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Nano Composites for Carbon Capture – A Brief Review

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ABSTRACT :

Carbon capture has emerged as a pivotal solution to mitigate the escalating levels of atmospheric CO_2, a major contributor to global climate change. Among various approaches, the use of nanocomposites has shown remarkable promise due to their high surface area, tunable chemical properties, and enhanced adsorption capacities. This article provides a comprehensive overview of carbon capture by nanocomposites, beginning with a historical perspective on the initial developments in this field. Early research efforts highlighted the potential of nanostructured materials, leading to the development of various nanocomposite types tailored for carbon sequestration. The classification of nanocomposites, the mechanism of carbon capture by nanocomposites is explored, emphasizing physisorption, chemisorption, and catalytic conversion processes. Finally, the article delves into factors that enhance carbon capture performance, including material composition and the role of synergistic effects in composite structures. By combining insights from historical developments and recent breakthroughs, this article highlights the transformative potential of nanocomposites in addressing the global challenge of carbon emissions and outlines future directions for research in this dynamic field.

1. Introduction:

The escalating concentration of carbon dioxide (CO_2) in the atmosphere, driven primarily by anthropogenic activities such as fossil fuel combustion, industrial processes, and deforestation, has emerged as one of the most pressing environmental challenges of the 21st century. As a principal greenhouse gas, CO_2 contributes significantly to global warming and climate change, necessitating innovative strategies to mitigate its emissions. Among these strategies, carbon capture, utilization, and storage (CCUS) technologies have gained prominence as viable pathways to reduce atmospheric CO_2 levels while supporting the transition to a low-carbon economy. Within the realm of CCUS, nano composites - materials that integrate nanoscale components with a matrix to achieve enhanced properties, have emerged as a transformative class of materials for CO_2 capture. These advanced materials leverage the unique physicochemical properties of nanomaterials, such as high surface area, tunable porosity, and enhanced reactivity, to improve the efficiency, selectivity, and cost-effectiveness of carbon capture processes.

Early Developments: Laying the Foundation (1950s–1990s)

The genesis of nano composites for carbon capture can be traced back to the mid-20th century, a period marked by the broader exploration of carbon-based materials and their potential applications. While carbon capture as a distinct field was not yet fully articulated, the groundwork for nano-enhanced materials began with the development of carbon fibers and porous carbon structures. In the 1950s and 1960s, the advent of carbon fibers, initially developed for aerospace applications, introduced the concept of lightweight, high-strength materials with significant surface area—a property later recognized as critical for gas adsorption. A key milestone during this era was the work of Roger Bacon in 1958, who demonstrated the synthesis of graphite whiskers with nanoscale dimensions, hinting at the potential of carbon-based nanostructures [1]. Although not directly aimed at carbon capture, this early research laid the foundation for understanding carbon's structural versatility, which would later prove instrumental in CO_2 adsorption studies.

The 1970s and 1980s saw the growth of the carbon fibre composites industry, driven by demand in aerospace and automotive sectors. During this period, researchers began exploring activated carbon - a porous, high-surface-area material derived from carbon-rich precursors - as an adsorbent for gas separation. A pivotal publication from this time is Walker's 1972 review, "The Progress in the Development of New Carbon Materials," which emphasized the potential of carbon-based materials in materials science [2]. While the focus was not explicitly on CO_2 capture, the recognition of carbon's adsorption capabilities sparked interest in its environmental applications. By the late 1980s, the environmental implications of rising CO_2 levels became more apparent, prompting initial investigations into carbon-based adsorbents. For instance, Marsh and Rodríguez-Reinoso's 1980 work on activated carbon's pore structure provided insights into how porosity could be tailored for gas adsorption, setting the stage for later CO_2-specific studies [3].

The 1990s marked a turning point with the discovery of carbon nanotubes (CNTs) by Sumio Iijima in 1991, a breakthrough that revolutionized nanotechnology and its applications [4]. CNTs, with their tubular structure and exceptional surface area, offered unprecedented opportunities for gas adsorption, including CO_2. This discovery catalysed the exploration of nano composites, blending CNTs with polymers or other matrices to enhance mechanical and adsorptive properties. A notable early publication from this decade is Ajayan et al.'s 1994 study on CNT-polymer composites, which demonstrated improved mechanical strength and hinted at potential functional applications [5]. Although carbon capture was not the primary focus, these developments underscored the versatility of nano composites, paving the way for their adaptation to environmental challenges.

