighed by its battery chemistry mix, resulting in cobalt use of 3.2 kg, 129% higher than China's 1.4 kg. In terms of trends, the growing battery capacity within each segment drove material use upward notably in both China and the EU each year, though actual changes may vary due to other characteristics. Compared with generic PHEVs, EREVs in China are more oriented toward large segments, feature larger battery capacities, and exhibit a higher share of NCM-H rather than LFP batteries (Supplementary Fig. S61). As a result, EREVs show higher material use, reaching 4.6 kg of lithium, 3.4 kg of cobalt, and 25.7 kg of nickel, while China's generic PHEVs consume only 2.2, 0.7, and 3.3 kg, respectively, all of which are comparable to or no higher than the corresponding EU values (Supplementary Fig. S76). In terms of trends, China's generic PHEVs exhibit a clear shift toward LFP batteries, leading to substantial reductions in cobalt and nickel use (78% and 48%), whereas the decline for EREVs is less pronounced (Supplementary Fig. S77).

Discussion

Both China and the EU are under significant critical material supply challenges. In China, 65% of lithium, 98% of cobalt, and 93% of nickel rely on overseas sources[27]. The EU's reliance on imports of raw materials for lithium, cobalt, and nickel has remained around 80% over the past decade[28]. The comparisons of EV critical material use between these two regions and their sub-regions reveal opportunities for reducing critical material demand.

China's overall lower critical material use per EV than the EU is mainly due to its extensive adoption of LFP batteries. In 2023, China's EV LFP battery production capacity reached 403 GWh[29], surpassing the combined EV battery production capacity of the U.S. and Europe (180 GWh)[2]. Large-scale production has driven innovations that lower cell-level cost to 60 USD/kWh[30], boost cell-level specific energy to 240 Wh/kg[31], and enable a 400 km range after 10 min of charging[32]. EVs adopting LFP batteries are also favored by Chinese consumers, 80% of whom are aware of battery chemistry when making purchasing decisions[33], and prioritize the safety and cost-effectiveness that LFP offers[33,34]. As a result, the sales share of LFP-based trims exceeds their available share offered by automakers across all EV segments (Fig. 4c, e).

By contrast, EU automakers' reluctance to adopt LFP batteries likely stems from concerns over increasing dependence on China's supply chain[35], which currently dominates nearly 100% of global LFP cathode productions[2]. With its first LFP battery manufacturing facility only unveiled in 2023[36], the EU lacks the production capacity to catalyze comparable technology innovations. Rapidly scaling local LFP capacity through China's technology transfer and investment represents a potential strategy, though geopolitical tensions complicate such cooperation. While some progress has been made,

