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Views & Comments

The Underestimated Role of the Heat Pump in Achieving China's Goal of Carbon Neutrality by 2060

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1. The crucial role of heating decarbonization in achieving carbon neutrality in China by 2060

The decarbonization of heating, in both buildings and industries, presents a major challenge and opportunity for China if the nation is going to meet its 2060 commitment to carbon neutrality. Currently, as shown in Fig. 1(a) [1], the buildings and industrial sectors share the largest proportion (more than 70%) of end-use energy demand in China. In the buildings sector, heating accounts for half of the energy demand [2]; in the industrial sector, 50%–70% of the energy demand is for process heating [3]. As summarized in Fig. 1(b) [3], heating demand in the buildings sector usually requires temperatures below 80 °C; in different areas of the industrial sector—including but not limited to distillation, drying, and dyeing—the heating demand ranges across various temperatures that are mainly lower than 170 °C. On average, more than 40% of industrial heat consumption falls below 150 °C [4].

Therefore, as shown in Fig. 1(c), it can be preliminarily calculated that China's heat-related energy demand is greater than 42.7 exajoules (EJ; equal to 10^{18} joules), which accounts for 41% of China's end-use energy demand in 2020. Typically heating demand less than 150 °C is defined as a "low-and-medium-temperature" heat demand, China's low-and-medium-temperature heat demand adds up to more than 24.2 EJ, which accounts for more than 23% of China's end-use energy demand in 2020. Moreover, as shown in Fig. 1(d) [1], for the building sector, the end-use energy demand was 23.7 EJ in 2020 [5] and will increase to 33.6 EJ by 2060 [1], with most of the heating demand being for a temperature lower than 100 °C.

China's industrial end-use energy demand in 2060 is predicted to be less than that in 2020. At present, 41.75% of industrial process heating, on average, is below 150 °C; and there would be an even higher proportion of industrial process heating is below 150 °C in developed countries due to a different industrial structure (e.g., 53.5% in United Kingdom) [4]. With the upgrading and restructuring of China's industrial sector, it is expected that the proportion of low-and-medium-temperature heat consumption in the industrial sector will further increase. Such prediction indicates that more attention should be paid to low-and-medium-temperature demands—especially in the industrial sector, which is usually regarded as demanding higher temperatures and is considered as difficult to decarbonize [6]. At present, fossil fuels still dominate China's heating market, with coal-based district heating and coal-/gas-based boilers as the mainstream solutions for building and industrial heating, respectively [7]—both of which are emissions-intensive. Considering the large proportion of low-and-medium-temperature demand, electric resistance heating may be overqualified to meet these heat demands due to its relatively lower energy efficiency, whereas heat pumps may be a more techno-economically feasible solution, as they can absorb low-grade heat from waste heat or even ambient heat for a higher energy efficiency.

2. Summary of and prospect for heat pump research and application

Among various heating decarbonization technologies [8–10], the heat pump is a well-established technology based on the inverse Carnot cycle and has been used for more than 200 years. As shown in Fig. 2(a), when combined with clean electricity and a "free" heat source (e.g., ambient air, underground sources, or waste heat flux), a heat pump produces almost no emissions during its operation period. The coefficient of performance (COP) is usually adopted to evaluate heat-related facilities, especially electricity-driven vapor compression heat pumps. The COP is the ratio between the heat supply and the work consumed (i.e., electric consumption). A higher COP indicates higher efficiency, lower energy (power) consumption, and thus lower operating costs. The COP of heat pumps is always greater than one, because they pump "free" heat from a low-temperature heat source to a high-temperature heat sink. Therefore, heat pump technology can be the most energy-efficient option in comparison with other heating solutions.