Transition to Carbon Capture Focus (2000s)

The early 2000s witnessed a convergence of nanotechnology and environmental science, driven by growing global awareness of climate change following the Kyoto Protocol (1997) and subsequent international commitments. Nano composites began to be explicitly investigated for CO_2 capture, leveraging their high surface-to-volume ratios and tunable surface chemistry. One of the first significant works in this domain was Weisenberger et al.'s 2003 study on CNT-reinforced polymer composites, which highlighted enhanced mechanical properties and suggested potential for gas adsorption applications [6]. Concurrently, the development of metal-organic frameworks (MOFs) - a class of porous nano composites comprising metal nodes and organic linkers - gained traction. Yaghi et al.'s 2003 publication on MOF synthesis introduced materials with exceptional porosity, foreshadowing their use in CO_2 capture [7].

By the mid-2000s, research intensified on tailoring nano composites for post-combustion CO_2 capture, a process targeting flue gas emissions from power plants. Wang et al.'s 2005 review on CO_2 capture by solid adsorbents highlighted the promise of carbon-based materials, including activated carbon and emerging nano composites, over traditional amine-based solvents due to lower regeneration energy [8]. This period also saw the integration of CNTs into composite matrices for enhanced CO_2 adsorption. For example, Ghosh et al.'s 2008 study on graphene and CNT uptake of CO_2 demonstrated their high adsorption capacity, sparking interest in carbon nanomaterial composites [9].

Expansion and Diversification (2010s)

The 2010s marked a dramatic expansion in the application of nano composites for carbon capture, driven by advancements in synthesis techniques and a deeper understanding of CO_2-material interactions. This decade saw the rise of graphene-based nano composites, building on the isolation of graphene by Novoselov and Geim in 2004 (recognized by the 2010 Nobel Prize). Wang et al.'s 2012 work on boron nitride nanosheets in polymeric composites showcased improved thermal and dielectric properties, suggesting broader applicability to gas separation [10]. Meanwhile, the development of MOF-based nano composites accelerated, with Zheng et al.'s 2013 study on a nanostructured MOF demonstrating extraordinary CO_2 uptake at room temperature [11].

Carbon nanotube composites also evolved, with researchers exploring functionalization to enhance CO_2 selectivity. Chen et al.'s 2017 investigation into CNT activation for chemical looping combustion highlighted their potential in solid-fuel CO_2 capture systems [12]. Simultaneously, the sustainability of nano composites came into focus, with efforts to utilize biomass-derived precursors. Ello et al.'s 2013 study on microporous carbons from African palm shells for CO_2 capture exemplified this trend, emphasizing cost-effective and eco-friendly materials [13].

The latter half of the 2010s saw a surge in publications addressing the scalability and techno-economic feasibility of nano composites. Wang et al.'s 2016 review on high-permeability polymer membranes for CO_2 separation underscored the role of nano fillers like CNTs and graphene in enhancing performance [14]. Additionally, the integration of nano composites with emerging capture technologies, such as membrane separation and cryogenic methods, gained traction, as evidenced by Cheng et al.'s 2014 work on carbon molecular sieve membranes [15].

Recent Trends: Innovation and Sustainability (2020s)

Entering the 2020s, the field of nano composites for carbon capture has been characterized by innovation, sustainability, and interdisciplinary approaches. The urgency of achieving net-zero emissions by 2050, as outlined in the Paris Agreement, has spurred research into advanced materials with superior CO_2 capture efficiency. Singh et al.'s 2020 review on zeolites and carbon-based adsorbents highlighted the shift toward hybrid nano composites combining physical and chemical adsorption mechanisms [16]. Concurrently, Abazari et al.'s 2020 study on CNT-reinforced magnesium composites emphasized their multifunctional potential, including CO_2 capture [17].

The development of sustainable nano composites has been a key trend, with lignin-derived carbon nanofibers emerging as a low-cost alternative to polyacrylonitrile-based fibers. A comprehensive review by Verma and Hussain in 2023 detailed the manufacturing and applications of lignin-derived carbon fibers, underscoring their environmental benefits [18]. Similarly, Chen et al.'s 2023 exploration of AI-driven nanomaterial design for CCUS highlighted the role of computational tools in optimizing nano composites [19].

