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Long-Term Functional and Aesthetic Outcomes of Injectable Bone Substitute in Paediatric Condylar Fractures

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ABSTRACT

Background: The mandibular condyle is both an articular surface and a principal growth centre of the developing mandible, making paediatric condylar fractures a distinct clinical problem from their adult counterpart. Injectable bone substitutes such as calcium phosphate cements, hydroxyapatite cements, and bioactive glass have an established role in adult craniomaxillofacial and orthopaedic fracture augmentation, but their relevance to the growing paediatric skeleton has not been systematically synthesized. Objective: To review the long-term functional (mandibular growth, occlusion, range of motion) and aesthetic (facial symmetry) outcomes reported in paediatric condylar fracture management and to evaluate the evidence base for injectable bone substitute use in this population. Methods: A narrative review was conducted of the published literature on paediatric mandibular condylar fracture outcomes, immature-skeleton and paediatric orthopaedic evidence for injectable bone substitute biocompatibility, and analogous adult condylar fracture and bone augmentation studies, with all sources individually verified against original publications. Findings: Closed or functional management achieves favorable long-term occlusal, mobility, and symmetry outcomes in most paediatric condylar fractures, exploiting the condyle's substantial restitutional remodeling capacity; unfavorable outcomes cluster among children with associated arch fractures, bilateral injury, or very young age. Preclinical and paediatric orthopaedic data indicate that calcium phosphate cements are biocompatible and resorb without evident growth restriction when placed in immature bone, but no study has evaluated injectable bone substitutes specifically within paediatric condylar fracture fixation, and long-term follow-up into skeletal maturity remains limited across the field. Conclusions: Injectable bone substitutes remain a biologically plausible but clinically unproven adjunct for the small subset of severely comminuted or bone-deficient paediatric condylar fractures requiring open treatment. Prospective, multicentre paediatric cohorts with follow-up extending to skeletal maturity are needed before these materials can be considered a validated component of paediatric condylar fracture care.

Keywords: *paediatric condylar fracture; injectable bone substitute; mandibular growth; facial asymmetry; calcium phosphate cement*

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Introduction

The mandibular condyle is unique among facial fracture sites in the growing child: it is simultaneously an articular surface, a load-bearing structure, and the principal growth centre responsible for a large proportion of subsequent vertical ramus and mandibular length development. Condylar and subcondylar fractures account for a substantial share of paediatric mandibular trauma, yet the management philosophy that has emerged for this age group diverges sharply from that used in adults, driven by the child's superior remodeling capacity, the risk that surgical exposure or injury to the condylar growth cartilage poses to future facial growth, and the technical difficulty of instrumenting a small, cancellous, still-developing condylar fragment [1,2]. Multiple retrospective cohorts and systematic reviews have converged on the conclusion that closed or functional management is the first-line approach for the great majority of paediatric condylar fractures, reserving open treatment for a minority of cases with severe displacement, dislocation into the middle cranial fossa, or associated injuries that preclude functional rehabilitation [1,2,3,4].

Against this backdrop, injectable bone substitute materials—calcium phosphate cements, hydroxyapatite cements,

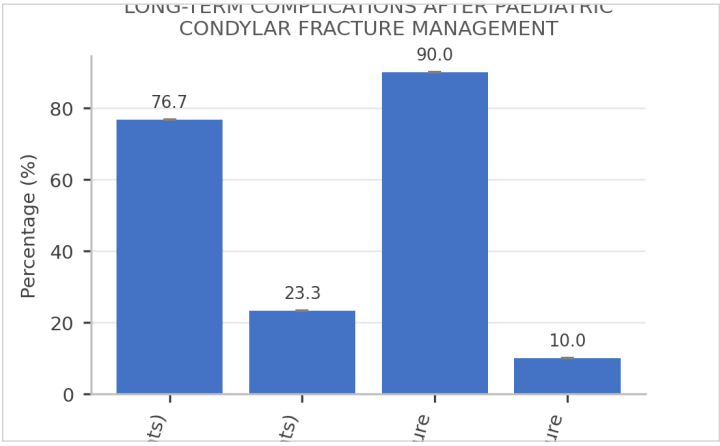
and bioactive glass—occupy an unusual position in paediatric condylar fracture care. These materials have an established, decades-long track record in adult craniomaxillofacial and orthopaedic reconstruction, where they fill bony voids, buttress fixation hardware, and support osteoconduction in comminuted or defect-associated fractures [5,6,7,8,9]. Their extension to the paediatric skeleton, however, raises considerations that are largely absent from the adult literature: the interaction of an alloplastic or ceramic material with an active growth cartilage, the long-term fate of the implanted material as the craniofacial skeleton continues to enlarge for a decade or more after injury, and the need for any intervention to be judged not only on short-term union but on facial symmetry and mandibular growth trajectory followed into skeletal maturity and, ideally, adulthood [10,11].