As summarized in Fig. 2(b), state-of-the-art heat pumps can supply temperatures of up to 168 °C [11–13], while their heating capacity can reach up to 18 MW [14]. At this performance range, putting aside techno-economic concerns, as mentioned above, heat

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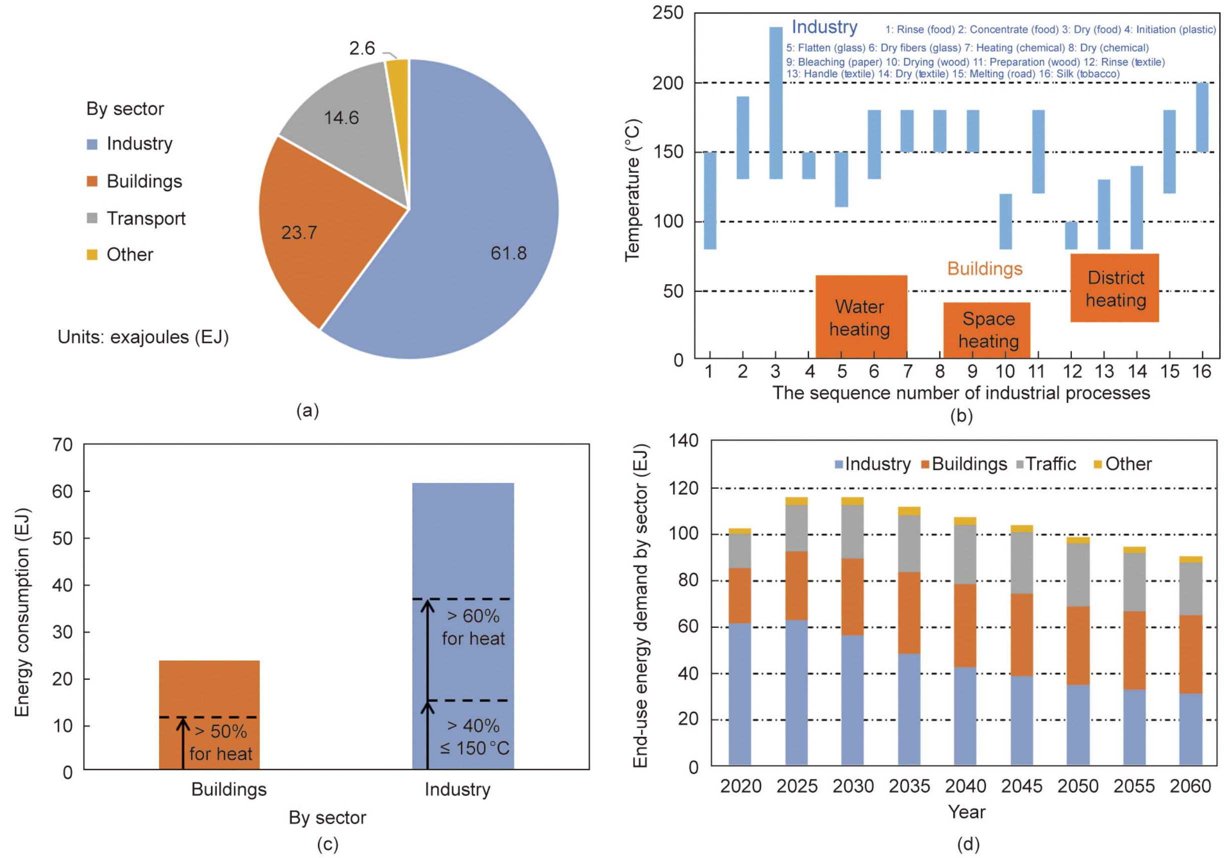

Fig. 1. Current end-use energy demand in China. (a) End-use energy demand in China in 2020 [1]; (b) heat temperature range in buildings and industries [3]; (c) heat-related end-use energy demand; (d) projection of end-use energy demand in China [1].