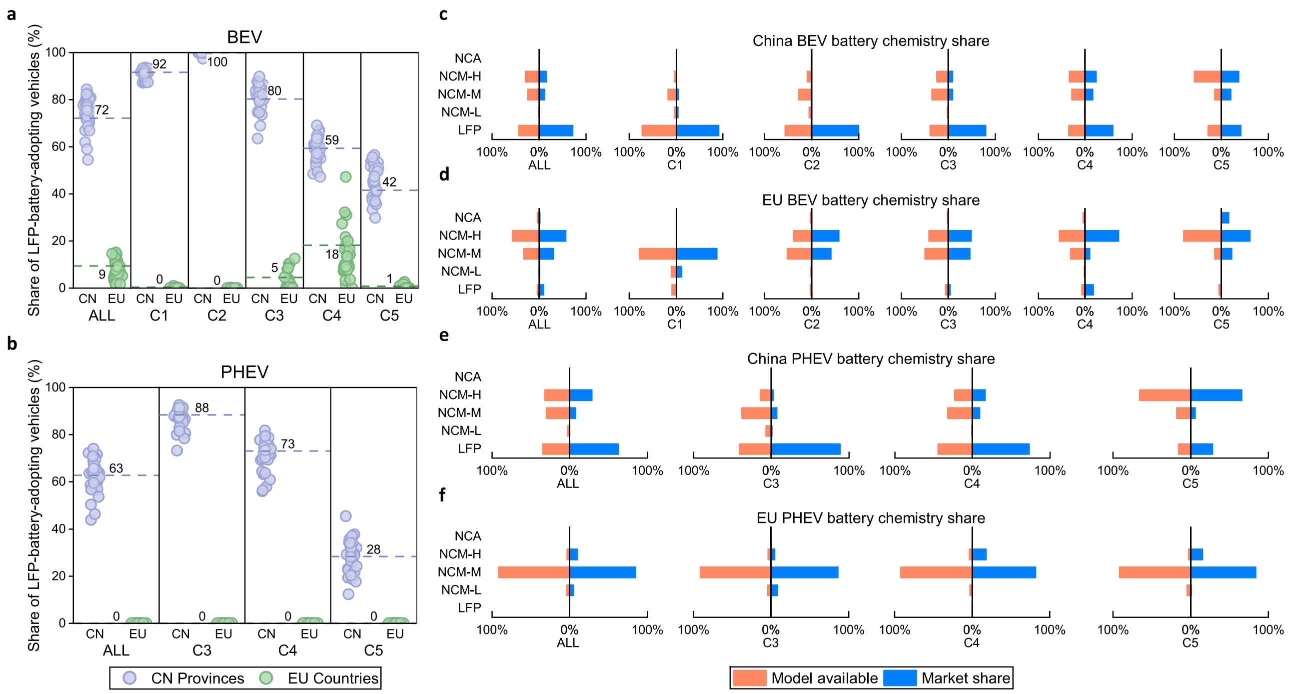


Fig. 4 | LFP battery adoption and battery chemistry distribution in China and the EU in 2023. Market share of LFP-battery-adopting vehicles in BEV (**a**) and PHEV (**b**), 2023; battery chemistry distribution of BEV (**c**) and PHEV (**d**) trims in China; battery chemistry distribution of BEV (**e**) and PHEV (**f**) trims in the EU. In **a**, **b**, the dots denote China's provinces (purple) and the EU's member states (green). Dots are jittered to avoid overlap. The dashed, purple, and green lines depict the aggregate values for China and the EU, respectively. In **c**–**f**, the bars on the left represent the battery chemistry distribution of available EV trims; the bars on the right represent the battery chemistry distribution of EV trim sales. Lithium manganese oxide battery (LMO) is not shown, as it held a very small percentage in all segments. All data presented in this figure are for 2023; battery chemistry mixes for sub-regions during 2019–2022 are provided in Supplementary Figs. S37–S60. BEV battery electric vehicle, PHEV plug-in hybrid electric vehicle. LFP lithium iron phosphate battery, NCM-L low-nickel content lithium nickel-cobalt-manganese oxide battery, NCM-M medium-nickel content lithium nickel-cobalt-manganese oxide battery, NCM-H high-nickel content lithium nickel-cobalt-manganese oxide battery, NCA nickel-cobalt-aluminum oxide battery.

such as Stellantis partnering with CATL for developing LFP batteries and establishing European Gigafactory[37], and AESC breaking ground on an LFP battery gigafactory in Spain[38], more such efforts face growing resistance. SVOLT canceled its German factory plan partially due to the EU's anti-subsidy investigations against Chinese EVs[39]. Farasis Energy suspended construction of its facility in Germany after years of regulatory hurdles[40]. Compounding these difficulties, China's recent revision of the Catalogue of Technologies Subject to Export Bans and Restrictions, effective July 2025, subjects LFP cathode preparation technologies with a compaction density of ≥2.58 g/cc to licensing requirements[41,42], with a further tightening to ≥2.50 g/cc proposed in October[43] and subsequently suspended[44], posing additional barriers to technology transfer. Enhancing bilateral dialogue is therefore essential: a mutual recognition agreement on battery technology standards could streamline licensing on both sides[45]. Meanwhile, South Korean manufacturers offer a complementary pathway: LG has signed a 5-year LFP battery supply agreement with Renault, and SK On targets LFP mass production by 2026[46]. Notably, Renault's dual-supplier model, sourcing from both CATL's Hungary plant and LG's Poland facility[46,47], illustrates how diversified partnerships can secure localized supply while managing geopolitical risk.

Beyond geopolitical constraints, LFP presents inherent limitations, such as capacity and power degradation in cold weather[48,49], reducing driving range and hill-climbing capability in such conditions. Their lower critical material content also challenges recycling economics, with recycling profits substantially below those of NCM batteries[50,51]. Nevertheless, toll-based recycling, whereby battery owners commission recyclers for a fee while retaining ownership of recovered materials, can decouple recycling viability from spot material prices, offering greater economic stability[1]. Alternative chemistries may further complement LFP by addressing its low-temperature limitations and offering the EU supply chain options less dependent on China. Sodium-ion batteries (SIBs) nearly eliminate the use of lithium, cobalt, and nickel[52], and exhibit superior low-temperature performance[53,54]. Moreover, SIBs offer a more diversified supply chain, with European startups, such as Sweden's Altris, advancing toward commercial-scale production using locally sourced materials[55,56]. However, current SIB deployments remain confined to small-end segments[57], and broader competitiveness with LFP battery will require improvements in energy density or sustained high lithium prices[1]. Solid-state batteries offer improved safety, higher energy density, and faster charging[58], but are likely to be commercialized initially through nickel-rich cathodes[59], leaving their critical material footprint still comparable to current NCM batteries. A variant employing silver–carbon (Ag–C) composite anodes achieves exceptional energy density and cycling stability[60], but would introduce significant new demand for silver, a metal already facing structural supply deficits[61,62].

