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REVIEW

Comprehending the Epidemiology and Aetiology of Childhood Obesity: Integrating Life Course Approaches for Prevention and Intervention

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ABSTRACT

Introduction: Childhood obesity is defined as a medical condition characterised by abnormally high amounts of body fat relative to lean body mass, which increases the risk of adverse health outcomes among children and adolescents from birth to 18 years. The prevalence of childhood obesity, which has serious healthcare implications, is surging, together with its healthcare burden. In this review we explore the intricate interplay of hereditary, environmental, behavioural, cultural and metabolic factors contributing to the global increase in childhood obesity rates. We examine the influence of prenatal factors, genetic

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predispositions and epigenetic mechanisms on obesity susceptibility and treatment strategies, emphasising the importance of a multilevel life course framework to understand the multifactorial causes of obesity.

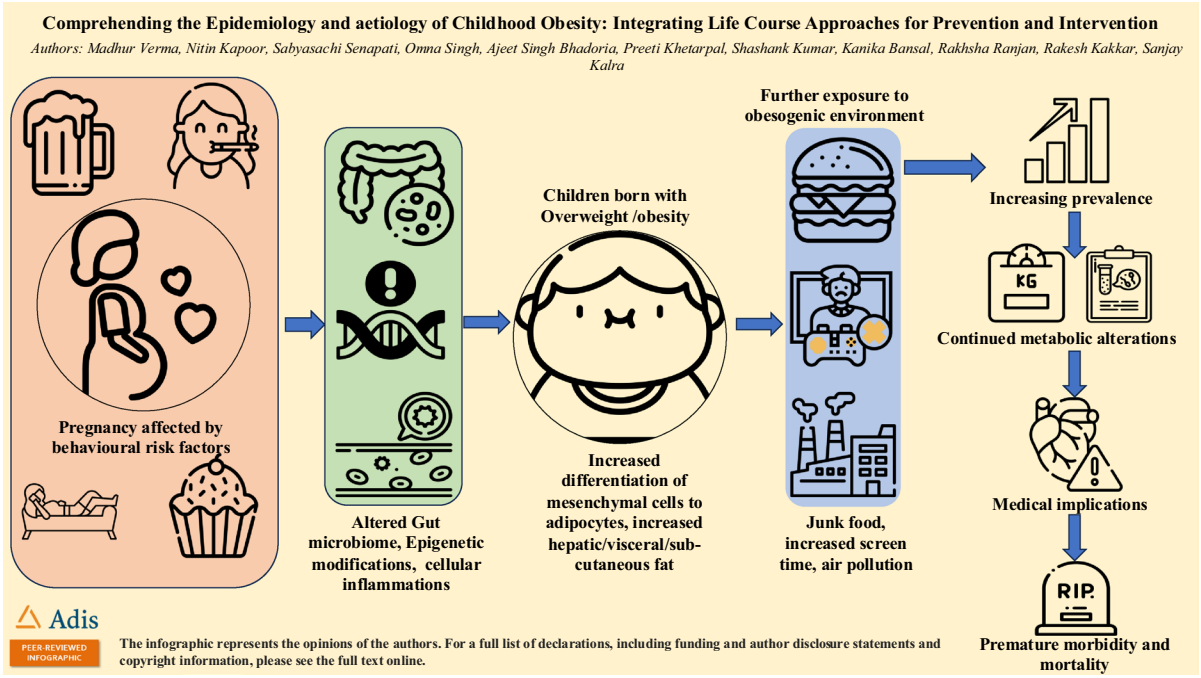
***Methods*:** This narrative review examines the epidemiology, burden, aetiology and impact of childhood obesity by focusing on published literature and the efficacy of multilevel interventions. Comprehensive algorithms are provided to illustrate the causes of childhood obesity through the lens of a multilevel life course framework, taking into consideration individual, family, community and societal factors.

***Results*:** Genetic predispositions, including inherited tendencies towards emotional eating, metabolic variations and body fat distribution, significantly influence a child's obesity risk. Environmental factors, such as limited access to nutritious food, sedentary behaviour, insufficient opportunities for physical activity and obesogenic environments, contribute to the increasing prevalence of childhood obesity. Prenatal influences, including maternal hyperglycaemia and nutritional exposures, lead to epigenetic alterations that predispose children to obesity and metabolic disorders. The social environment, including parental influences, cultural norms and peer dynamics, shapes children's dietary habits and physical activity levels. Additionally, the review highlights the importance of early detection of metabolic alterations associated with paediatric obesity and insulin resistance and the potential for epigenetic mechanisms as therapeutic targets. Recommendations are made for tailored medical nutrition therapy, screening for syndromic obesity and multilevel interventions targeting individual and societal factors.

***Conclusions*:** This review underscores the necessity of a comprehensive, multilevel approach that integrates genetic, environmental, behavioural and cultural factors along with lifestyle modifications and public health initiatives to address the complex and multifaceted issue of childhood obesity effectively. Targeted interventions across the life course, policy reforms, community engagement and technological innovations are recommended to mitigate obesity risks and promote long-term health.

An infographic is available for this article.