This narrative review synthesizes the published evidence relevant to injectable bone substitute use in paediatric mandibular condylar fracture management, organized around five themes: the anatomic and biological rationale for treating the growing condyle differently from its adult counterpart; the materials considerations specific to placing an injectable substitute adjacent to an active growth centre; the long-term functional outcomes—mandibular growth, occlusion, and range of motion—reported in paediatric condylar fracture cohorts; the long-term aesthetic outcomes, principally facial symmetry, that are followed from the time of injury into skeletal maturity; and the current state of evidence and translational gaps that must be closed before injectable bone substitutes can be considered a standard adjunct in this population. Because dedicated trials of injectable bone substitutes specifically in paediatric condylar fractures do not yet exist, this review draws on the paediatric condylar fracture outcome literature, the paediatric and immature-skeleton craniofacial bone substitute literature, and, where informative, analogous adult condylar fracture and orthopaedic augmentation evidence, while explicitly flagging where extrapolation rather than direct paediatric data is being used.

The Growing Condyle: Anatomic and Biological Rationale for a Distinct Paediatric Approach

The paediatric mandibular condyle differs from the adult condyle in ways that are directly relevant to any decision to instrument it or to place a foreign material against it. The condylar cartilage functions as a secondary growth centre with substantial appositional and adaptive capacity, and even severely displaced or dislocated condylar fragments in young children frequently undergo a process of resorption and reformation—so-called restitutional remodeling—that can restore a functional condylar contour without surgical intervention. Yadav and colleagues' study of children treated closed for condylar fractures directly interrogated this phenomenon, following patients radiographically and clinically and finding that most displaced and even dislocated fractures underwent substantial remodeling of the condylar head and neck over time, with clinical range of motion and occlusion typically outpacing the residual radiographic irregularity, though a subset of more severely displaced fractures showed incomplete morphological restitution [12]. This capacity for remodeling is the single most important biological argument for favoring closed or minimally invasive treatment in children and for treating any injectable augmentation strategy with caution, since a material that persists as a rigid, non-remodeling mass could theoretically impede the very adaptive process that gives the paediatric skeleton its therapeutic advantage over the adult skeleton.

Long-term complication outcomes among 43 children with condylar fractures and documented follow-up in a 20-year, 64-patient paediatric cohort treated predominantly with closed/functional management; complications were concentrated almost entirely in children with an associated mandibular arch fracture rather than the condylar injury itself (Ghasemzadeh et al., 2015).



Large paediatric cohorts reinforce this picture at a population level. Ghasemzadeh and colleagues' 20-year, 64-patient, 92-fracture retrospective series from a single paediatric trauma centre found that closed treatment yielded satisfactory occlusal and functional results in the overwhelming majority of children, with unfavorable outcomes—predominantly malocclusion—concentrated almost entirely among children who had an associated arch or symphyseal fracture rather than the condylar injury itself, and concluded that closed treatment should remain first-line specifically because of the developing mandible's remodeling capacity and because of the risks that surgical exposure of the immature condyle entails [1]. Zhou and colleagues' five-year cohort study of paediatric and adolescent condylar fractures similarly reported that conservative, function-based management achieved good long-term occlusal and mobility outcomes across most fracture patterns, while noting that growth disturbance, when it occurred, was more closely associated with younger age at injury and bilateral fracture than with the specific treatment modality selected [13]. Bottini and colleagues' multicentric retrospective study of 180 children and adolescents across several European centres compared expectant, maxillomandibular fixation, and open reduction-internal fixation approaches and reported a low incidence of complications and facial asymmetry across all three modalities at a minimum of six months' follow-up, underscoring that the paediatric condyle tolerates a range of management strategies reasonably well provided occlusion is restored and function is preserved during healing [4]. Malinge and colleagues' retrospective study of 108 children with condylar fractures involving articular impact similarly found favorable functional outcomes with predominantly functional treatment, reinforcing that even fractures with intracapsular or articular surface involvement respond well to non-surgical management in most cases [14]. Taken together, this evidence establishes the backdrop against which any injectable bone substitute strategy must be evaluated: the developing condyle already achieves good outcomes with conservative management in most cases, so any adjunctive material would need to demonstrate a clear incremental benefit, most plausibly in the minority of severely comminuted or bone-deficient injuries that proceed to open treatment.