The differences in average critical material use across sub-regions mainly stem from segment mix variations. Notably, numerous sub-regions exemplified high shares of small-end EVs through effective local efforts, serving as benchmarks for others. For example, in China's Guangxi province, mini (C1) and small (C2) BEVs account for 44% of the EV market, topping all provinces (Fig. 2e). This success has been summarized as the "Guangxi Mode"[63]. SAIC-GM-Wuling, the leading automaker in Guangxi province, developed China's best-selling mini BEV, the Baojun E-Series. Priced at USD 7000 and enabling an electric range of 100–200 km, this BEV model is well tailored to the price and utility demand balance of China's third- and fourth-tier city consumers[63]. The automaker attracted local consumers through large-scale test drives[63,64], while the local government developed tailored parking and charging incentives. For example, citizens were encouraged to identify available parking spaces, which were then designated specially for mini

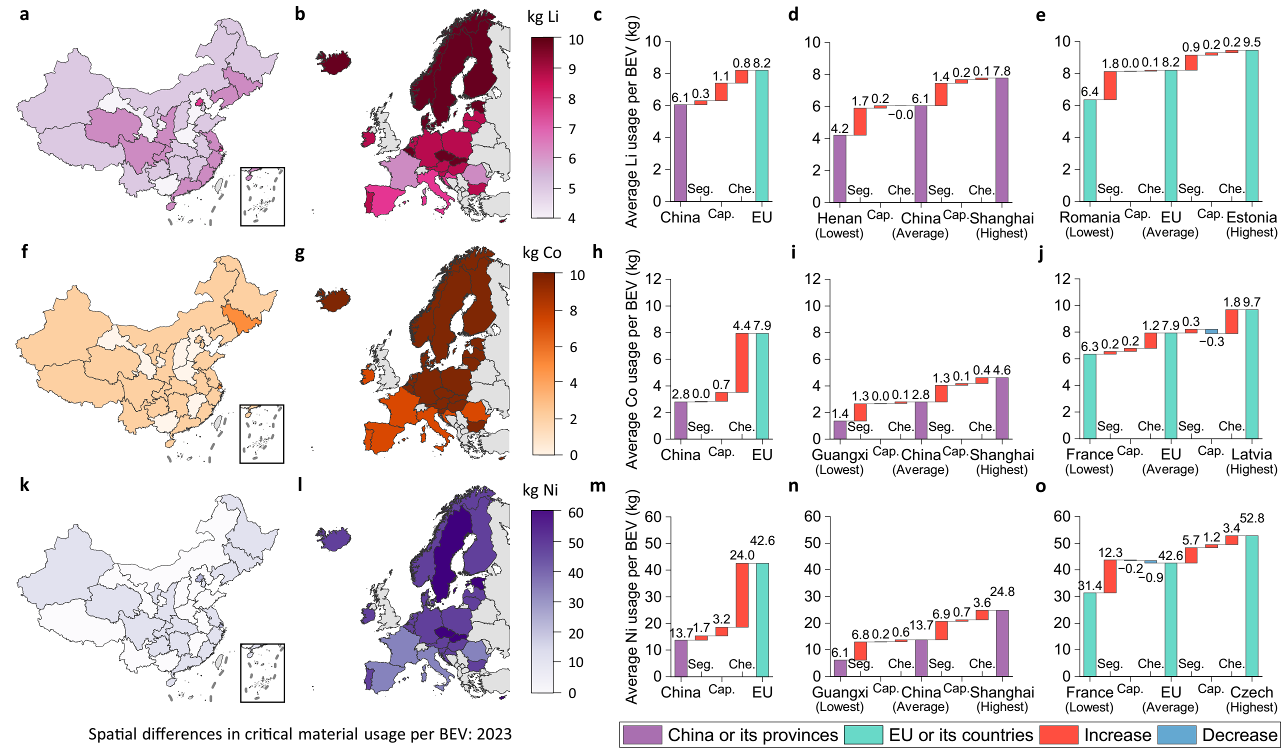


Fig. 5 | Lithium, cobalt, and nickel use per BEV in China and the EU in 2023, with LMDI decomposition of regional differences. Lithium/cobalt/nickel use from battery production per BEV in China (**a**, **f**, **k**) and the EU (**b**, **g**, **l**), 2023; LMDI decomposition of the differences between China and the EU (**c**, **h**, **m**), between China, and its lowest- and highest-use provinces (**d**, **i**, **n**), between the EU, and its lowest- and highest-use member states (**e**, **j**, **o**). The three critical materials are displayed using different color schemes, with darker colors indicating higher values. All data presented in this figure are for 2023; the average lithium, cobalt, and nickel use per BEV and per PHEV from 2019 to 2022, along with the corresponding LMDI decomposition results of material use differences between China and the EU, as well as across sub-regions in each year, are presented in Supplementary Figs. S64–S69. BEV battery electric vehicle, Li lithium, Co cobalt, Ni nickel, Seg. contribution attributable to differences in segment mix, Cap. contribution attributable to differences in battery capacity, Che. contribution attributable to differences in battery chemistry.

BEVs[63,64]. The government also provided cheap three-way charging sockets dedicated to charging these low-battery-capacity EVs[64]. Unsurprisingly, Guangxi emerged as the province with the lowest cobalt and nickel use per BEV in China (−50% and −54% compared to the national average, respectively, Fig. 5), primarily due to its advantageous segment mix. As a leading example in the EU, France's mini and small BEVs accounted for 33% of total EV sales (Fig. 2f), largely due to a range of effective incentives. It's "bonus écologique" incentivizes vehicles under 2.4 tons and discourages carbon-intensive large vehicles[65,66]. Paris increased parking fees for visiting SUVs, applicable to BEVs over 2000 kg[2]. Popular large and executive BEVs, like Volkswagen ID.4, are charged additional fees. All of this ultimately gave France the second-lowest lithium use and the lowest nickel use per BEV across the EU.