***Infographic*:**



Keywords: Childhood obesity; Non-communicable diseases; Behavioural risk factors; Community interventions

Key Summary Points
Childhood obesity is influenced by various factors requiring a multilevel life course intervention approach
Genetic predispositions and epigenetic mechanisms significantly impact obesity susceptibility, emphasising the importance of early-life interventions
Environmental and behavioural influences, including food environment, screen time and physical inactivity, contribute to the escalating prevalence of childhood obesity
Comprehensive prevention strategies must integrate healthcare system strengthening, community-based interventions, policy reforms and digital innovations
There is a need to concurrently focus on individual-, population- and healthcare systems-based approaches to address childhood obesity effectively

DIGITAL FEATURES

This article is published with digital features, including an infographic, to facilitate understanding of the article. To view the digital features for this article, go to https://doi.org/10.6084/m9.figshare.28624595.

INTRODUCTION

Childhood obesity is defined as a medical condition characterised by abnormally high amounts of body fat relative to lean body mass, which increases the risk of adverse healthcare outcomes among children and adolescents from birth to 18 years of age [1]. It is a complex and rapidly escalating global health crisis that may negatively impact the health and well-being of future generations by paving the way for chronic diseases and premature mortality. Preventing childhood obesity provides a unique opportunity to halt progression to an unhealthy adult life [2]. At the 2011 United Nations High-Level Meeting on Non-Communicable Diseases (NCD), governments worldwide set a target to 'halt the rise in obesity at 2010 levels, by 2025', and a similar target was also set for childhood obesity. However, it is feared that we are off track to meet this target. Childhood obesity is attributed to multiple factors, necessitating an urgent need for evidence-based policies and interventions. In this article, we review the existing literature on childhood obesity through the lens of a multilevel life course framework. By exploring the epidemiology and aetiology of obesity across different developmental stages, we delineate how hereditary, behavioural, environmental, cultural and socio-economic factors contribute to obesity through molecular and metabolic alterations [3, 4]. We also highlight the importance of preventing and controlling of obesity on future outcomes. This comprehensive review will help identify effective prevention strategies tailored to specific life stages and target individuals and their ecosystems, ultimately aiming to mitigate the risk of obesity and promote long-term health.

This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

BURDEN OF CHILDHOOD OBESITY

A growing body of global literature underscores the escalating healthcare burden of childhood obesity. Obesity is projected to affect over 100 million children aged 5–9 years and over 150 million adolescents aged 10–19 years worldwide by 2030 [5]. The highest prevalence of childhood obesity is in the Western Pacific region, which also has the highest number of children with obesity. This systematic review covering 154 different countries depicted an overall prevalence of obesity in children and adolescents of around 8.5% (95% confidence interval [CI] 8.2–8.8), with pooled estimates of 14.8% (95% CI 14.5–15.1) and 22.2% (95% CI 21.6–22.8), respectively [5]. The authors also observed

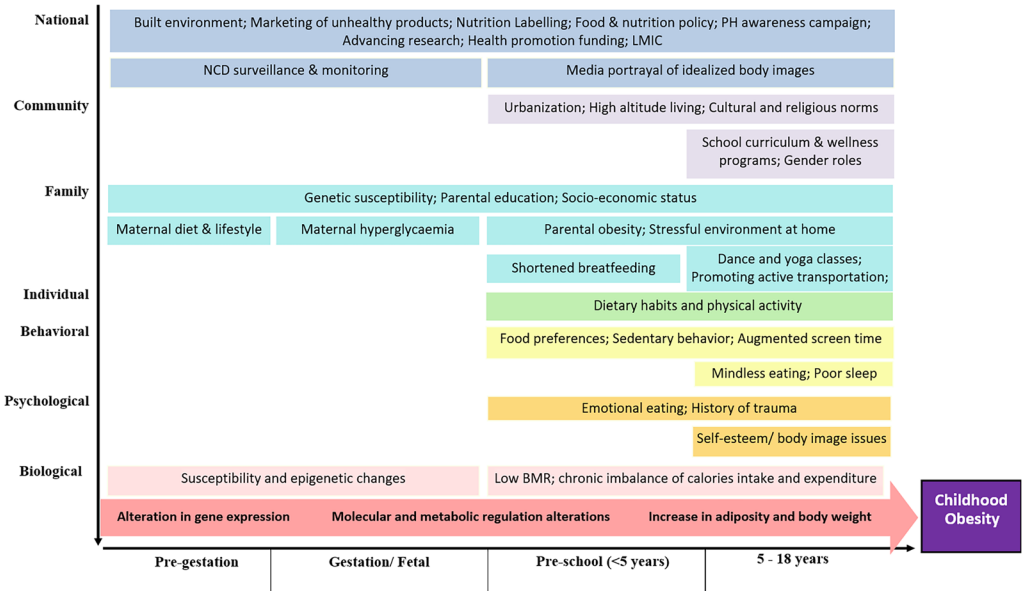


Fig. 1 Multilevel life course framework depicting the causes of childhood obesity. *BMR* Basal metabolic rate, *NCD* non-communicablediseases, *LMIC* low-to middle-income countries, *PH* pulmonary hypertension

