The Saudi Journal of Medical Insights, Vol. 1, Page 161-168, December 2025

Impact of Maternal Preterm Labor on Pediatric Neuro-Urological Development

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ABSTRACT

Preterm birth, defined as delivery before 37 weeks of gestation, is a major global health challenge. While advancements in neonatal care have significantly improved survival rates, there is growing recognition of the long-term consequences for organ systems undergoing critical development during the truncated third trimester. The brain and urological system are particularly vulnerable, yet their interconnected outcomes are often examined in isolation. This comprehensive narrative review synthesizes current evidence on the impact of maternal preterm labor and subsequent preterm birth on the coordinated development of the neurological and urological systems in children, tracing pathways from etiology to lifelong health. A narrative search was conducted across major databases (PubMed, Embase, Scopus) for studies, reviews, and meta-analyses published from 1990 onward. Findings were integrated thematically to explore definitions, normal development, pathophysiological mechanisms, epidemiological evidence, and long-term outcomes. Inflammation, oxidative stress, and hemodynamic instability as shared mechanisms disrupting cerebral white matter development and nephrogenesis. Epidemiological data confirm a strong, dose-dependent relationship between earlier gestational age and increased risks of neurodevelopmental impairments (e.g., cerebral palsy, cognitive deficits, executive dysfunction, ADHD) and urological-renal sequelae (e.g., reduced nephron endowment, bladder dysfunction, hypertension, and chronic kidney disease). These outcomes are frequently co-morbid, linked by both shared initial insults and direct neural injury affecting bladder control. The consequences extend into adulthood, demanding a lifespan model of care. Preterm birth is not merely a neonatal event but a lifelong condition with interconnected neuro-urological morbidities. A proactive, integrated approach to monitoring and intervention, from the neonatal intensive care unit through adult healthcare, is essential to mitigate risks and optimize the quality of life for this growing population.

Keywords: Preterm Birth, Neurodevelopment, Cognitive Outcomes, Executive Function, Nephrogenesis, Chronic Kidney Disease.

INTRODUCTION

Preterm labor, defined as the onset of regular uterine contractions resulting in cervical changes before 37 completed weeks of gestation, remains a leading cause of neonatal morbidity and mortality worldwide[1].

It represents a critical disruption to the normal intrauterine environment, effectively cutting short a period of profound and orchestrated fetal development. The global prevalence is estimated at approximately 11% of all live births, though this figure exhibits significant geographical and socioeconomic disparity, with rates substantially higher in low- and middle-income countries[2].

The consequences of preterm birth extend far beyond the immediate neonatal period of intensive care, imposing a significant long-term burden on the child's neurodevelopmental and physiological trajectory with particular vulnerability observed in the neurological and urological systems.

The classification of preterm births is essential for understanding risk stratification and potential outcomes. Preterm births are commonly categorized based on gestational age: extremely preterm (less than 28 weeks), very preterm (28 to less than 32 weeks), and moderate to late preterm (32 to less than 37 weeks)[3].

Each category carries distinct prognoses, with decreasing gestational age correlating strongly with increasing risks of adverse neurodevelopmental and systemic sequelae. Furthermore, preterm births can be classified as spontaneous (with or without preterm

Received: 01/12/2025
Accepted: 31/12/2025

premature rupture of membranes) or indicated (medically initiated due to maternal or fetal compromise)[4].

This distinction may influence the underlying pathophysiology and the subsequent pattern of organ system vulnerability. The placenta, often implicated in the etiology of preterm labor, may itself be a source of inflammatory or ischemic insults that independently affect fetal brain and genitourinary development[5].

Methodology

This study employed a comprehensive narrative review methodology to synthesize the current evidence on the impact of maternal preterm labor on pediatric neuro-urological development. Extensive search of the peer-reviewed literature was conducted using major electronic databases, including PubMed/MEDLINE, Embase, Scopus, and Web of Science. The search strategy utilized a combination of Medical Subject Headings (MeSH) terms and keywords related to the core concepts: "preterm birth," "neurodevelopment," "brain injury," "cerebral palsy," "cognitive development," "executive function," "renal development," "nephrogenesis," "chronic kidney disease," "bladder dysfunction," and "neurogenic bladder." Boolean operators (AND, OR) were used to refine the search. The search was limited to human studies published in English from 1990 to the present, with a particular emphasis on longitudinal cohort studies, meta-analyses, and seminal review articles to ensure both historical context and contemporary understanding were captured. Reference lists of key articles were hand-searched to identify additional relevant publications.