Although battery capacity plays a minor role compared to battery chemistry mix and segment mix in shaping material use, its notable difference between China and the EU highlights potential for further optimization. Chinese BEVs tend to have smaller batteries, a result of multiple factors. Infrastructure-wise, China's leading charging network—with a high public charger-to-vehicle ratio of 0.12 compared to the EU's 0.07[67]—alleviates consumers' range anxiety, thereby reducing their demand for larger batteries. As reflected in consumer choice (Fig. 3e), among various trims for Tesla Model Y, 63% of EU consumers chose the trims with longer range (battery capacity ≥ 70 kWh), while only 19% of Chinese consumers did so. Industrial policies also contributed: China implemented specific energy consumption limits for EVs[68], and incentivized energy-efficient EVs with higher credit in its dual-credit policy[69], which encourages automakers to reduce fuel consumption of ICEVs and produce EVs through a comprehensive credit system. These indirectly discouraged manufacturers from producing EVs with very large batteries that come with additional weight and energy consumption penalties. In contrast, the EU lacks comparable incentives. Some member states' policies even encouraged larger batteries, although unintentionally. For example, Denmark, which ranked fourth in average BEV battery capacity, subsidized EV purchases in proportion to their battery capacities[70], reducing the financial barrier for consumers to purchase EVs with larger batteries.

Conclusion

As the world's two largest EV markets, China and the EU have formed two distinct electrification pathways with varying material implications. Their differences stem from complex socio-economic, production, consumption, infrastructure, and policy contexts. While there is no simple answer as China or the EU is the way to follow, the measures we discuss to reduce material use have common implications for global electrification efforts, i.e., facilitating supply chain integration to ramp up LFP battery production capacity, promoting the diffusion of small-end EVs through synthesized business and policy efforts, constraining battery capacity with improved charging infrastructure and policy incentives, identifying best practice at the sub-region level, etc. The high-resolution bottom-up approach proposed in this study can be applied beyond China and the EU, allowing other countries to be informed about the material implications and improvement opportunities in their electrification process, and to identify the sub-regional best practices worthy of wider promotion.

Methods

This study adopts the bottom-up approach previously developed in our work[24] to derive EV market characteristics, which are further utilized in this