marked regional variations, ranging from 0.4% (Vanuatu) to 28.4% (Puerto Rico). The frequency of children aged 7 to 9 years with overweight and obesity is alarming, according to a recent analysis that examined data from 33 countries in the World Health Organisation (WHO) European Region. The frequency of overweight and obesity was higher among boys (31%) than among girls (28%), with the results showing that 29% of youngsters in the nations assessed are living with obesity/overweight [6]. About one in five children and adolescents in the USA suffer from childhood obesity, which remains a serious public health issue. However, not all populations bear the same burden of obesity. Obesity rates are disproportionately greater among some populations, such as teenagers, Hispanic and non-Hispanic Black children, and among children from lower-income families [7]. The prevalence has been reported to be proportional to the Human Development Index scores [8]. Childhood obesity was originally considered to be commonplace in high-income nations, but the latest research suggests that the problem is becoming more widespread even in low-middle-income nations (LMICs) [9]. About 2.3% of children in Asia and sub-Saharan Africa are living with overweight and obesity [10, 11]. In countries like India and China, where a lower prevalence of overweight and obesity has been reported, the absolute number of children living with overweight and obesity is overwhelming. This has led to the projection that Southeast Asia, despite currently having relatively low childhood obesity levels compared to other regions, will be the largest contributor to childhood obesity by 2030. The extended 2030 Sustainable Development Goals set a target to reduce and maintain children with overweight to < 3% [12].

CAUSES

Understanding the multifaceted nature of the epidemiology and aetiology of childhood obesity requires a multilevel life course framework that integrates various stages of development and the multiple levels of influence that shape healthcare outcomes across an individual's lifespan (Fig. 1). A multilevel life course framework considers the interplay between individual, family, community and societal factors, as well as

the critical periods of development that influence obesity risk. Factors such as genetic predisposition, socio-economic conditions and cultural, behavioural and environmental influences interact in complex ways to contribute to the obesity epidemic [3, 13]. By examining these factors within a multilevel life course framework, we can identify critical periods for intervention and develop strategies that target multiple stages and levels of development.

In most cases, obesity results from chronic imbalance, with more calories consumed than expended each day. While caloric intake is a contributing factor, attributing sudden weight gain solely to this variable oversimplifies the intricate influences shaping the obesity phenotype. The aetiology of childhood obesity is a complex interplay of multifactorial elements encompassing genetic predispositions (heredity), environmental exposures, metabolic intricacies, behavioural patterns, mental health considerations and cultural influences (described in more detail in the following sections). Genetic and environmental influences contribute to an individual's risk of obesity, and interventions should consider both aspects for effective prevention and management.

Heredity Factors

Heredity can influence obesity as genetics plays a role in determining factors like metabolism and body fat distribution. Garver et al. [14] explored the substantial evidence supporting obesity as a heritable disorder. Genetic susceptibility, interacting with environmental factors, increases adiposity and body weight. Twin, family and adoption studies reveal heritability estimates ranging from 40% to 70%. Advancements in genomic research, particularly Genome-Wide Association Studies (GWAS) and Next Generation Sequencing, have unveiled over 500 obesity-related genes in humans [15, 16]. Notably, the risk for rare forms of childhood obesity, while less prevalent, is elevated among infants born to consanguineous parents [17, 18]. The inherited obesity disorder spectrum encompasses defects in pivotal genes and proteins such as leptin [19], POMC (pro-opiomelanocortin) [20], MC4R (melanocortin 4 receptor) [21] and FTO (fat mass and obesity-associated) [22]. Genetic predispositions inherited from parents may contribute to the tendency to gain weight [23]. Genetic factors can influence a child's basal metabolic rate (BMR), and the energy that the body needs at rest. Individuals with a lower BMR may be more prone to weight gain if their caloric intake is not adjusted accordingly [24]. Some genetic syndromes are associated with obesity in childhood, such as Prader-Willi syndrome, Bardet-Biedl syndrome, among others in which obesity is a characteristic feature [25]. Genetic factors, including food preferences, can influence a child's eating behaviour [26]. Inherited tendencies towards emotional eating or response to food cues may also contribute to obesity. Genetic factors may influence muscle composition and the body's efficiency to burn calories during physical activity. Some individuals may have a genetic predisposition to lower physical activity [27]. It has been reported that hyperglycaemia during pregnancy leads to a higher risk of the fetus developing obesity [25]. Elevated glucose levels during pregnancy can lead to epigenetic changes in the fetus [28], with the possibility that alterations in gene expression may influence the child's susceptibility to obesity and metabolic disorders later in life. The relationship between hyperglycaemia during pregnancy and childhood obesity involves a complex interplay of genetic and environmental factors. While genetics may play a role, the postnatal environment, including dietary habits and physical activity, significantly influences the child's weight [29].