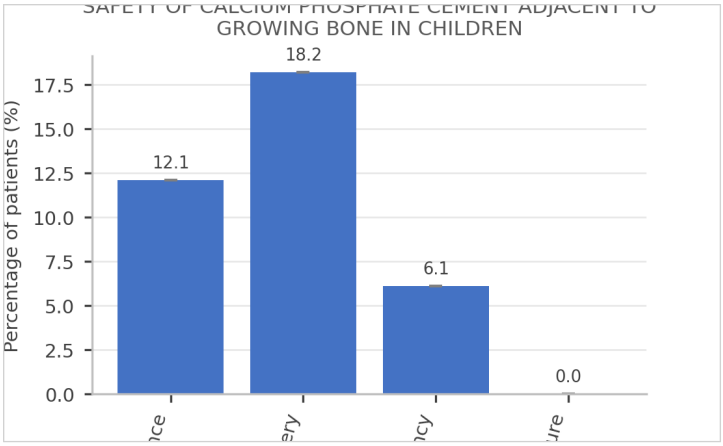
Injectable Bone Substitutes: Materials Considerations for the Immature Craniofacial Skeleton

The materials science of injectable calcium phosphate cements, hydroxyapatite cements, and bioactive glass is well characterized in the adult craniomaxillofacial and orthopaedic literature, but data on how these materials behave when placed adjacent to, or within, a growing bone are comparatively sparse and derive almost entirely from cranial vault and long-bone metaphyseal studies rather than from the mandibular condyle specifically. The most directly relevant body of evidence comes from Kirschner and colleagues' quantitative study of craniofacial growth following repair of the immature craniofacial skeleton with a calcium phosphate cement in an animal model, which found that cement placed within actively growing craniofacial bone did not produce clinically significant growth restriction or asymmetry relative to untreated controls over the observation period, and that the cement was progressively resorbed and remodeled rather than persisting as an inert, non-biological mass [10]. Smartt and colleagues extended this work with a direct comparison of a carbonated calcium phosphate cement placed in both immature and mature craniofacial skeletons, reporting comparable biocompatibility, osteoconductivity, and remodeling capacity in the immature bone, with histological evidence of new bone formation and cement resorption occurring alongside continued skeletal growth rather than in opposition to it [11]. These two studies constitute the closest available preclinical analogue for placing an injectable calcium phosphate material near an active growth centre and offer cautious reassurance that appropriately formulated cements need not be growth-restrictive, though neither study addresses the condyle specifically, and both concern a cranial vault rather than a load-bearing, articulating growth cartilage.

Injectable and moldable bone substitute material classes and paediatric- or immature-skeleton-relevant evidence referenced in this review.

Material class	Setting mechanism	Immature-skeleton / paediatric evidence	Key reference
Injectable calcium phosphate cement	Dissolution-precipitation into nanocrystalline apatite/brushite	No growth restriction in immature craniofacial skeleton model; resorbed and remodeled with growth	Kirschner et al. 2002; Smartt et al. 2005
Carbonated calcium phosphate cement	In situ carbonated apatite setting	Comparable biocompatibility and remodeling capacity in immature vs mature craniofacial bone	Smartt et al. 2005
Calcium phosphate cement (orthopaedic paediatric)	Dissolution-precipitation setting	Low rate of growth-related complication after tumour curettage defect filling in children	Nakamura et al. 2016
Hydroxyapatite cement	In situ moldable apatite cement	Established craniofacial contour/defect repair evidence, predominantly adult	Friedman & Costantino 1997
Bioactive glass	Surface ion exchange, hydroxycarbonate apatite layer formation	Maxillofacial bone regeneration evidence, predominantly adult	Profeta & Huppa 2016; Saghiri et al. 2025