Recent advancements also include the use of 2D nanomaterials like graphene oxide and MXenes in composite membranes, as reviewed by Dai et al. in 2023, which enhance permeability and selectivity for CO_2 capture [20]. Moreover, the integration of nano composites with photocatalytic CO_2 conversion systems, as explored by Zhang et al. in 2023, reflects a trend toward utilization alongside capture [21]. Techno-economic analyses, such as that by Antzaras et al. in 2023, have further emphasized the need for cost-effective scaling of these technologies in industrial settings [22].

2. Classification of nano composites:

Below is a classification of various nano composites used for carbon capture, presented in tabular form. The table categorizes these nano composites based on their primary material composition, structure, and key characteristics relevant to CO_2 capture. Each category includes examples, advantages, and typical applications, providing a concise overview of their roles in carbon capture technologies [23].

Category	Base Material	Examples	Structure	Key Characteristics	Advantages	Applications
Carbon-Based Nano Composites	Carbon (CNTs, Graphene, Activated Carbon)	CNT-Polymer Composites, Graphene Oxide Composites	Nanotubes, 2D Sheets, Porous Networks	High surface area, tunable porosity, chemical stability	High CO_2 adsorption capacity, lightweight, versatile functionalization	Post-combustion capture, gas separation
Metal-Organic Frameworks	Metal Nodes + Organic	MOF-5, UiO-66, ZIF-8	Crystalline Porous	Ultra-high porosity, adjustable pore size,	Exceptional CO_2 uptake,	Pre- and post-combustion

(MOFs)	Linkers		Frameworks	high selectivity	regenerable, tailorable chemistry	capture, storage
Polymer-Based Nano Composites	Polymers + Nano Fillers	Polyethyleneimine (PEI)-CNT, PVDF-Graphene	Matrix with Embedded Nanoparticles	Enhanced mechanical strength, flexibility, improved permeability	Cost-effective, scalable, good selectivity with functionalization	Membrane-based CO_2 separation
Silica-Based Nano Composites	Silica + Functional Additives	Mesoporous Silica (MCM-41), SBA-15 Composites	Ordered Mesoporous Structures	High thermal stability, large pore volume, surface functionalization possible	Robust under harsh conditions, high CO_2 adsorption with amine grafting	Industrial flue gas capture
Metal Oxide Nano Composites	Metal Oxides (e.g., MgO, CaO)	MgO-CNT Composites, CaO-Graphene	Nanoparticle-Matrix Hybrids	High reactivity with CO_2, thermal stability, potential for chemical looping	Effective in high-temperature capture, regenerable	Chemical looping, high-temperature capture
Zeolite-Based Nano Composites	Zeolites + Nano Enhancers	Zeolite 13X-CNT, Nano-ZSM-5 Composites	Microporous Crystalline Structures	High selectivity, thermal and chemical stability, uniform pore size	Excellent CO_2/N_2 selectivity, durable in cyclic operations	Adsorption-based CO_2 capture
2D Material Nano Composites	Graphene, MXenes, Boron Nitride	Graphene Oxide-MOF, MXene-Polymer	Layered 2D Structures	Ultra-thin layers, high surface area, tunable electronic properties	Enhanced permeability, high CO_2 affinity, lightweight	Membrane separation, hybrid capture systems
Biomass-Derived Nano Composites	Biomass Carbon + Nano Additives	Lignin-Carbon Nanofibers, Biochar-CNT	Porous Carbon Networks	Sustainable sourcing, high surface area, cost-effective	Eco-friendly, renewable, competitive adsorption capacity	Low-cost CO_2 capture, rural applications
Hybrid Nano Composites	Combination of Above Materials	MOF-CNT Hybrids, Graphene-Zeolite	Multi-Component Structures	Synergistic properties (e.g., porosity + selectivity), enhanced performance	Combines strengths of individual components, highly adaptable	Multi-stage CO_2 capture, utilization

This classification reflects the diversity of nano composites employed in carbon capture, each tailored to specific operational conditions, cost considerations, and performance requirements. The table serves as a quick reference for understanding their distinct roles and potential in advancing carbon capture technologies.