The literature screening and selection process involved a two-stage approach. Initially, titles and abstracts were reviewed for relevance to the predefined subheadings of the review (e.g., mechanisms, epidemiology, long-term outcomes). Full-text articles of potentially relevant studies were then obtained and assessed for inclusion based on their methodological rigor, sample size, and direct contribution to understanding the neuro-urological sequelae of preterm birth. Data synthesis aimed to construct a coherent, critical narrative that connects prenatal and perinatal events to lifelong health consequences, identifying gaps in knowledge and highlighting consistent findings across studies to provide a holistic overview for clinicians and researchers.

Neurodevelopmental Milestones in Early Childhood

Normal neurodevelopment is a precisely sequenced, genetically guided, and experience-dependent cascade of events that begins in utero and continues for decades. The third trimester of pregnancy, precisely the period often truncated by preterm birth, is a phase of exceptionally rapid and critical brain growth. This period is characterized by exponential increases in cerebral volume, driven by processes such as dendritic arborization, axonal growth, synaptogenesis, and the beginning of myelination[6]. The cortex becomes increasingly folded, and crucial neurotransmitter systems establish their foundational networks. Concurrently, the subplate—a transient fetal brain structure essential for guiding thalamocortical connections—reaches its peak activity before gradually dissolving[7]. The fetus in the womb is not a passive entity but is engaged in spontaneous movement and sensory experiences that shape these neural circuits.

The attainment of early childhood milestones provides a window into the integrity of this underlying neurological scaffolding. In the first year, milestones progress from primitive reflexes and visual tracking to social smiling, head control, rolling, sitting, crawling, and the emergence of babbling and first words[8]. The second and third years see the development of refined motor skills (walking, running, stacking blocks), explosive language acquisition, symbolic play, and the early foundations of executive function, such as impulse control and working memory. These milestones are not merely behavioral checkboxes but are outward manifestations of complex, interconnected neural networks maturing on schedule. They rely on the successful completion of earlier, invisible prenatal processes, many of which are vulnerable to disruption.

Preterm birth abruptly halts the protected intrauterine environment and exposes the immature brain to a plethora of potential insults in the neonatal intensive care unit (NICU). These include, but are not limited to, inflammation, oxidative stress, hypoxia-ischemia, nutritional deficiencies, and exposure to toxins or medications[9]. The developing oligodendrocytes, precursors to myelin-producing cells, are exquisitely sensitive to these insults, leading to a high incidence of non-cystic and cystic periventricular leukomalacia (PVL), a hallmark injury of the preterm brain[10]. Furthermore, the intricate process of neuronal migration and cortical organization can be disturbed, and the delicate subplate neurons can be injured, leading to miswired thalamocortical and intracortical circuits[11]. This disruption of typical brain architecture and connectivity directly undermines the substrate upon which developmental milestones are built.

Consequently, children born preterm, especially those born at earlier gestational ages, are at significantly elevated risk for delays in reaching motor, language, and cognitive milestones. The trajectory is often one of "catch-up" in some domains but persistent deficit in others. For instance, independent walking may be achieved only a few months later than term-born peers, but fine motor coordination and the complexity of language may show more protracted delays[12]. These early

milestone delays are potent predictors of later diagnoses such as cerebral palsy (primarily spastic diplegia related to PVL), developmental coordination disorder, language impairments, and later learning disabilities[13]. Screening for milestone achievement in this population is therefore not a routine exercise but a critical surveillance tool for identifying children in need of early intervention services, which can harness neuroplasticity to mitigate long-term disability.

Urological Development in Pediatric Patients

The normal development of the urological system is a protracted process that begins in embryonic life and continues through adolescence to achieve full functional maturity. The kidneys undergo a definitive sequence: the pronephros regresses, the mesonephros functions transiently, and the metanephros, appearing in the fifth week, becomes the permanent kidney[14]. Nephrogenesis—the formation of nephrons—commences by week 9 and is mostly complete by 32-36 weeks of gestation in humans, with no new nephrons formed after birth[15]. This timeline is crucial, as preterm birth occurs during this active phase of nephron formation. The final nephron number, a key determinant of lifelong renal functional reserve, is largely set at birth and varies widely; preterm birth is a recognized risk factor for suboptimal nephron endowment[16].