Safety outcomes after calcium phosphate cement placement adjacent to growing bone in 33 paediatric patients treated with cement augmentation following tumour curettage, the closest available paediatric analogue for injectable bone substitute use near an active growth centre; observed limb-length discrepancy was attributed to pre-operative pathological fracture rather than iatrogenic growth-plate injury (Nakamura et al., 2016).



Evidence from paediatric orthopaedic practice offers a complementary, if again non-craniofacial, perspective. Nakamura and colleagues' study of calcium phosphate cement used to fill bone defects after tumour curettage in 33 paediatric patients, with a median follow-up exceeding six years, found that the great majority of patients had no growth-related complications attributable to the cement itself, with the two observed instances of limb-length discrepancy attributed to pre-operative pathological fracture rather than iatrogenic growth plate injury, and the authors explicitly recommended follow-up to growth plate closure given the residual uncertainty about very long-term developmental effects [15]. This pattern—favorable short- and medium-term safety with an explicit caveat about the need for follow-up into skeletal maturity—recurs across the paediatric bone substitute literature and applies directly to the central research question motivating this review: because condylar growth activity continues for years after a childhood fracture, any injectable material placed at or near the condyle would need long-term, growth-completion follow-up data that do not yet exist for this specific anatomic application. Combined with the general craniomaxillofacial materials evidence for calcium phosphate cement, hydroxyapatite cement, and bioactive glass established in the adult literature [5,8,9,16], the paediatric-specific preclinical and analogous clinical data support cautious optimism about biocompatibility and resorption behavior, while leaving open the more specific question of condylar growth cartilage interaction that only dedicated paediatric condylar outcome studies could resolve.

Long-Term Functional Outcomes: Mandibular Growth, Occlusion, and Range of Motion

Functional outcome reporting in the paediatric condylar fracture literature has matured considerably, with several groups now following children beyond the immediate healing period into later

childhood or adolescence, which is the timeframe in which mandibular growth disturbance, if present, becomes clinically apparent. Jenkyn and colleagues' systematic review of 20 studies comparing surgical and non-surgical management of paediatric condylar fractures found no significant difference in occlusal or functional outcomes between approaches in pooled analysis, with most children in both arms achieving good mandibular movement and occlusion; notably, approximately half of patients showed some radiographic condylar remodeling abnormality that only rarely required further intervention, illustrating the disconnect between radiographic appearance and clinical function that is characteristic of the paediatric condyle [2]. Ríos Esposito and colleagues' systematic review focusing specifically on surgically treated paediatric condylar fractures similarly found that, when open treatment was undertaken—typically for more severe or high-fracture-level injuries—functional outcomes including maximum interincisal opening and occlusal stability were generally favorable, though the authors cautioned that the surgical paediatric literature remains dominated by small, heterogeneous case series with limited long-term follow-up [3].

Representative paediatric mandibular condylar fracture outcome studies cited in this review.

Study	Design	Cohort	Principal long-term finding
Ghasemzadeh et al. 2015	Retrospective, 20-year single-centre series	64 patients, 92 fractures	23.3% complication rate among followed patients; complications concentrated with associated arch fracture
Yadav et al. 2021	Retrospective cohort with radiographic follow-up	Closed-treated children	Restitutional remodelling of condylar head/neck common even after displacement/dislocation
Zhou et al. 2019	Retrospective cohort, 5-year	Children and adolescents	Growth disturbance associated with younger age and bilateral fracture, not treatment modality
Jenkyn et al. 2023	Systematic review (20 studies)	Surgical vs non-surgical paediatric cases	No significant difference in occlusal/functional outcome; ~50% showed radiographic remodeling abnormality, rarely needing intervention
Bottini et al. 2024	Multicentric retrospective study	180 children and adolescents	Low incidence of complications and facial asymmetry across expectant, MMF, and ORIF groups
Malinge et al. 2022	Retrospective study	108 children, articular impact fractures	Favorable functional outcomes with predominantly functional treatment