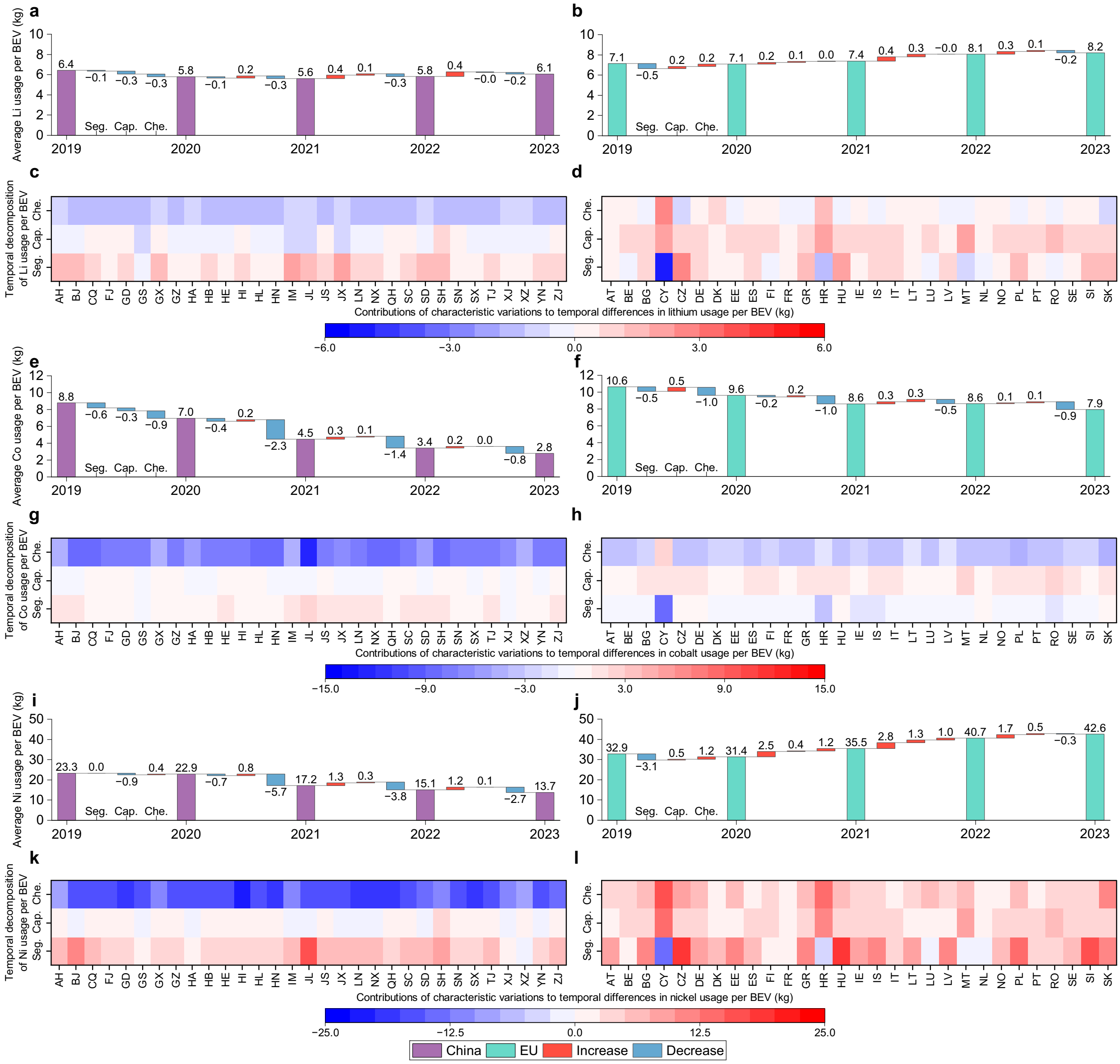


Fig. 6 | LMDI decomposition of annual differences in lithium, cobalt, and nickel use per BEV in China and the EU, 2019–2023. LMDI decomposition of the differences in lithium/cobalt/nickel use per BEV between China's annual values (**a**, **e**, **i**), between the EU's annual values (**b**, **f**, **j**); differences in lithium/nickel/cobalt use per BEV from 2019 to 2023 attributable to variations in three EV characteristics in Chinese provinces (**c**, **g**, **k**) and EU countries (**d**, **h**, **l**). BEV battery electric vehicle, Li lithium, Co cobalt, Ni nickel, Seg. contribution attributable to differences in segment mix, Cap. contribution attributable to differences in battery capacity, Che. contribution attributable to differences in battery chemistry.

study to calculate critical material use (Fig. 7) and conduct the subsequent LMDI decomposition, providing additional analytical insights beyond the previous work. We first collect the sales and characteristic information of the trims from different data sources, which are processed and supplemented to organize 60 × 5 × 12 meta-categories by spatial, segmental, and powertrain classifications. The EV market penetration, segment mix, sales-weighted average battery capacity, and battery chemistry mix characterization at the sub-regional level and the overall level are obtained by aggregating the meta-category estimations. By combining the EV market characteristics with existing material intensity datasets, the critical material use can be calculated.

All methods related to the EV market characterization, including the definition of geographical boundaries, data sources, data processing, trim classification (Fig. 8), and characteristic calculation, follow our previous study[24]. In this work, we extend the temporal boundary to 2019–2023 and provide a detailed analysis of EV market characteristics, which was not included in the earlier study that only presented the dataset and methodology. To effectively showcase the differences and trends in critical material use, we present EV market characteristics only for the latest available year, 2023. An illustrative analysis of the temporal evolution of EV market characteristics is provided in Supplementary Note S2.

Comparison of distribution characteristics between available trims and market sales

This paper compares the distribution differences between available trims and the actual market sales for the battery chemistry mix (Fig. 4c–f), an analysis not included in our previous work[24]. It is based on the assumption that vehicles registered in our database represent those available on the market, i.e., we exclude trims that may be on sale but have never been registered. In the characterization of battery chemistry mix, "the battery chemistry distribution of available EV trims" is calculated by counting the number of trims offered with each