Simultaneously, the lower urinary tract evolves. The bladder develops from the upper portion of the urogenital sinus, and the urethra from the lower portion. The detrusor muscle, urethral sphincters, and the complex neural control systems that govern storage and voiding develop in a coordinated fashion[17]. Normal infant voiding is characterized by small, frequent volumes with involuntary detrusor contractions. Over the first few years of life, through a process of neurological maturation and behavioral learning, the child gains first conscious awareness of bladder filling, then voluntary initiation of voiding, and finally full voluntary control over the sphincter, achieving daytime and nighttime continence typically between ages 3 and 5[18]. This process depends on intact neural pathways between the brainstem, spinal cord, peripheral nerves, and the cerebral cortex.

Preterm birth intrudes upon these delicate developmental processes in several ways. First, and most fundamentally, it can arrest nephrogenesis prematurely. Animal models and human autopsy studies suggest that the stressful extrauterine environment, marked by factors like nephrotoxic medications (e.g., aminoglycosides, certain diuretics), episodes of hypotension, and nutritional challenges, can lead to a significant reduction in the final nephron count[19]. This condition, termed oligonephropathy, programs the individual for a lifelong risk of hypertension, proteinuria, and chronic kidney disease in adulthood[20]. Second, the central and peripheral nervous systems that control bladder function are as vulnerable to the insults of prematurity as the brain areas governing cognition. Injury to the periventricular white matter, which contains descending cortical pathways, or to the spinal cord, can disrupt the developing neural circuits for micturition control[21].

This neural disruption can manifest as a neurogenic bladder or bladder dysfunction, ranging from detrusor overactivity (leading to urgency, frequency, and incontinence) to detrusor-sphincter dyssynergia (a lack of coordination between bladder contraction and sphincter relaxation)[22].

Furthermore, the high prevalence of recurrent urinary tract infections (UTIs) in preterm infants, due to instrumentalization (catheters), immunological immaturity, and functional abnormalities, can cause renal scarring, compounding the risk of long-term renal impairment[23]. Therefore, the urological consequences of preterm birth are a dual threat: a structural reduction in functional renal units and a functional disruption of the plumbing system that manages their output, setting the stage for a spectrum of pediatric urological disorders that may persist silently into adulthood.

Mechanisms Linking Preterm Labor to Neuro-Urological Outcomes

The pathway from preterm labor to adverse neuro-urological outcomes is not a simple chain of cause and effect but a complex, multifactorial network of interacting biological mechanisms. These mechanisms often originate from the same upstream insults that triggered the preterm labor itself, creating a shared pathophysiology for brain and urological system injury.

A primary and unifying mechanism is inflammation and infection. Intrauterine infection (chorioamnionitis) is a major cause of spontaneous preterm labor. The fetal inflammatory response syndrome (FIRS) ensues, with systemic release of pro-inflammatory cytokines such as interleukin-1β (IL-1β), IL-6, and tumor necrosis factor-α (TNF-α)[24]. These cytokines can breach the immature blood-brain barrier and activate microglia, the brain's resident immune cells. Activated microglia can damage developing oligodendrocytes, leading to white matter injury, and can disrupt neuronal migration and synaptic pruning[25]. Similarly, inflammatory cytokines can impair nephrogenesis in the developing kidney, reducing nephron numbers, and can contribute to renal tubular and vascular injury[26]. This shared inflammatory cascade directly links the etiology of preterm birth to injury in both target organ systems.

Oxidative stress is another critical mediator. The transition from the relatively hypoxic intrauterine environment to the hyperoxic extrauterine world, often necessitated by respiratory support, creates a surge in

reactive oxygen species (ROS) that overwhelms the preterm infant's underdeveloped antioxidant defenses (e.g., low levels of superoxide dismutase, catalase, glutathione)[27]. The brain, with its high lipid content and metabolic rate, is particularly susceptible to lipid peroxidation. In the white matter, this leads to oligodendrocyte precursor cell death and PVL. In the kidney, ROS cause direct cellular damage to the nephrogenic zone, arresting nephron formation, and injure the renal tubules and vasculature[28]. The brain and kidneys, both high-flow organs, are thus simultaneously exposed to this toxic oxidative milieu.

Hemodynamic instability is a hallmark of the preterm neonatal course. The immature cerebral and renal vasculature has impaired autoregulation, meaning blood flow is pressure-passive[29].

Episodes of hypotension, common in septic or extremely preterm infants, can lead to watershed ischemic injuries in the brain (affecting periventricular white matter and subcortical structures) and in the kidney (causing acute kidney injury and potentially permanent loss of nephrons). Conversely, fluctuations towards hypertension can risk hemorrhagic injury, such as intraventricular hemorrhage (IVH), which can itself disrupt adjacent white matter tracts and hypothalamic-pituitary structures.