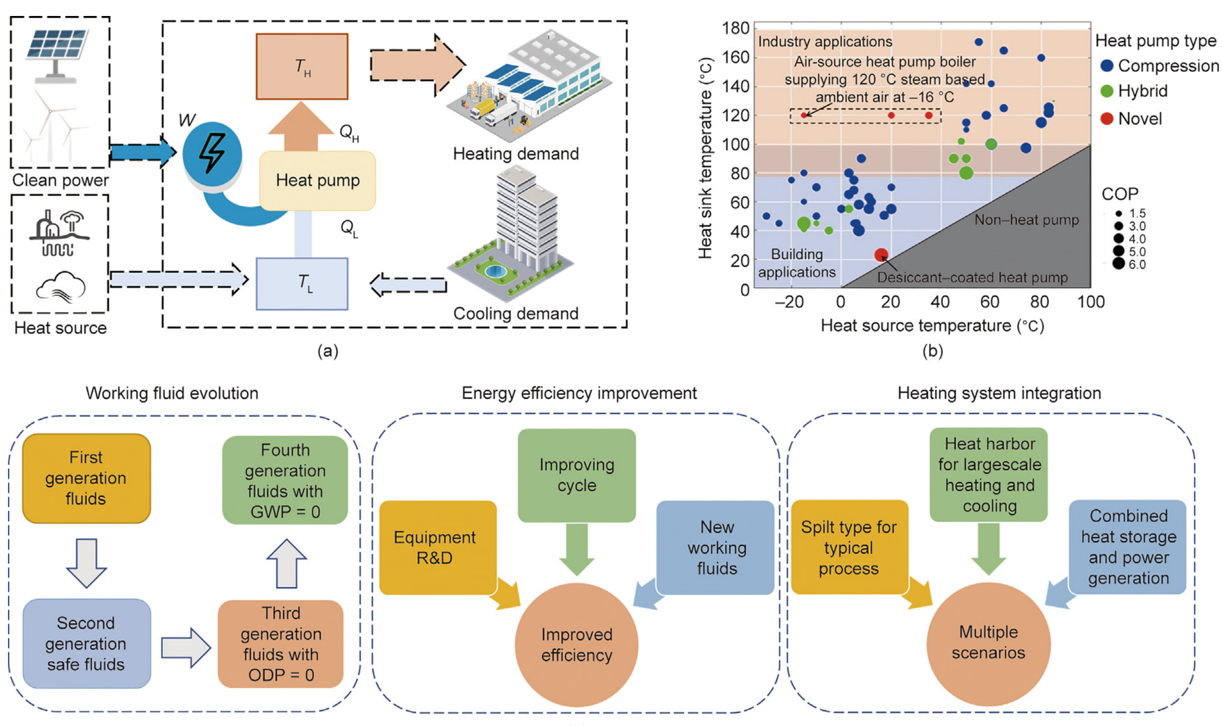

Fig. 2. Summary of and prospect for heat pump research and application. (a) The working principle of the heat pump, where Q_H is the heat transferred to heat sink with high temperature (T_H), Q_L is the heat collected from heat source with low temperature (T_L), while W is power input; (b) performance summary of heat pumps in different settings; (c) the prospect for heat pump development. COP: coefficient of performance; ODP: ozone depletion potential; GWP: global warming potential; R&D: research and development.

pumps can meet almost all building heating demand, and 40% of industrial process heating demand [3]. In terms of application scenarios, heat pumps could serve as follows:

(1) An air-source heat pump can be used in many cases to address building heat demand, since ambient air is the easiest heat source to obtain. According to spatial analysis, an air-source heat pump can reach different COPs at different locations, such as a seasonal heating COP of 3.2 in Qingdao and 3.5 in Shanghai [15]. For severe cold areas (i.e., where the coldest month average temperature is less than −10 °C) [16], where single-stage air-source heat pumps could suffer from problems of low efficiency and frosting [17], improved cycles [18,19] such as vapor injection [20] could be adopted. With vapor injection cycle, it is possible to achieve a COP of over 2.7 when ambient temperature reaches as low as −15 °C. In that case, a geothermal heat pump would have more favorable operating conditions [21]; thus, a higher energy efficiency (i.e., a seasonal COP of about 4.32 in Qingdao and 4.79 in Shanghai [15]) could be gained, given access to enough underground wells and space [22]. For areas with existing heating pipelines for district heating, large-scale heat pumps combined with thermal plant or industrial waste heat could achieve a better performance. In a validated case study, a centrifugal heat pump system was applied to recover the waste heat from a steel plant and achieved a COP of 6.67 for 180 000 m^2 of district heating [23]. Such cases [24] could be categorized as the so-called fourth-generation district heating conception (i.e., integrating low-temperature heat sources with smart district energy systems using non-fossil energy as the heat source) [25].