Environmental Factors

Extensive research underscores the paramount significance of environmental determinants in the escalating prevalence of childhood obesity. The individual microenvironment plays a pivotal role in shaping the propensity towards a physically active or sedentary lifestyle. Recent findings indicate that children residing in areas with enhanced access to restaurant facilities exhibit an increased susceptibility to obesity, while those having access to well-established

bike lanes depicted a reverse trend [30]. At the same time, those dwelling in deprived conditions, marked by disturbances or high crime rates, manifest a decreased proclivity towards obesity [28]. Noteworthy, environmental factors encompass limited access to healthy food, sedentary behavioural patterns, augmented screen time and inadequate secure outdoor spaces for physical activities. Beyond the physical environment, the social environment significantly influences children's body mass index (BMI) maintenance. Proximal influencers in cultivating a conducive social environment for children are parents, friends and family members, all of whom are in the position of frontline agents [32]. Moreover, the hereditary component is evident, as offspring of parents with obesity exhibit a heightened predisposition to developing this disorder [33]. The influence of peers on eating habits and physical activity levels can contribute to adopting unhealthy behaviours, and children may be influenced by the choices of their friends [34]. Parents' eating habits, physical activity levels and attitudes toward health play a significant role. Higher level parental education is often linked to a better understanding of nutrition and healthier lifestyle choices [35]. The availability of nutritious food in school cafeterias and the inclusion of nutrition education impact dietary habits [36]. Other than the built environment and food environment, the natural environment of a child also plays a significant role in developing childhood obesity. Many studies have reported that children living in higher altitude areas were found to be heavier and more bulky than those living in lower altitude regions [37]. It has been estimated that climate change due to the greenhouse effect and obesity are closely linked factors as they alter a person's behaviour, leading to aggressive eating [38].

Behavioural Factors

Other than hereditary, environmental and molecular factors, another major factor influencing childhood obesity is behavioural [39]. A child's behaviour determines their probability to live with overweight. The dietary choices made by an individual, the level of physical activity and eating patterns followed by an individual together impact the risks of developing the disease [40]. Poor eating habits, such as intake of high calorie-rich sugary beverages and processed foods and low intake of fruits and vegetables contribute to obesity [41]. Another major cause of weight gain can be a sedentary lifestyle and insufficient physical activity. Lack of regular exercise is a significant behavioural factor in obesity [39]. Any disturbance in the body's metabolism may contribute to sudden weight gain. Bad eating habits and irregular eating patterns, such as skipping meals, are crucial causes of disturbance in metabolism [43]. Overeating, which is consuming huge portions of a meal at one time, results in excessive calorie intake over time. Recent research found that watching T.V. or using a smartphone or any other apparatus can be distracting. At the same time, eating is often associated with mindless eating, contributing to overconsumption and increasing total calorie intake by 15% [44]. Poor sleep quality and inadequate sleep duration have also been linked to obesity, affecting hormonal balance and appetite regulation [45, 46]. Children with shortened duration of breastfeeding are at higher risk of developing sudden weight gain [47].

Mental Health Factors

There are various psychological factors that contribute to the development and maintenance of childhood obesity in addition to physical aspects. Hence, it is necessary to address both the physical and mental aspects when tackling childhood obesity. Most of the time, childhood obesity is caused by emotional eating during any stressful condition or negative emotion [48]. Another major factor contributing to this disorder can be low self-esteem, body image issues or a history of trauma [49]. The psychological environment at home influences the child's eating habits, sleep patterns and

physical activity level [50]. As such, a stressful environment at home may result in emotional eating and hence contribute to childhood obesity [51]. A stressful environment also leads to the availability of convenience food that generally includes packaged and processed food [52]. Social isolation due to body image bullying also contributes to emotional eating and sedentary behaviour [50]. Cultural beauty body standards and ideal weight societal norms lead to extra peer pressure among children, creating unwanted stress among children who are in the growing stage of their life course [54]. Media portrayal of idealised body images can impact a child's self-perception, with unrealistic standards contributing to dissatisfaction with one's body and potentially unhealthy weight control behaviours [52].

Cultural Factors

Culturalfactors play a significant role in shaping a child's diet and, hence, directly and indirectly contribute to the development of this disorder. Cultural values and beliefs develop gradually over time and are generally followed by the whole social group. Certain cultures may emphasise large-portion diet intake, resulting in sudden weight gain and childhood obesity. Parents usually prefer traditional food over processed, packaged Western food as it symbolises keeping their culture alive. Most ethnic groups believe that babies in the higher weight percentile are proof of good health [56, 57]. In one study, parents from different regional backgrounds were found to have different opinions regarding physical activity. Weather conditions were one of the major factors responsible for not promoting childhood physical activity, together with other factors, such as safety concerns and religious beliefs. Many false beliefs, such as girls should not play outside, project a lack of awareness among the parents [58]. Food marketing often tailors advertisements to cultural preferences, promoting unhealthy products. Children may be more susceptible to these marketing messages, thus adapting their food choices [59].

Socio-economic Factors

Socio-economic factors, similar to a positive history, play a role in the development of obesity. The authors of previous studies on childhood obesity report that children living in LMICs are at higher risk of developing this disorder. Limited access to nutritious food due to financial constraints, lack of opportunities for physical activity in lower-income neighbourhoods and inadequate health education can contribute to higher rates of obesity among children from disadvantaged backgrounds [60]. The increasing consumption of low-nutrient and high-calorie food, available in food stores and markets at a lower cost, is one of the crucial factors contributing to childhood obesity [61]. Healthier food options, such as vegetables and fruit rich in nutrients, are generally more expensive and, hence, are not easily obtained by people in LMICs. The unavailability of healthy food items at affordable prices can be a hurdle to achieving a healthy food environment and also increases the steady consumption of unhealthy and fast food items that are readily available in the cheaper price range [62]. A lack of dietary education and awareness among children leads to the consumption of unhealthy junk food [63]. Housing and accommodation situations are major role players in validating whether or not a person will live with obesity. Children living in poor-income areas cannot access the benefits of playgrounds, leading to decreased physical activity [64]. Lower-income communities are often targeted by the aggressive marketing of unhealthy foods, contributing to the preference for less nutritious options [59].