Finally, there are direct anatomical and functional interconnections. The neural control centers for bladder function reside in the brainstem (pontine micturition center) and are modulated by higher cortical centers. Injury to the periventricular white matter, the most common brain lesion in prematurity, can disrupt the descending pathways from the prefrontal cortex and other regions that are crucial for voluntary control and voluntary micturition[30].

Thus, a single area of brain injury can directly cause neurogenic bladder dysfunction. Furthermore, systemic complications like bronchopulmonary dysplasia (BPD) can create a state of chronic hypoxia and increased intra-abdominal pressure from labored breathing, potentially impacting long-term renal function and bladder dynamics[31].

These intertwined mechanisms illustrate that neuro-urological sequelae are not independent comorbidities but frequently co-manifestations of a shared developmental insult.

Table 1: Key Mechanisms Linking Preterm Birth to Neuro-Urological Injury

Mechanism	Pathophysiological Process	Neurological Impact	Urological Impact
Inflammation	FIRS; cytokine release (IL-1β, IL-6, TNF-α) crossing BBB & affecting organs[24] .	Microglial activation, oligodendrocyte injury, disrupted neuronal migration. White matter damage (PVL)[25]	Impaired nephrogenesis, renal tubular injury, predisposition to scarring from UTIs[26]
Oxidative Stress	Excess ROS from hyperoxia, inflammation, ischemia; overwhelms immature antioxidant systems[27]	Lipid peroxidation in white matter; oligodendrocyte precursor death; PVL[27]	Arrest of nephrogenesis; tubular and vascular injury in the kidney[28]
Hemodynamic Instability	Pressure-passive cerebral & renal circulation due to impaired vascular autoregulation[29]	Watershed ischemic white matter injury; Intraventricular Hemorrhage (IVH)[29]	Acute Kidney Injury (AKI); permanent nephron loss; renal vascular injury[29]
Direct Neural Injury	Periventricular white matter lesion disrupting descending cortical pathways[30]	Motor deficits (e.g., spastic diplegia), cognitive impairments.	Disruption of neural circuits for bladder control → Neurogenic bladder (detrusor overactivity, dyssynergia) [30]

Epidemiological Evidence and Studies

A robust and growing body of epidemiological research has consistently demonstrated a strong, dose-dependent association between preterm birth and an increased risk of adverse neurodevelopmental and urological outcomes. Large-scale cohort studies, both national and international, have been instrumental in quantifying these risks and identifying modifying factors.

In the realm of neurodevelopment, landmark studies like the EPICure study (following children born at ≤25 weeks in the UK and Ireland) and the EPIPAGE studies in France have provided critical long-term data. The EPICure cohort showed that at 11 years of age, only 22% of extremely preterm children were free from any neurodevelopmental impairment, with 40% having moderate to severe disabilities, including cognitive deficits, cerebral palsy, visual, and hearing impairments[32]. Population-based registers in Scandinavia, with their exceptional linkage capabilities, have confirmed that the risk of cerebral palsy increases exponentially with decreasing gestational age. Compared to term infants, the relative risk is about 80 times higher for those born at 23-27 weeks and 10 times higher for those born at 32-36 weeks[33]. Beyond major disabilities, subtler dysfunctions are highly prevalent. A meta-analysis confirmed that preterm birth is associated with significantly lower IQ scores, with a mean difference of approximately 12 points for very preterm infants compared to term controls, and deficits persist into adulthood[34]. The risk of Autism Spectrum Disorder (ASD) and Attention-Deficit/Hyperactivity Disorder (ADHD) is also elevated, with pooled odds ratios ranging from 2.5 to 3.5 for very preterm infants[35].

The epidemiological evidence for urological consequences has solidified more recently, as long-term follow-up of preterm cohorts has extended into adolescence and adulthood. Large registry studies have shown that former preterm infants, particularly those with very low birth weight, have a higher lifetime incidence of hospitalizations for urinary tract infections and renal disorders[36]. Follow-up studies using sensitive measures like cystometry and uroflowmetry reveal a high prevalence of lower urinary tract symptoms (LUTS) in school-aged children born preterm, including daytime incontinence, urgency, and voiding postponement, far exceeding rates in term-born peers[37]. Perhaps the most compelling evidence comes from studies of renal function. Research employing measured glomerular filtration rate (GFR) or novel biomarkers like cystatin C has consistently shown that young adults born preterm have significantly lower GFR and higher blood pressure than those born at term, indicating a reduced renal functional reserve[38]. A systematic review concluded that preterm birth is associated with a two-fold increased risk of developing chronic kidney disease (CKD) from childhood into mid-adulthood[39].