(2) Industrial heat pumps have a relatively higher temperature demand; thus, industrial waste heat is often adopted as the heat source. These waste-heat-based heat pumps for 120 °C heating can achieve a COP of about 5.7–6.5 (based on waste heat at 90 °C) [14,26] or a COP of about 2.2–2.8 (based on waste heat of 50 °C) [11,27]. Furthermore, it is expected that further technological advancements in multistage compression and the absorption cycle [28] could increase the heat pump heating supply to over 180 °C. Recent advances in air-source heat pump boilers also show that—even only using ambient air as the heat source—heat pumps can be a reliable heating solution. This further indicates the huge untapped potential from the use of heat pumps for industrial heating. It has been verified that an air-source heat-pump-based water vapor compression system can generate steam at 120 °C with a COP of over 1.3 at an ambient temperature of −18 °C, or a COP of 2.1 at an ambient temperature of 35 °C [29]. Such a performance could be further improved by the adoption of a ground source.

From the above summary, it can be concluded that current heat pumps can already meet various heating demands. Moreover, based on literature review and expert judgement from project experience, research and development (R&D) on heat pumps could further focus on the following aspects for better performance and wider applications (Fig. 2(c)):

- The first aspect involves the evolution of working fluid, with low- Global Warming Potential (GWP) refrigerants ranging from synthetic to natural refrigerants. Synthetic low-GWP refrigerants already exist, such as R1234yf [30], R1234ze(E) [31], and R1233zd(E) [32], which could enable the use of heat pumps to meet buildings' and industrial heating demands. Recently, natural fluids [33] (e.g., water [34], ammonia [35], hydrocarbons [36], and CO_2 [37]) have received a great deal of attention due to their excellent performance advantages in some certain applications, such as high-temperature heating [11,14] and simultaneous heating and cooling for buildings [38]. Although these natural fluids pose some difficulties for equipment manufacturing, their advantages of efficiency and lower environmental footprint are obvious and worthwhile [39].
- The second aspect is the optimization of components (i.e., compressors [40] and heat exchanges [41]), materials (i.e., working fluids and heat-resistant accessories), and improving cycles [42]. One possible focus could be the centrifugal compressor, which could enable large scale heat pump with high efficiency [43].
- The third aspect is the integration of heat pumps into different energy systems. Heat pumps have the double effect of both heating and cooling. Recent progress on the so-called fifth district heating–cooling mode (5GDHC) suggests that heat pumps could serve as a "heat harbor" for regional heating and cooling demands [44–46]. In such cases, thermal storage systems are usually incorporated into the network for a more stable output [47]. At present, validated cases already exist in Europe; most cases have gained a higher seasonal COP of over four or even as high as six [48], showing that the concept is feasible and worthwhile. However, retrofitting existing heating system would be more difficult, as a validated case in the UK revealed difficulties in optimizing the pumping control and temperature control when gradually replacing gas boilers with heat pumps [49]. Therefore, considering the excellent performance achieved by 5GDHC, such practices in China could follow a learning-by-doing style, especially with large-scale industries and communities [50]. For example, it is estimated that the power consumption of data centers and 5G stations will exceed 6×10^{11} kW·h in China [51] and will be accompanied by a cooling demand of more than 7 GJ, which account for at least 15% of the heating needs in Northern China. Such potential should be well considered, and a reasonable design in the long run is needed. Moreover, industrial processes have heating demands across different temperature ranges [52], which is particularly the case for industrial parks with various industry clusters [53]. In such cases, the benefits of coupling heat pumps with other heating sources such as solar power should be explored in order to realize heating and cooling flexibly and efficiently. Heat pumps could also be integrated with Carnot Battery for bidirectional heat and electricity transfer [54]. In such cases, heat pumps could pump heat for temperature lifting and capacity increment, and could enable an affordable electricity price [55]. To summarize, with China's huge heat market and various heating demands, it is feasible to learn from international experience and use appropriate heat pump systems in suitable scenarios to materialize China's low-carbon heating potential.

3. The decarbonization potential of heat pumps in China

The contribution of heat pumps to decarbonization relies on clean electricity input and heat pump efficiency. It is expected that the power grid emission intensity will reach a maximum value in 2030, then gradually decrease to close to zero emissions with an increasing share of zero-emission power [56]. Currently, the electricity life-cycle greenhouse gas (GHG) emission intensity in China is as high as 717 $gCO_2eq\cdot(kW\cdot h)^{-1}$ [57] (CO_2 equivalent (CO_2eq), the direct CO_2 emission intensity of power generation is around 589 $g\cdot(kW\cdot h)^{-1}$ [58]). In such cases, the total GHG emission intensity of heat pumps would be comparable to that of natural-gas-based heating, with a GHG emission intensity of around 200 $gCO_2eq\cdot(kW\cdot h)^{-1}$ when the COP is above 3.5. Such a performance indicator is already the case for air-source heat pumps (ASHPs) when used for space heating in mild climate zones. As shown in Fig. 3(a) [58], with the progressive decarbonization of the power grid, when the life-cycle GHG emission intensity is less than 400 $gCO_2eq\cdot(kW\cdot h)^{-1}$ after 2030, the emission intensity of heat-pump-based heating will be lower than that of natural gas when