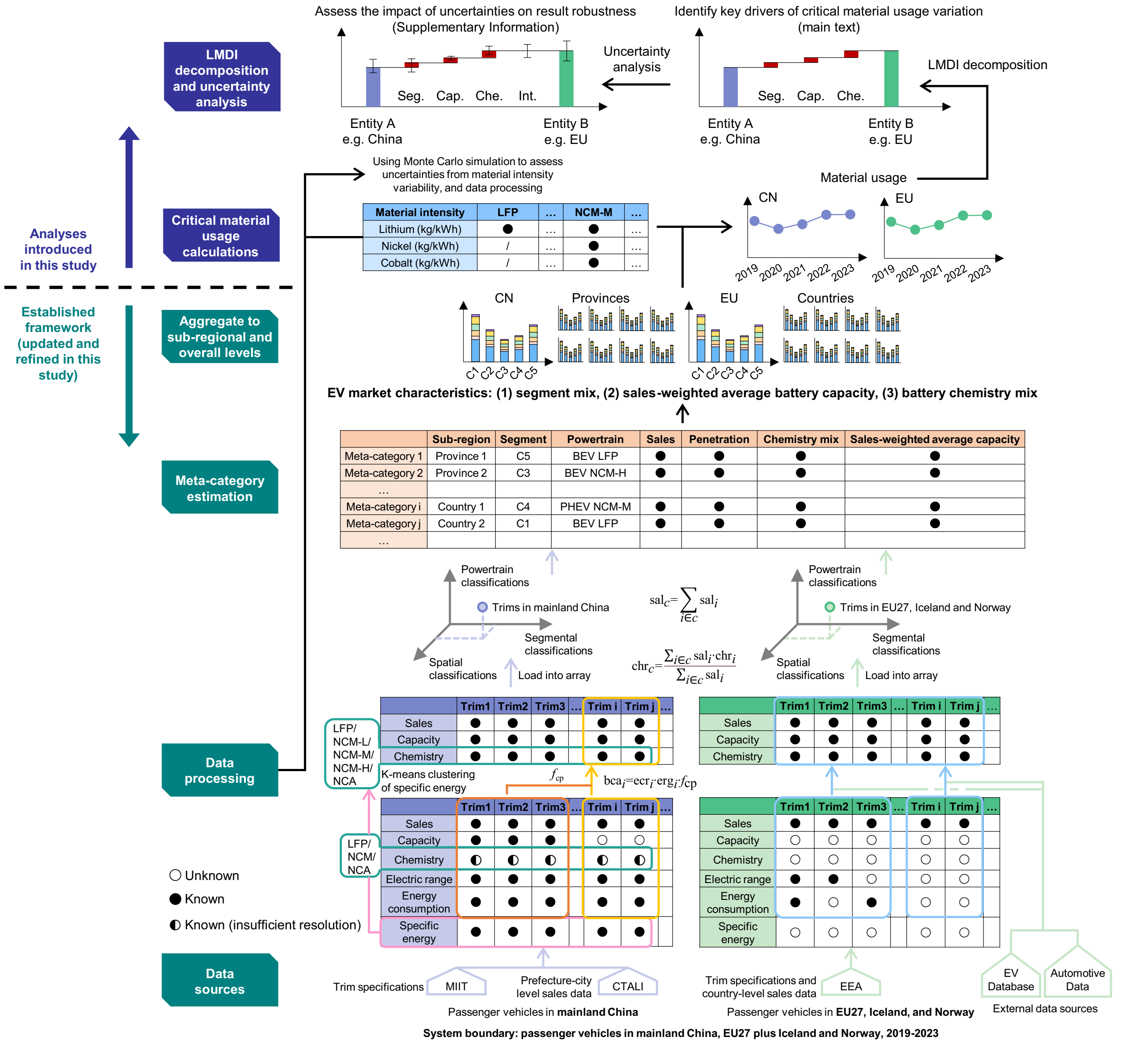


Fig. 7 | Schematic diagram of the bottom-up approach for estimating critical material use via EV market characterization derived from trim data, with subsequent LMDI decomposition and uncertainty analysis. The trim data are obtained from several databases, with solid circles in the table indicating that the trim possesses the characterization information, hollow circles indicating that the information is missing, and semi-solid circles indicating that the information is incomplete (e.g., the chemistry is NCM but cannot differentiate between the proportions of nickel, cobalt, and manganese). The processing of trim data, calculation of meta-category estimates, and the derivation of overall EV market characteristics follow our previous study[24], with key data processing procedures incorporating modest refinements based on improved data availability, detailed in the Supplementary Note S4 for ease of reference. Building on this, the critical material use can be calculated by combining the characteristics with existing material intensity datasets. Based on the estimated material use, differences between entities (e.g., China and the EU) are further decomposed using the LMDI method, yielding the contributions of segment mix, battery capacity, and battery chemistry to the overall differences, thereby identifying the main drivers. Considering that the use of a single material intensity may not capture real-world inter-entity variations, and that data processing introduces uncertainties related to battery chemistry, a Monte Carlo-based uncertainty analysis is conducted, with methods and results described in the Supplementary Information. MIIT the Ministry of Industry and Information Technology, CTALI China's Compulsory Traffic Accident Liability Insurance, EEA European Environment Agency, EV electric vehicle, BEV battery electric vehicle, PHEV plug-in hybrid electric vehicle, LFP lithium iron phosphate battery, NCM-L low-nickel content lithium nickel-cobalt-manganese oxide battery, NCM-M medium-nickel content lithium nickel-cobalt-manganese oxide battery, NCM-H high-nickel content lithium nickel-cobalt-manganese oxide battery, NCA nickel-cobalt-aluminum oxide battery, LMDI Logarithmic Mean Divisia Index, Seg. contribution attributable to differences in segment mix, Cap. contribution attributable to differences in battery capacity, Che. contribution attributable to differences in battery chemistry.

battery chemistry, with all trims weighted equally, reflecting the distribution of options available in the market. In contrast, "the battery chemistry distribution of EV trim sales" is calculated based on the number of units sold for each battery chemistry, showing the actual sales distribution.

Calculation of material use

We calculated sales-weighted average material use per vehicle based on three EV market characteristics in this study: (1) segment mix, (2) sales-weighted average battery capacity in each segment, and (3) battery chemistry mix in each segment. Their corresponding variables (seg_s, cap_s,