Critically, epidemiology also reveals effect modifiers. The association is strongest for those born earliest and smallest, but even late preterm birth carries measurable risk. Male sex, the presence of neonatal complications like severe IVH or BPD, and lower socioeconomic status act as multipliers, worsening outcomes[40]. Twin studies have helped disentangle the effects of prematurity from shared genetic or familial factors, generally supporting a causal role for the preterm birth event itself[41]. This vast epidemiological landscape not only confirms the association but underscores its public health significance, driving the need for lifelong monitoring and targeted intervention strategies for this large and vulnerable population.

Impact on Cognitive and Behavioral Development

The cognitive and behavioral profile of individuals born preterm is characterized by a pattern of diffuse, often subtle, deficits rather than focal losses, reflecting the widespread nature of the brain's vulnerability. These challenges frequently co-occur, creating complex functional impairments that affect academic achievement, social integration, and quality of life.

Cognitive impacts are pervasive. General intellectual ability, as measured by IQ, is on average lower, with the distribution shifted leftward. The deficit is typically in the range of 10-15 IQ points for very preterm children, but more critically, the proportion with intellectual disability (IQ<70) is substantially increased[34]. However, IQ scores often mask a distinctive pattern of strengths and weaknesses. A hallmark cognitive signature of preterm birth involves significant difficulties with executive functions. These are the higher-order, self-regulatory cognitive processes orchestrated primarily by the prefrontal cortex and its connections, which are highly susceptible to white matter injury. Specific deficits are commonly observed in working memory (holding and manipulating information), inhibitory control (suppressing impulsive responses), cognitive flexibility (switching between tasks or mindsets), and planning/organization[12]. These executive dysfunctions can exist even in children with normal-range IQ, making them a primary barrier to independent functioning.

Related to executive dysfunction are pronounced challenges in visual-motor integration and visuospatial processing. These skills, dependent on posterior white matter tracts and parietal lobe integrity, are critical for handwriting, copying shapes, manipulating objects, and

navigating space. Children born preterm often struggle with tasks like the Beery VMI, and this contributes significantly to academic difficulties, particularly in mathematics and sciences that require spatial reasoning and graph interpretation[13]. Language development may show a atypical pattern: basic vocabulary may be relatively spared, but complex syntax, narrative discourse, and pragmatic language skills (the social use of language) are frequently impaired, linked to deficits in associated memory and processing speed networks.

The behavioral and psychiatric sequelae are equally consequential. The risk of Attention-Deficit/Hyperactivity Disorder (ADHD), particularly the inattentive subtype, is markedly elevated. Symptoms often reflect underlying deficits in sustained attention, processing speed, and executive control rather than pure hyperactivity, and may respond less robustly to standard stimulant medications[35]. Autism Spectrum Disorder (ASD) symptoms are also more prevalent, with studies suggesting a 2-5 fold increased risk. The phenotype may differ from idiopathic ASD, sometimes featuring less severe social motivation deficits but prominent sensory sensitivities and rigidity, possibly linked to cerebellar and sensory processing disturbances from prematurity[35].

Furthermore, internalizing disorders like anxiety and depression are common, with rates increasing in adolescence and adulthood. This likely stems from a combination of factors: the biological vulnerability of stress-response systems (e.g., hypothalamic-pituitary-adrenal axis), the psychological impact of growing up with learning challenges and subtle social difficulties, and the experience of repeated medical interventions from a young age[40]. Social difficulties are a central feature, often arising from a mix of pragmatic language problems, impaired emotion recognition, and poor social problem-solving skills linked to frontal-executive dysfunction. This complex cognitive-behavioral phenotype underscores that the impact of preterm birth is lifelong, affecting not just what one learns but how one thinks, regulates behavior, and interacts with the world.

Long-term Health Consequences and Interventions

The journey for individuals born preterm does not end in childhood; the early-life insult sets a trajectory for a unique pattern of adult health, demanding a shift from pediatric to adult-centered, lifespan healthcare models. The neuro-urological vulnerabilities established in the perinatal period evolve and interact over decades.