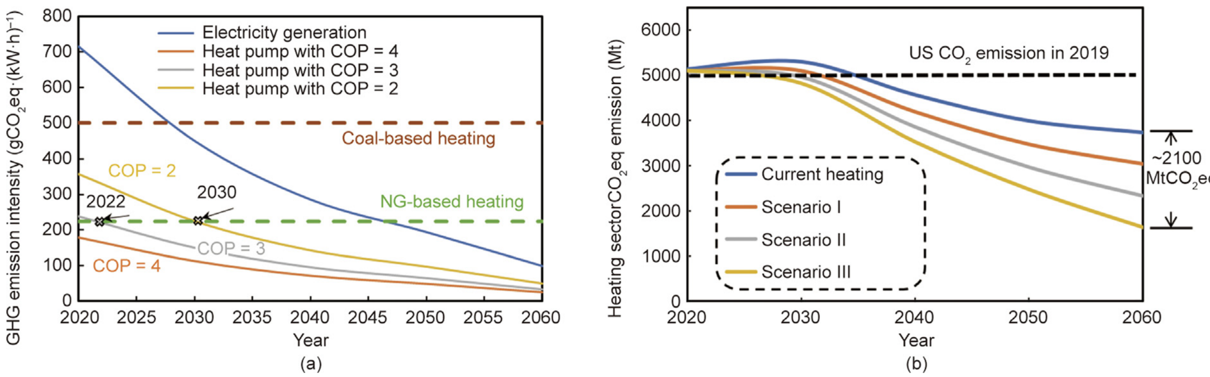

Fig. 3. Projection of heat-pump-based emission intensity from today to 2060 and corresponding CO_2eq emission reduction potential. The decarbonization potential is based on three scenarios with an increasing share of heat pump proportion at 30%, 60%, and 90%, respectively, in 2060. (a) Projection of heat-pump-based emission intensity [58]; (b) CO_2eq emission potential of heat pumps. NG: natural gas.

the heat pump COP is above two. In this case, even an air-source heat pump boiler generating high-temperature steam could be used in mild climate zones, let alone waste-heat-based industrial heat pumps.

Eventually, in a net-zero electricity emission scenario (there is a lack of estimation on the electricity life-cycle GHG emission intensity in China in 2060; thus, we adopt herein 100 $gCO_2eq{\cdot}(kW{\cdot}h)^{-1}$, which covers most renewable power sectors and nuclear power, as investigated [59]), the huge emission reduction potential from heat pumps will be fully unleashed.

However, the current market shares of heat pumps in these two sectors are still too low (less than 6% in the buildings sector and even lower in the industrial sector [57]), thus the market share must be further increased to enable the promised decarbonization effect. To quantify heat pumps' GHG emission reduction potential with increasing market share, three different scenarios were analyzed (Fig. 3(b)). In these scenarios, the share of heat pumps in the building and industrial heating markets continuously increases from 2020 to 2060, eventually reaching 30%, 60%, and 90%, respectively, of the maximum theoretical market share. In other words, the proportion of heat-pump-based heating in buildings and industries will account for 90% (i.e., 90% × 100%; here, it is estimated that heat pumps could meet 100% of the needs for buildings) and 36% (i.e., 90% × 40%; here, it is estimated that heat pumps could meet 40% of the heating demand for industrial heating) of the overall heating energy use in the two sectors, respectively. By combining such statistics with the electricity grid emission projection, the heat-pump-enabled GHG emission reduction potential can be quantified. Although the difference in the 2030 emissions offset is very small among these scenarios, this gap will gradually enlarge over time due to both the larger heat pump market share and the lower electricity emission intensity. Eventually, the gap between each of the three scenarios will exceed 700 by 2060. In the third scenario, the 2060 emission offset potential from heating electrification would reach 1470 and 635 $MtCO_2eq$ for buildings' and industrial heating, respectively. Industrial energy consumption is predicted to be less than buildings' energy consumption by 2060, resulting in a lower emissions reduction in 2060 for the industrial sector. The overall mitigation potential of heat pumps is more than 20% of the country's CO_2 emissions in 2020. When a less optimistic future heat pump market share is assumed, the overall mitigation potential decreases to 1400 and 700 $MtCO_2eq$ for a 60% and 30% heat pump penetration level, respectively.