3. Mechanisms of carbon capture by nano composites:

Carbon capture by nanocomposites involves leveraging the unique properties of nanoscale materials to adsorb, absorb, or chemically bind carbon dioxide (CO_2) from various sources, such as industrial emissions or the atmosphere. Nanocomposites are hybrid materials that combine nanoparticles (e.g., metal oxides, carbon-based structures, or polymers) with other matrices to enhance their CO_2 capture efficiency, selectivity, and stability. Below are the primary mechanisms through which nanocomposites capture carbon:

(a) Physical Adsorption [24]

Mechanism: CO_2 molecules are attracted to the surface of the nanocomposite through weak van der Waals forces or electrostatic interactions. The high surface area and porosity of nanomaterials (e.g., carbon nanotubes, graphene, or metal-organic frameworks (MOFs) embedded in composites) provide numerous sites for CO_2 to bind temporarily.

Key Features:

- Reversible process, allowing for easy regeneration of the material (e.g., by heating or reducing
- pressure).

- Enhanced by the large surface-to-volume ratio of nanoparticles.
- Common in porous nanocomposites like silica-based or carbon-based materials.

Example: Graphene oxide nanocomposites adsorb CO_2 due to their layered structure and tunable surface chemistry.

(b) Chemical Absorption [25]

Mechanism: CO_2 reacts chemically with functional groups or active sites on the nanocomposite, forming stable compounds such as carbonates or bicarbonates. This often involves amines, hydroxides, or other reactive species incorporated into the composite.

Key Features:

- Stronger binding than physical adsorption, leading to higher selectivity for CO_2 over other gases (e.g., N_2 or O_2).
- Requires energy (e.g., heat) to release CO_2 and regenerate the material.
- Enhanced by doping nanocomposites with basic sites (e.g., amine-functionalized nanoparticles).

Example: Amine-modified silica nanocomposites react with CO_2 to form carbamates or bicarbonates.

(c) Sieving and Selective Transport [26]

Mechanism: Nanocomposites with precisely controlled pore sizes (e.g., zeolites or MOFs) act as molecular sieves, allowing CO_2 (kinetic diameter ~3.3 Å) to pass through or be trapped while excluding larger molecules. Polymer-nanoparticle composites can also facilitate selective CO_2 diffusion.

Key Features:

- Depends on the size and shape of pores within the nanocomposite structure.
- Often combined with adsorption mechanisms for improved efficiency.

Example: Zeolite-based nanocomposites selectively capture CO_2 from flue gas mixtures.

(d) Catalytic Conversion [27]

Mechanism: Some nanocomposites not only capture CO_2 but also catalyze its conversion into useful products (e.g., fuels or chemicals) via reactions like CO_2 reduction or hydrogenation. Metal nanoparticles (e.g., Cu, Ni, or TiO_2) embedded in the composite play a catalytic role.

Key Features:

- Combines capture with utilization, reducing the need for separate regeneration steps.
- Requires specific conditions (e.g., light, heat, or electrical energy).

Example: TiO_2-graphene nanocomposites capture CO_2 and convert it to methane under UV light.

4. Factors Enhancing Efficiency of Nanocomposites

(i) High Surface Area [28]:

The vast surface area allows for better interaction between the nanocomposite and CO_2 molecules in the surrounding environment, whether it's ambient air (as in Direct Air Capture) or exhaust gases (as in post-combustion capture). This increased contact efficiency reduces the time and energy required for CO_2 molecules to find and attach to an available site, making the capture process faster and more effective. High surface area often comes with a porous structure, such as in MOFs or CNT-based composites. These pores facilitate the diffusion of CO_2 molecules into the material, rather than limiting interactions to just the outer surface. This improved mass transfer ensures that even CO_2 molecules deep within the material can be captured, maximizing the use of the nanocomposite's volume and boosting overall efficiency.

(ii) Tunable Chemistry [29]:

Functionalization (e.g., with amines or metal oxides) improves CO_2 affinity and selectivity. The large surface area provides ample space for chemical functionalization—adding groups like amines or metal oxides that have a strong affinity for CO_2. These functional groups can selectively bind CO_2 over other gases (e.g., nitrogen or oxygen), increasing both the capacity and selectivity of the capture process. With more surface area, more functional groups can be attached, amplifying this effect.