Long-term Neurological and Cognitive Health: In adulthood, the cognitive deficits often persist, with executive dysfunction and slower processing speed being the most prominent residuals, affecting higher education attainment, career progression, and independent living[40]. The risk for early-onset neurodegeneration is an area of active investigation, with some studies suggesting altered brain aging trajectories. Mental health remains a critical concern, with higher lifetime prevalence of anxiety, depression, and in some studies, psychotic disorders. The increased risk of cerebral palsy brings lifelong challenges of spasticity, contractures, pain, and accelerated musculoskeletal wear-and-tear, requiring ongoing physical therapy and orthopedic management.

Long-term Urological and Renal Health: The reduced nephron endowment (oligonephropathy) creates a lifelong risk. The hyperfiltration in the remaining nephrons, a compensatory mechanism, leads over time to glomerulosclerosis, progressive loss of renal function, hypertension, and proteinuria[20]. Thus, young adults born preterm are at risk for premature chronic kidney disease (CKD) and end-stage renal disease. They also constitute a pool of "hidden" causes of essential hypertension in young adults[39]. Bladder dysfunction may persist or even first become symptomatic in adulthood, manifesting as overactive bladder syndrome, voiding dysfunction, or recurrent UTIs, which can further jeopardize renal health.

Interventions and Management Strategies:

Management must be proactive, multidisciplinary, and staged across the lifespan.

- Prevention & Acute Neonatal Neuro/Uro-Protection: The primary goal is to prevent preterm birth through public health initiatives and targeted obstetric care. When unavoidable, neonatal care focuses on minimizing insults: using gentle ventilation strategies, maintaining stable hemodynamics, judicious use of nephrotoxic drugs, aggressive treatment of infections, and optimizing nutrition. Promising neuroprotective agents (e.g., erythropoietin, melatonin) are under investigation[9].
- Early Childhood Monitoring & Intervention: Systematic, protocol-based follow-up is essential. This includes serial developmental assessments (Bayley Scales, etc.), neuroimaging (cranial ultrasound, MRI) for high-risk infants, and early referral to physical, occupational, and speech therapy at the first sign of delay. Renal ultrasound should screen for structural abnormalities and scarring. Prophylactic antibiotics may be considered for children with high-grade vesicoureteral reflux. Urotherapy, including structured voiding regimens and pelvic floor biofeedback, can be effective for bladder dysfunction[37].
- School-Age & Adolescent Transition: Focus shifts to educational support (Individualized Education Programs), cognitive rehabilitation for executive functions, and psychosocial support. Regular monitoring of blood pressure, urinalysis for proteinuria, and periodic assessment of renal function

(serum creatinine, cystatin C) should become routine. Transition of urological care to adult specialists is critical for those with neurogenic bladders or known renal issues.

- Adult Lifespan Care: A paradigm shift is needed where adult healthcare providers routinely obtain a birth history. Former preterm adults should be recognized as a high-risk population for early hypertension, CKD, and cardiometabolic disease. Annual screening should include blood pressure, renal function, and urinalysis. Lifestyle counseling regarding sodium intake, weight management, and avoidance of additional nephrotoxic insults (e.g., NSAIDs) is crucial. Cognitive-behavioral therapy and vocational support can address persistent executive and mental health challenges.

LIMITATIONS

As a narrative review, this study is inherently limited by its methodological design. The findings are synthesized from existing literature rather than original data, which may introduce selection bias and does not allow for quantitative analysis or definitive causal conclusions. Additionally, the heterogeneity of the included studies in terms of populations, definitions, and outcome measures may affect the consistency and generalizability of the review's conclusions.

CONCLUSION

Maternal preterm labor initiates a cascade that permanently alters the developmental programming of the brain and urological system. The consequences are not merely neonatal but lifespan, interweaving cognitive, behavioral, renal, and urological health in a complex, lifelong condition. Future research must focus on refining predictive biomarkers, developing effective neuroprotective strategies in the NICU, and establishing integrated, lifelong clinical care pathways to optimize the health and quality of life for the growing global population of preterm birth survivors.

DECLARATIONS

Ethics Approval and Consent to Participate

Not Applicable.

Consent for Publication

Not Applicable.

Funding

None.

Competing Interests

None.

Authors' Contributions

All authors made substantial contributions to this work. All participated in the conceptualization, literature review, and critical discussion of the manuscript's intellectual content. Each author was involved in drafting or critically revising the work and approved the final version for publication. The corresponding author, coordinated the collaboration and manuscript preparation.

Acknowledgements

None.

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