4. Outlook

Despite the promising future offered by heat-pump-enabled decarbonization, the current market share of heat pumps is still low. The reasons for this lie in both techno-economic and social policy factors. Regarding techno-economic issues, the initial investment for heat pumps is usually several times larger than that for other competing heating facilities with similar heating capacity. Such a high initial investment will result in a long payback period and lead to great difficulties in rollout and scaleup. For buildings heating, it has been found that heat pumps have a comparable or even lower cost compared with other heating methods (e.g., coal, natural gas, or electric boiler) in many cases [60–62]. For industrial heating, our previous study showed that even air-source heat pump boilers (which only use ambient air as a heat source, generating 120 °C steam with an average COP of about 1.7) would have a lower total cost than natural gas heating in China's southeastern region, when taking a long lifetime of 15 years into account [63], let alone waste-heat-based industrial heat pumps [12,32]. Through learning-by-research and learning-by-doing in the future, the economic advantages of heat pumps will be further enhanced in terms of cost savings, improved efficiency, and other factors. Regarding social policy issues, more attention is currently being paid to the decarbonization of power rather than the electrification of heating facilities. The latest progress in heat pumps has not been fully incorporated into much of the research on decarbonizing pathways. Although heat pumps are already considered as potential residential heating facilities [64], they are regarded in many cases as isolated heating facilities, and heat pumps in the industrial sector are only considered for auxiliary use in some specific scenes [6].

It should be recognized that heating facilities are usually designed to have an operation life of more than 15 years, or even as much as 20 years; therefore, there will be only a few rounds of replacements before the 2060 carbon–neutral milestone. As a result, underestimation of heat pumps installation in the future heating market might cause us to miss the "low-hanging fruit" of heat pumps through electrification in the short term and thus prevent us from kicking off the necessary learning-by-doing curve in the long term. In a carbon–neutral future, a higher proportion of renewable power and a larger portion of electrification are expected to be two typical features. Some shift in R&D and policy attention [65] from solar/wind power [66,67] on the supply side to heat pumps on the demand side is clearly needed. Given the enormous decarbonization potential enabled by heat pumps, there is an urgent need for a clear heat pump oriented development roadmap. Moreover, the promotion strategy for heat pumps could be location-specific, since China has a vast territory with complicated natural conditions and economic development levels. For example, the south and southeast regions of China have warmer climate conditions and relatively higher natural gas prices, creating better conditions for heat-pump-based heating compared to natural gas heating. Pilot heat pump projects (e.g., air-source heat pump boilers, which have gained an average payback period of less than ten years [63]) in such regions, which host more than 70% of China's industrial revenue, could be important first steps toward heat pump utilization. Such pilot demonstrations could further kick off the scalability process and thus reduce the cost of heat pump investment.

In short, to achieve the maximum heating decarbonization potential enabled by heat pumps , both technological advancement and policy incentives are needed. Considering customers' core needs for product reliability and affordability, companies' demands for profitability, and policymakers' pursuit of the lowest carbon emissions, the promotion of heat pumps is a complex issue that requires coordinated efforts from the government, manufacturers, and users, all other stakeholders together. We expect this article can lift heat pumps from playing a greatly underestimated role to playing a key role in China's 2060 carbon–neutral roadmap.

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Authors' contributions

As the leading corresponding author, Ruzhu Wang proposed the concept and guided the whole research. Ruzhu Wang and Chuan Zhang designed the study and planned the analysis. Hongzhi Yan and Chuan Zhang conducted the data analysis and drafted the paper, they contributed equally in this work. Zhao Shao provided the graphical abstract. All authors offered revision suggestions and contributed to the interpretation of the findings.

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