MOLECULAR AND METABOLIC REGULATION/ALTERATIONS

Childhood obesity strongly correlates with decreased insulin sensitivity or increased insulin resistance [65, 66]. Obesity increases visceral and intraperitoneal adipose deposition, which ultimately increases levels of circulating free fatty acids and inflammatory factors, leading to

insulin resistance [67]. Adipose tissue secretes the biologically active compounds leptin (pro-inflammatory), adiponectin (anti-inflammatory) and resistin, which lead to the development of obesity and insulin resistance [68]. In Saudi Arabia, 126 controls and 168 children with obesity were included in a study to assess the association between blood leptin, its gene expression and the likelihood of obesity and overweight [69]. The researchers found that compared to controls, children with obesity/overweight had greater leptin levels and increased expression of the leptin gene. Another study revealed that serum resistin levels were higher in people with overweight and obesity than in lean adults, children and adolescents [70]. Furthermore, it has been proposed that resistin concentrations are linked to children's distribution of fat and total body fat [71].

Spiegeleer et al. [72] recently reported that the primary metabolites at the crossroad of dysregulated metabolic pathways underlying childhood obesity could be tracked down to one central disturbance, i.e. impending insulin resistance. The authors of this study applied metabolomics, which allowed for the early identification of unique metabolite changes linked to paediatric obesity (and insulin resistance) and related pathways [72]. The results of the study show distinct changes in several pathways related to the metabolism of lipids, carbohydrates and amino acids. In children with obesity, there was a clear shift towards hypoxic conditions, as indicated by high levels of lactate, pyruvate, alanine and acetate, along with unique changes in lipid metabolism. Additionally, aberrations in amino acid metabolism pathways, most notably those belonging to tryptophan metabolism, were found to be altered in children with obesity. The results of this study clarify the use of early-stage biomarkers as indicators of phenotypes that would eventually be metabolically harmful, although reference values and standardised measurements are currently lacking [72].

The most notable property of adipose tissue is its capacity to store lipids and to swell when excessive calories are consumed. It is still unclear how adipose tissue grows and how this impacts the equilibrium of the metabolic system in the body. Additionally, most of the mechanisms by which increased adiposity persists into adulthood and its effects on metabolic health remain unclear. Palacios-Marin et al. [73] summarised the dynamics of white adipose tissue, from its developmental origins to the mechanisms that allow it to grow and expand during obesity in children [73]. Determination of embryonic stem cells that develop into adipocytes is the first step in foetal adipogenesis. Thus far, only a few molecules have been discovered as being involved in prenatal adipogenesis. These molecules include ZFP423, perilipin, adiponectin, mesenchymal stromal cell antigen-1 (MSCA1) and a cluster of differentiation 36 (CD36). Embryonic preadipocytes have been shown to use the expression of transcription factors (ZFP423 and C/EBPα) to expand the adipose-lineage cell population [74, 75]. According to Hanschkow et al. MSCA1 and CD36 are crucial indicators of adipocyte progenitor cells and significantly impact children's adipose tissue functions, with this study emphasising the role of MSCA1 and CD36 in pediatric populations with obesity [76].

In a number of different studies, researchers have studied DNA methylation in the whole blood and saliva of children with obesity and compared the values to those of age- and sex-matched normal children [77, 78]. Huang et al. found that each 1% increase in the methylation of TAOK3 and PIWIL4 was associated with a 0.91-fold decrease and a 1.03-fold increase, respectively, in the odds of obesity [77]. Oelsner et al. [78] reported the results of their genome-wide DNA methylation (DNAm) analysis of 92 saliva samples collected from Hispanic preschool children, which had the aim to investigate the epigenetic patterns. These authors discovered a relationship between methionine degradation, cysteine production, circadian rhythms and methylation at the 17 CpG sites [78]. In a different study, Kaufman et al. [79] identified the association of loci such as UDP-galactose-4-epimerase (GALE), MAP kinase activating death domain (MADD), PR/SET domain 16 (PRDM16), peroxidase (PXDN), HID1 domain containing (HID1), BCAT1, C-X-C motif chemokine ligand 10 (CxCl10) and phosphoenolpyruvate carboxykinase 2 (PCK2) with the risk of obesity in children aged 8 to 15 years [79].

In a cross-sectional study, Prats-Puig et al. [80] identified significant differentially expressed circulating microRNAs (miRNAs: miR-28, miR-221, miR-130b, miR-142, miR-423 and miR-486) in prepubertal obesity [80]. The BMI and other measures of obesity in the test subjects were linked to the circulating concentrations of the miRNAs. Environmental contaminants that can disrupt the proper functioning of the hormone system are known as endocrine disruptors (also referred to as obesogenic chemicals). Obesogens such as food additives, electronic wastes and synthetic fertilisers may increase the risk of diseases in children [81]. Paciencia et al. [82] found higher levels of obesogens (cyclohexanone, 2-butoxyethanol, butylated hydroxytoluene, cyclohexanone, styrene and hexane) in schoolchildren, and that the levels were associated with increased BMI and obesity in the test population [82].