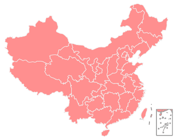
Dimension		Classification	Code/ Abbreviation	Notes
Spatial		 31 Chinese provinces and municipalities	Abbreviations using province initials (e.g., Beijing-BJ, Tibet-XZ)	Referring to the region where the vehicle is registered
		 27 EU member states, Iceland, and Norway	alpha-2 country code specified in ISO 3166 (e.g., Germany-DE, Greece-GR)	
Segmental		Mini	C1	Wheelbase (mm): C1 Mini / 2450 / C2 Small / 2600 / C3 Medium / 2750 / C4 Large / 2900 / C5 Executive. The five segments are delineated by four wheelbase thresholds, where vehicles with a wheelbase exceeding a given threshold are categorized into the next segment.
		Small	C2	
		Medium	C3	
		Large	C4	
		Executive	C5	
Powertrain	Overall configuration	Internal combustion engine vehicle	ICEV	Used exclusively for penetration rate calculation
		Plug-in hybrid electric vehicle	PHEV	Including extended-range electric vehicles (EREVs), which are compared with other generic PHEVs in the Supplementary Information
		Battery electric vehicle	BEV	
		Fuel cell electric vehicle	FCEV	Not considered in this study
	Battery chemistry	Lithium iron phosphate battery	LFP	Battery chemistry is distinguished by the cathode material. The anode material is graphite for all categories
		Lithium manganese oxide battery	LMO	
		Low-nickel content lithium nickel-cobalt-manganese oxide battery (N:C:M=1:1:1)	NCM-L	
		Medium-nickel content lithium nickel-cobalt-manganese oxide battery (N:C:M=6:2:2 or 5:2:3)	NCM-M	
		High-nickel content lithium nickel-cobalt-manganese oxide battery (N:C:M=7:1:2 or 8:1:1 or 9:0.5:0.5)	NCM-H	
		Nickel-cobalt-aluminum oxide battery	NCA	

Fig. 8 | Passenger vehicle classification scheme used in this study, based on prior work[24]. All vehicle trims are classified into corresponding meta-categories based on their registration location, wheelbase, and powertrain. The combination of these three dimensions results in 60 (31 provinces/municipalities in China, 27 EU member states, Iceland, and Norway) × 5 segments (wheelbase-defined) × 12 (combinations of overall powertrain configuration and battery chemistry). For example, BEVs registered in Guangdong province, belonging to the mini segment (C1), and equipped with LFP batteries, constitute one meta-category. As the classification of NCM batteries into NCM-L, NCM-M, and NCM-H under different proportion assumptions may introduce uncertainty, an uncertainty analysis accounting for this is described in the Supplementary Methods to derive uncertainty ranges of material use and characteristic contributions, thereby assessing the robustness of the results (Supplementary Figs. S70–S77).

che_{sj}) are calculated according to Eqs. 1–3. The sales-weighted average material use per vehicle can be derived from a series of multiplications and additions with the three characteristics and the material intensity (int_j), as shown in Eq. 4.

$$seg_s = \frac{sal_s}{\sum_s sal_s} \tag{1}$$

$$cap_s = \frac{\sum_j \sum_{i\in I_{sj}} cap_i \cdot sal_i}{\sum_j \sum_{i\in I_{sj}} sal_i} \tag{2}$$

$$che_{sj} = \frac{\sum_{i\in I_{sj}} cap_i \cdot sal_i}{\sum_j \sum_{i\in I_{sj}} cap_i \cdot sal_i} \tag{3}$$

$$usg = \sum_s \left(seg_s \cdot cap_s \cdot \sum_j che_{sj} \cdot int_j \right) \tag{4}$$

where,

sal_s is the sales volume of all vehicle trims in segment s;

seg_s is the ratio of sales for segment s to the total sales;

I_{sj} is the set of all vehicle trims in segment s with battery chemistry j;

sal_i is the sales volume of vehicle trim i in segment s with battery chemistry j;

cap_i is the battery capacity of vehicle trim i in segment s with battery chemistry j (kWh);

cap_s is the sales-weighted average battery capacity of all vehicle trims in segment s (kWh);

che_{sj} is the share of the battery installation of vehicle trims with battery chemistry j in the total battery installation of all vehicle trims in segment s;

int_j is the lithium/cobalt/nickel intensity of the battery chemistry j, referring to ref. 26 (kg/kWh);

usg is the average material use per vehicle (kg per vehicle), calculated on a sales-weighted basis.

LMDI decomposition of differences in material use

The differences in critical material use between China and the EU can be further attributed to the three EV market characteristics, offering reduction potential insights. Given the structure of the characteristic-related variables in Eq. 4, this study adopts the LMDI decomposition approach to decompose variations in critical material use. The LMDI decomposition approach is a dominant method within index decomposition analysis (IDA)[71], widely recognized for its desirable properties, such as perfect decomposition without residuals and the ability to handle zero values[72]. The approach allows for flexibility along three dimensions: (1) method type (LMDI-I vs. LMDI-II), (2) decomposition procedure (additive vs. multiplicative), and (3) aggregation indicator (quantity vs. intensity). In this study, we apply the LMDI-I method, use the additive decomposition procedure, and adopt the quantity indicator.