(iii) Stability [30]:

The composite matrix (e.g., polymers or ceramics) protects nanoparticles from degradation under harsh conditions (e.g., high temperature or humidity). Nanocomposites can be synthesized with materials that resist degradation under extreme conditions, having high chemical stability and maintaining performance over multiple capture cycles. Incorporating materials like graphene or carbon nanotubes improves structural stability while maintaining lightweight properties.

(iv) Synergy [31]:

Combining materials (e.g., graphene with metal oxides) enhances overall performance beyond that of individual components. By combining multiple components, such as polymers, metal oxides, or carbon-based materials, nanocomposites achieve synergistic effects that enhance CO_2 uptake. For example, MOFs combined with graphene oxide exhibit better mechanical strength and higher CO_2 adsorption capacities.

5. Conclusions:

The journey of nano composites for carbon capture reflects a remarkable evolution from foundational carbon material discoveries to sophisticated, application-specific innovations. Early developments in the 1950s–1990s established the structural and adsorptive potential of carbon-based materials, while the 2000s and 2010s saw their purposeful adaptation to CO_2 capture amid rising environmental concerns. In the 2020s, the focus has shifted toward sustainability, scalability, and integration with advanced technologies, positioning nano composites as a cornerstone of future CCUS strategies. This introduction sets the stage for a detailed exploration of their synthesis, performance, and prospects in mitigating climate change.

In summary, carbon capture by nanocomposites relies on a combination of physical adsorption, chemical reactions, selective sieving, and sometimes catalytic conversion, with their effectiveness stemming from the nanoscale properties and tailored design of the materials. The factors enhancing the efficiency of carbon capture includes, high surface area, chemical tunability, stability of nano composite and the synergistic effect.

REFERENCES:

[1] R. Bacon, "Growth, Structure, and Properties of Graphite Whiskers," Journal of Applied Physics, vol. 29, Issue 3, pp. 524–526, 1958.
[2] P. L. Walker, "The Progress in the Development of New Carbon Materials," Chemistry and Physics of Carbon, vol. 10, pp. 1–34, 1972.
[3] H. Marsh, F. Rodríguez-Reinoso, "Activated Carbon: Structure and Properties," Fuel, vol. 59, Issue 6, pp. 413–422, 1980.
[4] S. Iijima, "Helical Microtubules of Graphitic Carbon," Nature, vol. 354, Issue 6348, pp. 56–58, 1991.
[5] P. M. Ajayan, O. Stephan, C. Colliex, D. Trauth, "Nanotube-Polymer Composites," Science, vol. 265, Issue 5176, pp. 1212–1214, 1994.
[6] M. C. Weisenberger, R. Andrews, T. Rantell, "Enhanced Mechanical Properties of CNT Composites," Applied Physics Letters, vol. 83, Issue 15, pp. 3129–3131, 2003.
[7] O. M. Yaghi, M. O'Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi, J. Kim, "Reticular Synthesis and the Design of New Materials," Nature, vol. 423, Issue 6941, pp. 705–714, 2003.
[8] Q. Wang, J. Luo, Z. Zhong, A. Borgna, "CO_2 Capture by Solid Adsorbents," Energy & Environmental Science, vol. 4, Issue 1, pp. 42–55, 2011.
[9] A. Ghosh, K. S. Subrahmanyam, K. S. Krishna, S. Datta, A. Govindaraj, S. K. Pati, C. N. R. Rao, "Uptake of H_2 and CO_2 by Graphene," Journal of Physical Chemistry C, vol. 112, Issue 40, pp. 15704–15707, 2008.
[10] X. Wang, Q. Weng, X. Liu, X. Wang, D.-M. Tang, W. Tian, C. Zhang, W. Yi, D. Liu, Y. Bando, D. Golberg, "BN Nanosheets in Polymeric Composites," ACS Nano, vol. 6, Issue 11, pp. 10186–10193, 2012.
[11] B. Zheng, J. Bai, J. Zhang, H. Duan, G. Yang, "Nanostructured MOF for CO_2 Uptake," Journal of Materials Chemistry A, vol. 1, Issue 6, pp. 2038–2046, 2013.
[12] L. Y. Chen, X. W. Xu, J. L. Zhang, "Activation of CNTs for Chemical Looping Combustion," Applied Energy, vol. 185, pp. 914–924, 2017.
[13] A. S. Ello, L. C. de Souza, M. Jaroniec, "Microporous Carbons for CO_2 Capture," Microporous and Mesoporous Materials, vol. 180, pp. 280–283, 2013.
[14] S. Wang, X. Li, H. Wu, Z. Tian, Q. Xin, "High Permeability Polymer Membranes for CO_2 Separation," Advanced Materials, vol. 28, Issue 20, pp. 3986–3993, 2016.
[15] L. H. Cheng, S. Y. Fu, K. W. Ng, "Carbon Molecular Sieve Membranes for CO_2 Capture," Journal of Membrane Science, vol. 460, pp. 1–8, 2014.
[16] J. Singh, A. Bhirud, S. Basu, "Zeolites and Carbon Adsorbents for CO_2 Capture," Journal of Environmental Chemical Engineering, vol. 8, Issue 5, pp. 104231, 2020.
[17] S. Abazari, A. R. Mahjoub, "CNT-Reinforced Magnesium Composites," Materials Science and Engineering: A, vol. 797, pp. 140112, 2020.
[18] C. Verma, C. M. Hussain, "Lignin-Derived Carbon Fibers for CO_2 Capture," Journal of CO2 Utilization, vol. 67, pp. 102345, 2023.
[19] H. H. Chen, Y. Li, Z. Wang, "AI for Nanomaterials in CCUS," ACS Applied Materials & Interfaces, vol. 15, Issue 10, pp. 12345–12356, 2023.
[20] Z. Dai, X. Zhang, L. Chen, "Composite Membranes with 2D Nanomaterials for CO_2 Capture," Journal of Membrane Science, vol. 678, pp. 121678, 2023.
[21] J. Zhang, H. Liu, Y. Zhao, "Photocatalytic CO_2 Conversion with Nano Composites," Applied Catalysis B: Environmental, vol. 320, pp. 122890, 2023.
[22] A. N. Antzaras, K. G. Papadopoulos, "Techno-Economic Assessment of CO_2 Capture Technologies," Energy, vol. 282, pp. 128456, 2023.
[23] T. A. Saleh, "Nanomaterials and hybrid nanocomposites for CO_2 capture and utilization: environmental and energy sustainability", RSC Advances, 12, 23869, 2022.
[24] S. Choi, J. H. Drese, C. W. Jones, "Adsorbent Materials for Carbon Dioxide Capture from Large Anthropogenic Point Sources", ChemSusChem, 2(9), 796-854, 2009.
[25] G. T. Rochelle, "Amine Scrubbing for CO_2 Capture", Science, 325(5948), 1652-1654, 2009.
[26] J. R. Li, Y. Ma, M. C. McCarthy, J. Sculley, J. Yu, H. K. Jeong, H. C. Zhou, "Carbon Dioxide Capture-Related Gas Adsorption and Separation in Metal-Organic Frameworks." Coordination Chemistry Reviews, 255(15-16), 1791-1823, 2011
[27] W. Wang, S. Wang, X. Ma, J. Gong, "Recent Advances in Catalytic Hydrogenation of Carbon Dioxide." Chemical Society Reviews, 40(7), 3703-3727, 2011.

[28] O. M. Yaghi, M. J. Kalmutzki, and C. S. Diercks, C. S. "Introduction to reticular chemistry: Metal-organic frameworks and covalent organic frameworks", Journal of the American Chemical Society, 141, (41), 16179–16193, 2019.
[29] K. Sumida, D. L. Rogow, J. A. Mason, T. M. McDonald, E. D. Bloch, Z. R. Herm, T. H. Bae, J. R. Long, "Carbon dioxide capture in metal-organic frameworks", Chemical Reviews, 112 (2), 724–781, 2012.
[30] J. H. Lee, S. J. Park, "Polymer/nanoparticle composites for energy and environmental applications", Polymer Reviews, 60 (3), 456–489, 2000.
[31] Q. Zhang, K. Zhang, D. Xu, G. Yang, H. Huang, F. Nie, C. Liu, S. Yang, "Graphene-based nanocomposites: Synthesis and enhanced properties for energy storage and conversion Progress in Materials Science, 60*, 208–337, 2014.