Regarding obesity, the integrin families of cell-surface receptors mediate bidirectional signalling between cell adherence to extracellular matrix (ECM) proteins and cell–cell adhesion. Collagen is a vital structural element of adipose tissue, playing a role in wound healing, cell adhesion, migration, differentiation and morphogenesis. Collagen IV is essential for the survival of the basement membranes of adipocytes [83, 84]. Matrix metalloproteinases (MMPs) are essential for the breakdown of ECM proteins, which are crucial for the growth of adipose tissue [85]. In a study which focused on children, children and adolescents with obesity were found to have higher plasma levels of MMP-9 and TIMP metallopeptidase inhibitor 1 (TIMP-1) [86]. In another study investigating MMP9 levels, the concentrations of MMP9 in the plasma of preterm babies were significant higher than those in the plasma of term babies. When compared to controls, preterm births were linked to nearly threefold higher plasma MMP9 levels. MMP-9 genotypes and haplotypes are linked to increased MMP-9 levels in children with obesity [85], indicating that genetic variables may modify the critical pathogenic pathways underlying the development of cardiovascular problems linked to childhood obesity. Compared to prepubertal children of average weight, children with obesity have been found to have higher expression levels of genes (TNMD and NQO1) in visceral adipose tissue associated with the regulation of the ECM [87].

ROLE OF MACROSOMIA, AND ITS PREDISPOSING FACTORS IN CHILDHOOD OBESITY

Crucial pre-gestational and gestational factors are associated with macrosomia that lead to childhood obesity and are detailed below:

Maternal Influence on Childhood Obesity

Maternal diet during pre-pregnancy and pregnancy, dietary patterns and lifestyle habits during the early stage of a newborn's life can affect the risk of obesity development through epigenetic mechanisms during childhood [88]. The epigenetic mechanism involves chemical modifications of the DNA or RNA that do not modify the nucleotide sequence but regulate gene expression.

DNA Epigenetics and Expression of Candidate Obesity Genes

Substantial evidence links epigenetic modifications involving DNA methylation and histone modifications of candidate "obesity" genes with obesity across different age periods [88] that are involved in processes like appetite regulation, glucose homeostasis, feeding and fasting regulation, adipogenesis, glucose transport and lipid storage. Regulation of expression through methylation has been reported for *LEP* [89], *IRS1* [90], *INS* [91], *GLUT4* [92], *FTO* [93] and *FASN* [94]. Based on the results of genome-wide analysis of DNA methylation of human preadipocytes and mature adipocytes, methylation is an essential mechanism in adipocyte differentiation [95]. Methylation requires the availability of methyl donor S-adenosylmethionine (SAM), which is influenced by the nutrition of the expecting mother or infant [96]. It also requires the

presence of vitamin A [97], vitamin B12 [98], folates [99] and several other nutrients. Several nutrients and metabolic co-factor enzymes have also been linked with histone methylation [100]. Thus, nutrients that act as methyl donors or methylation co-factors have an undisputed role in altering DNA methylation patterns, signifying the effect of maternal diet on childhood obesity.

RNA Epigenetics and its Role in Lipid Metabolism

Like DNA methylation, methylation is the most common reversible epigenetic modification of RNA molecules, regulating gene expression. *N*6-methyladenosine (m6A) has been identified as the most abundant internal modification. Other modifications include *N*1-methyladenosine (m1A), ribose-methylation (2′-O-Me), 5-methylcytosine (m5C) and pseudouridine [101]. Modifications of m6A in the target messenger RNA (mRNA) and the corresponding m6A regulators play a significant role in lipid metabolism [102]. Its role has also been reported in the ultraviolet-induced DNA damage response, which is regulated by the methyltransferase METTL3 (methyltransferase-like 3) and the demethylase FTO (fat mass and obesity-associated protein) [103] along with differentiation and pluripotency [104]. Recent studies have shown decreased m6A modification in adipose tissue through FTO-mediated demethylation [105].

Epigenetics of Proteins, Transcription Factors and their Role in Energy Homeostasis

The acetylation state of many cytoplasmic proteins is regulated by histone acetyltransferases (HATs) and histone deacetylases (HDACs), which are essential metabolic enzymes involved in white and brown adipocyte differentiation and adipogenesis [106]. Lysine acetylation is vital for metabolic pathways and may regulate the balance between energy storage and expenditure [107]. The lipogenic genes are regulated at the transcriptional level with factors such as upstream stimulatory factors (USFs), liver X receptors (LXRs) and carbohydrate-responsive element-binding protein (ChREBP). Blood glucose and insulin levels activate lipogenic genes [108] through several pathways [109] that control the post-translational modifications of transcription factors via phosphorylation or acetylation, thus affecting their functions which, when dysregulated, can contribute to hepatosteatosis, associated with Obesity [110].

IMPLICATIONS OF CHILDHOOD OBESITY

The WHO Commission on Ending Childhood Obesity found that childhood obesity, including obesity in preschool children and adolescents, is reaching alarming proportions in many countries and poses an urgent and severe health challenge [111].