Mandibular growth itself, as distinct from short-term occlusal and mobility outcomes, has been assessed less frequently but is central to the paediatric-specific concerns motivating this review. Zhou and colleagues' cohort data indicated that growth disturbance, when present, clustered among younger children and those with bilateral fractures, a pattern consistent with the biological expectation that injury closer to the peak growth period, or injury affecting both condylar growth centres simultaneously, carries greater risk of asymmetric mandibular development regardless of treatment modality chosen [13]. Ghasemzadeh and colleagues' long-term series likewise found that occlusal and functional problems tracked with associated arch fractures rather than with the condylar fracture pattern per se, suggesting that concomitant injury complexity, rather than condylar fracture management strategy alone, is often the dominant determinant of long-term functional outcome [1]. Bottini and colleagues' larger multicentric cohort, which explicitly compared expectant, maxillomandibular fixation, and ORIF approaches with a minimum six-month follow-up, reported a low incidence of complications across all three strategies, again suggesting that in contemporary paediatric practice the specific choice of management—rather than any particular injectable adjunct—is the primary lever available to clinicians for optimizing occlusal and range-of-motion outcomes [4]. No paediatric study identified in this review reported long-term mandibular growth or range-of-motion outcomes specifically stratified by injectable bone substitute use, underscoring that any functional benefit or harm attributable to these materials in the paediatric condylar population remains, at present, a theoretical extrapolation from the general paediatric condylar fracture outcome literature summarized here combined with the materials safety data reviewed in the preceding section [2,3,10,11].

Long-Term Aesthetic Outcomes: Facial Symmetry and Growth into Adulthood

Facial symmetry is the aesthetic outcome domain most specific to, and most anxiety-provoking in, paediatric condylar fracture management, because asymmetric mandibular growth arrest—classically producing progressive chin deviation, unilateral ramus shortening, and occlusal cant—can continue to manifest for years after the inciting injury and is not reliably predictable from the acute radiographic appearance of the fracture. The paediatric literature converges on the reassuring but nuanced finding that overt facial asymmetry is an uncommon long-term sequela across treatment modalities when children are followed to skeletal maturity, but that it is not entirely eliminated, particularly after bilateral fractures, dislocation, or injury sustained in very young children with substantial residual growth remaining. Bottini and colleagues' 180-patient multicentric cohort explicitly assessed facial asymmetry as an outcome measure and reported a low incidence across expectant, maxillomandibular fixation, and ORIF groups at follow-up, providing among the largest contemporary datasets addressing this specific aesthetic endpoint in children [4]. Ghasemzadeh and colleagues' 20-year experience similarly found that unfavorable aesthetic and functional outcomes were concentrated in the minority of children with combined condylar and arch fracture patterns, rather than being a generalized feature of condylar injury managed closed, which is consistent with contemporary teaching that isolated, appropriately functionally treated paediatric condylar fractures carry a comparatively low risk of long-term facial asymmetry [1].

Where the evidence is thinner is in follow-up that extends fully into adulthood, after the pubertal growth spurt that determines final mandibular proportions has been completed; most available paediatric condylar fracture cohorts, including the largest series discussed in this review, report follow-up measured in months to a small number of years rather than the decade-plus interval required to observe the complete growth trajectory from childhood injury to adult facial form [4,13,2]. This gap is particularly consequential for evaluating any injectable bone substitute, because a material's effect on facial symmetry could plausibly be neutral or even favorable in the short term—by providing structural support during healing—while only

becoming apparent as a growth-restrictive or growth-distorting influence, or conversely as a fully inert and resorbed non-issue, once growth is complete. The immature-skeleton calcium phosphate cement studies of Kirschner and Smartt and colleagues, while reassuring regarding growth restriction in a cranial vault model, similarly did not follow their preclinical models through a complete growth cycle equivalent to human puberty, and neither study measured a symmetry-analogous outcome relevant to a paired, load-bearing structure like the mandibular condyle [10,11]. Ríos Esposito and colleagues' review of surgically managed paediatric condylar fractures likewise identified limited long-term aesthetic follow-up as a recurring weakness of the surgical paediatric literature, reinforcing that facial symmetry into adulthood is the single outcome domain most in need of extended, standardized, multicentre follow-up before any adjunctive technology, including injectable bone substitutes, can be properly evaluated against it [3].