To facilitate decomposition, we define:

$$\text{cheint}_s = \sum_j \text{che}_{sj} \cdot \text{int}_j \tag{5}$$

where,

cheint_s is the average lithium/cobalt/nickel material intensity (in kg/kWh) at segment s, determined by the battery chemistry at that segment. Actually, cheint_s is jointly determined by the market share of each battery chemistry (che_{sj}), and the material intensity of each chemistry (int_j). In the main text, consistent with the prevailing assumption in the literature, we treat material intensity as invariant across regions, years, and vehicle trims for a given battery chemistry. Under this assumption, differences in int_j between entities are absent and therefore contribute nothing to the decomposition, such that the contribution of cheint_s reduces entirely to that of che_{sj}. Nevertheless, to assess the sensitivity of the main findings to potential cross-entity material intensity differences and to battery chemistry uncertainty arising from cross-database matching, we further decompose the contribution of cheint_s into the separate contributions of che_{sj} and int_j in the Supplementary Methods, with results from this extended LMDI decomposition reported in Supplementary Figs. S70–S77. In the main text, we retain cheint_s as the decomposition indicator, and Eq. 4 can be accordingly rewritten as:

$$\text{usg} = \sum_s \left(\text{seg}_s \cdot \text{cap}_s \cdot \text{cheint}_s\right) \tag{6}$$

Based on the additive decomposition method, the difference in material use between two entities can be decomposed into the sum of contributions from three EV market characteristics, as shown in Eqs. 7–10.

$$\Delta\text{usg} = \Delta\text{usgSE} + \Delta\text{usgCA} + \Delta\text{usgCH} \tag{7}$$

$$\Delta\text{usgSE} = \sum_s \left(\frac{\text{usg}_s^B - \text{usg}_s^A}{\ln\left(\text{usg}_s^B\right) - \ln(\text{usg}_s^A)} \ln\left(\frac{\text{seg}_s^B}{\text{seg}_s^A}\right) \right) \tag{8}$$

$$\Delta\text{usgCA} = \sum_s \left(\frac{\text{usg}_s^B - \text{usg}_s^A}{\ln\left(\text{usg}_s^B\right) - \ln(\text{usg}_s^A)} \ln\left(\frac{\text{cap}_s^B}{\text{cap}_s^A}\right) \right) \tag{9}$$

$$\Delta\text{usgCH} = \sum_s \left(\frac{\text{usg}_s^B - \text{usg}_s^A}{\ln\left(\text{usg}_s^B\right) - \ln(\text{usg}_s^A)} \ln\left(\frac{\text{cheint}_s^B}{\text{cheint}_s^A}\right) \right) \tag{10}$$

where,

Δusg is the total difference in material use per vehicle between entities A and B (kg per vehicle);

ΔusgSE is the contribution of differences in segment mix to the overall material use difference (kg per vehicle);

ΔusgCA is the contribution of differences in sales-weighted average battery capacity across segments to the overall material use difference (kg per vehicle);

ΔusgCH is the contribution of differences in battery chemistry across segments to the overall material use difference (kg per vehicle);

usg_s^A and usg_s^B are the material use at segment s for entities A and B, respectively (kg per vehicle);

seg_s^A and seg_s^B are the shares of total sales from trims in segment s for entities A and B, respectively;

cap_s^A and cap_s^B are the sales-weighted average battery capacities for trims within segment s for entities A and B, respectively (kWh);

cheint_s^A and cheint_s^B are the average material intensity for segments s of entities A and B (kg/kWh), determined by their respective market share of each battery chemistry, and their material intensity of each chemistry.

This study applies the LMDI decomposition to two types of comparisons:

(1) Cross-entity comparisons within the same year. For example, decomposing the difference in material use between China and the EU in 2023. In such cases, China is designated as entity A (the baseline), and the EU as entity B. The method is also used to compare a country/region with its sub-regions that exhibit the highest or lowest material use. In such cases, the entity with lower material use is treated as entity A (the baseline).

(2) Temporal comparisons for the same entity. For example, comparing China in 2020 (entity B) with China in 2019 (entity A). In these temporal comparisons, the earlier year is taken as the entity A (the baseline).

Validation

The validation follows the framework established in our previous study[24], with bottom-up results compared against existing top-down estimates, and extends the comparison period to 2019–2023 (see Supplementary Note S3 for details on the differences between the two approaches). Country-level EV market penetration rates are cross-checked against data from the International Energy Agency's Global EV Data Explorer (see Supplementary Table S2)[73]. Estimated battery installation capacities by battery chemistry for electric passenger vehicles in China are compared with available top-down numbers (see Supplementary Table S3).

Data availability

Detailed values of EV characteristics and critical material use per newly registered BEV/PHEV at both overall and sub-regional levels in China and the EU are available at https://doi.org/10.6084/m9.figshare.29552081. The EV market characteristics required for calculating material use were derived using a bottom-up multi-dataset fusion approach, based on trim-level vehicle registration and specification data, which can be obtained from the following databases: China's Compulsory Traffic Accident Liability Insurance (CTALI), the Ministry of Industry and Information Technology (MIIT), the European Environment Agency (EEA), EV Database (https://ev-database.org), and Automotive Data (https://www.auto-data.net/en).

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Author contributions
L.M., M.L. conducted the analysis and wrote the original draft. L.M., H.H. led the revision of the manuscript. X.S., F.M., Z.W., and J.E.T. reviewed and edited the paper. Y.G., H.H. provided guidance on the paper. H.H. supervised the work and secured funding for the project. L.M., Z.D., and H.L. provided data for the analysis. J.G., H.D., and Y.D. helped with the methodology. F.B., Z.L., and F.Z. reviewed the paper and provided suggestions.

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The authors declare no competing interests.

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