Medical Implications

Extremely high BMI values considerably increase risks to children's physical and mental health [112]. Children with obesity are at an elevated risk of developing a range of obesity-related comorbidities, as obesity-induced inflammation contributes to endothelial dysfunction, thereby increasing the risk of hypertension, dyslipidaemia and insulin insensitivity in adulthood. Such children may also develop non-alcoholic fatty liver disease (NAFLD), which is currently the most common cause of liver disease in children. NAFLD can progress to non-alcoholic steatohepatitis (NASH), fibrosis and even cirrhosis, leading to long-term liver damage. Other medical complications include musculoskeletal problems, obstructive sleep apnea, asthma and gastrointestinal disorders such as gastroesophageal reflux disease (GERD). Childhood obesity is also linked to hormonal imbalances, leading to early puberty, polycystic ovary syndrome (PCOS) in girls and hypogonadism in boys. Insulin resistance associated with obesity also exacerbates the risk of type 2 diabetes and cardiovascular diseases. The psychological repercussions of childhood

obesity are equally profound. Children with obesity are at a higher risk of developing low self-esteem, body dissatisfaction and social isolation. They are more likely to experience bullying and weight-related stigma, leading to anxiety, depression and eating disorders, including binge eating and emotional eating. The emotional burden and social consequences can impair academic performance and social development. In severe cases, the psychological distress associated with obesity may result in suicidal ideation and self-harm.

Fig. 2 Concerns of a child seeking treatment for obesity

Reduced Quality of Life

Children with overweight and obesity also experience significant reductions in quality of life as they are often subjected to weight bias and obesity stigma. These children have poorer psychological well-being and are at a greater risk of teasing, bullying and social isolation. These conditions are in turn associated with poor body image and body dissatisfaction; low self-esteem and self-confidence; feelings of worthlessness and loneliness; suicidal thoughts and acts; depression, anxiety and other psychological disorders (e.g. maladaptive eating patterns); avoidance of physical activity; stress-induced pathophysiology; and avoidance of medical care [112].

Economic Implications and the Burden on the Healthcare System

Also, once childhood obesity is established, it is difficult to reverse through interventions and tracks through to adulthood. This has serious health consequences as adult obesity is associated with increased risk of other long-term morbidities, such as heart disease, stroke, metabolic syndrome, type 2 diabetes, some cancers (like colorectal cancer, kidney cancer and oesophageal cancer) and premature mortality. Treating obesity is very expensive; in the UK, the treatment of obesity has an estimated price card of between £8000 and £10,000, while in the USA the average cost of this surgery is $8000 to $27,000. Studies have reported that in India, the economic household burden of obesity accounted for an extra 5% of expenditure when compared to normal-weight women [113, 114].

SCREENING, DIAGNOSIS AND EVALUATION

Excess adiposity is having an abnormally high amount of body fat relative to lean body mass, which increases health risks. Excess adiposity is commonly screened using the weight-for-height charts. In children younger than 5 years, overweight and obesity are defined when values are > 2 and > 3 standard deviations, respectively, above the median value of the WHO Child Growth Standards. Children with obesity and overweight aged between 5 and 19 years are identified using the BMI-for-age > than 1 and 2 standard deviations, respectively, above the median WHO Growth Reference values, which are equivalent to to BMI 25 and 30 kg/m^2 at 19 years [115].

The most reliable tool in clinical practice is the BMI, combined with waist circumference; the use of both parameters makes either parameter more predictable of high-risk phenotypes. Also, wrist circumference measurements have recently been easier to use to identify metabolic risk, although more studies are needed to validate the age-appropriate cut-offs for overweight and obesity. The results of directly measuring body fat using dual-energy x-ray absorptiometry,

skinfold thickness, bioelectrical impedance and densitometry correlate well with BMI. Comorbidity screening for hypertension (HTN), sleep hygiene, tonsillar hypertrophy, chest examination, lipid profile, liver ultrasound, blood sugar and oral glucose tolerance test (OGTT), among others is indicated in all children aged >10 years with obesity. Routine testing of endocrine causes in associated short stature and genetic testing in rapid onset and early obesity is not recommended. Clinical examination should focus on the possible causes, future disease risk and modifiable behavioural factors. Short stature, skin changes, micropenis (hypogonadism) and dysmorphism hint at possible endocrine and genetic syndromes. The waist-hip ratio, especially in adolescents, has a role in the future prediction of visceral obesity, metabolic syndrome and cardiovascular disease risk. Counselling should address behavioural factors like eating habits, physical activity/exercise, quality of sleep and sleep hygiene and screen time, which are modifiable causes of exogenous obesity [63, 116]. Children with overweight and obesity benefit from health behaviour and lifestyle treatments (nutrition and physical activity-related health information) supported through a multi-disciplinary team involving paediatricians, paediatric healthcare providers, psychologists, nurses, exercise specialists and social workers, and extending to families, schools, communities and health policy [117].

Role of Continuous Surveillance in Preventing Childhood Obesity

The sustainable development goals set by the United Nations in 2015 also identify the factors relating to the prevention and control of NCDs, including obesity, as core priorities [118]. Three major approaches are used to collect primary data for nutrition surveillance: repeated cross-sectional surveys, community-based sentinel monitoring and data collection in schools.

a. *Large-scale national surveys* use standard survey methodology, which stakeholders prefer as a reliable data collection methodology. However, the disadvantages of this approach is that it only allows for temporal analysis, and is resource-exhaustive [119].
b. *Repeated sub-national surveys* use probability sampling methods and are undertaken at fixed time intervals [119].
c. *Community-based sentinel sites* is an approach used in highly vulnerable communities where data are collected periodically. Such an approach is relatively quicker and cheaper, with fewer sites and more detailed data collection. However, there is a risk of having an unknown level of bias, which is likely to vary on a case-by-case basis depending on the environmental context and exact methods applied [119].