Toward Evidence-Based Use of Injectable Bone Substitutes in Paediatric Condylar Fracture Care

Synthesizing the paediatric condylar fracture outcome literature with the immature-skeleton and analogous adult bone substitute literature yields a coherent but cautious picture. On the clinical side, closed or functional management achieves good long-term occlusal, mobility, and symmetry outcomes in the large majority of paediatric condylar fractures, with unfavorable results concentrated among children with associated arch fractures, bilateral condylar injury, or very young age at injury [1,13,2,4,14,12]. Open treatment is reserved for a minority of severely displaced, dislocated, or otherwise unreconstructable fractures, and it is specifically within this surgical minority—where bone stock may be deficient or comminuted, echoing the adult scenario in which injectable bone substitutes have shown the clearest mechanistic rationale—that an adjunctive material could plausibly be considered [3,17,6,7]. On the materials side, calcium phosphate cements and bioactive glass have demonstrated favorable biocompatibility, osteoconductivity, and resorption behavior when placed in immature bone in preclinical and paediatric orthopaedic settings, without clear evidence of growth restriction, though this evidence base does not extend to the mandibular condyle specifically and does not cover a full growth cycle to skeletal maturity [10,11,15].

No study identified in this review has evaluated injectable bone substitute augmentation specifically within paediatric condylar fracture fixation, and this absence is itself an important finding: the paediatric condylar fracture literature and the paediatric bone substitute literature currently run in parallel rather than intersecting. Constructing the evidence needed to justify or refute a role for these materials in paediatric condylar fracture care will require prospective, multicentre paediatric cohorts that specifically capture the injectable-bone-substitute subgroup within the small proportion of children undergoing open treatment for severely comminuted or bone-deficient condylar fractures, with structured long-term follow-up extending to, or beyond, completion of pubertal growth and reporting mandibular growth vectors, occlusal stability, range of motion, and quantitative facial symmetry alongside conventional union and complication endpoints [18,19,20]. Registries analogous to the multicentric paediatric condylar fracture cohort assembled by Bottini and colleagues offer a template for how such data could plausibly be gathered, provided a subgroup of injectable-bone-substitute-augmented cases can be prospectively identified and followed for a sufficient duration [4]. Until such data accumulate, injectable bone substitutes in paediatric condylar fracture management should be regarded as a biologically plausible extrapolation from adult and orthopaedic paediatric evidence rather than a validated intervention, appropriate only for individualized consideration in the rare child with a severely comminuted, bone-deficient condylar fracture proceeding to open treatment, and always accompanied by counselling that long-term growth and symmetry data specific to this application do not yet exist.

Conclusion

Paediatric mandibular condylar fractures are managed successfully in the great majority of cases through closed or functional treatment that exploits the growing condyle's substantial remodeling capacity, with long-term functional and aesthetic outcomes—occlusion, range of motion, and facial symmetry—generally favorable when fractures are isolated and appropriately treated, and less favorable primarily in the presence of associated arch fractures, bilateral injury, or very young age [1,13,2,4,12]. Injectable bone substitutes bring a mature adult craniomaxillofacial and orthopaedic evidence base and a reassuring, if limited, body of immature-skeleton preclinical and paediatric orthopaedic safety data regarding biocompatibility and resorption in growing bone [10,11,15,5,9]. However, dedicated evidence evaluating these materials specifically within paediatric condylar fracture fixation, and specifically tracking mandibular growth and facial symmetry into skeletal maturity and adulthood, does not yet exist. Closing this gap—through prospective, long-duration, multicentre paediatric cohorts focused on the small subgroup of severely comminuted condylar fractures in which augmentation is mechanistically most plausible—represents the clearest and most clinically consequential direction for future research in this field [3,17,14].

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Van Dijk T conceived the review, conducted the literature search, and drafted the manuscript. Wagner H contributed paediatric clinical framing and critically revised the manuscript for important intellectual content. Russo C contributed additional biomechanical and radiological context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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