MANAGEMENT OF CHILDHOOD OBESITY

Clinical Management

In terms of clinical practice, a child with obesity seeks a physician's help to answer multiple questions (Fig. 2). Often, such children want to know why they have gained so much weight despite seeing so many other children eat large quantities of food and still not putting on weight. They often ask the treating doctor to provide medications for obesity as they would have already tried lifestyle modifications on several occasions. Sometimes, the aim of these children is to achieve significant weight loss before a landmark celebration, festival or family event. The treating physician often needs to explain to the child and their parents that there is a need to manage obesity as a chronic disease that requires a structured approach with long-term follow-up (Fig. 3). It is important that the physician emphasise that short-stop solutions only work in the short term. Elements of a structured approach to managing obesity include formal dietary advice, physical activity recommendations, reduction in screen time, cognitive behavioural therapy, management of co-existing

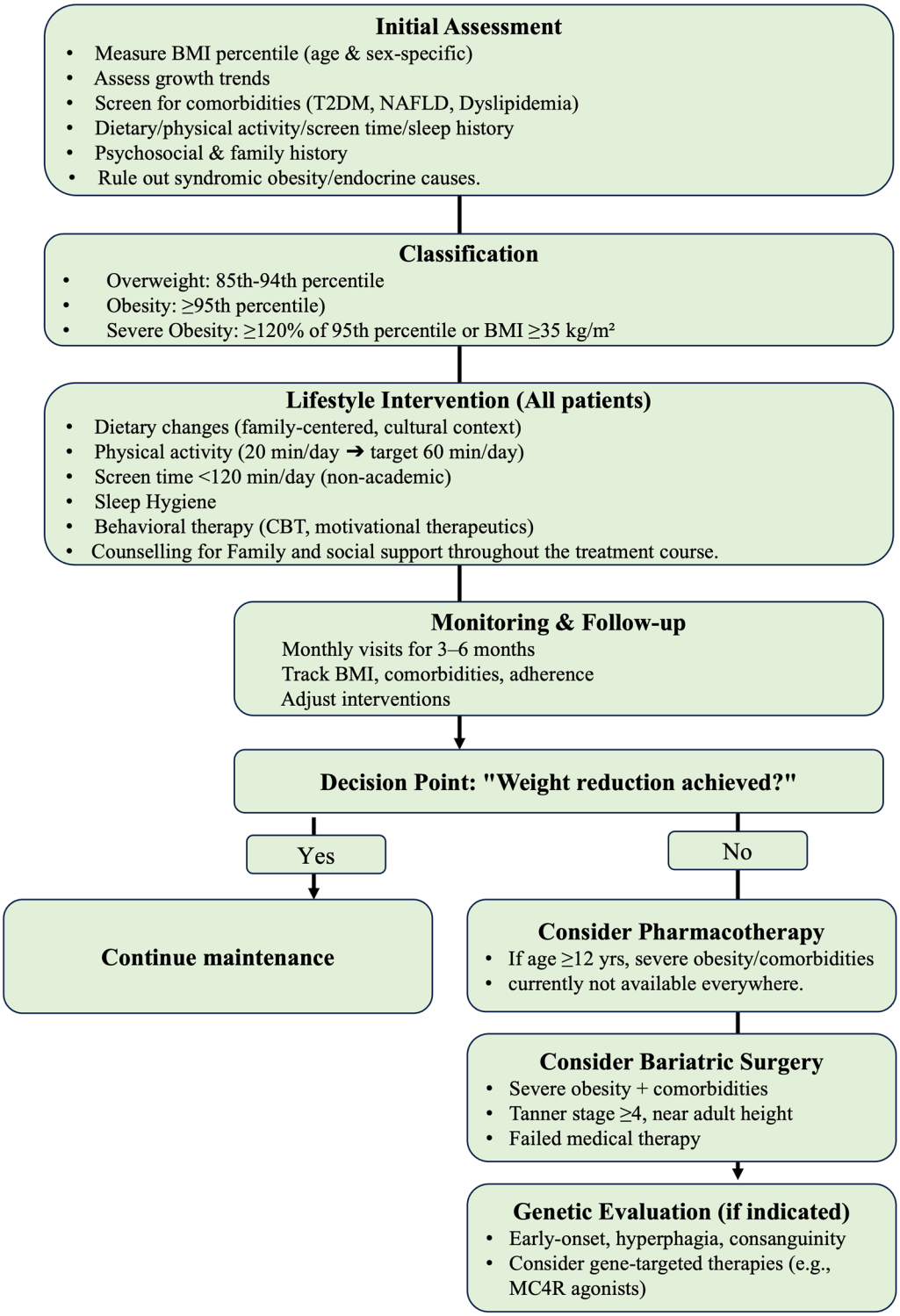


Fig. 3 Algorithm on the approach to clinical management of pediatric obesity. *BMI* Body mass index, *CBT* cognitive behavioural therapy, *NAFLD* non-alcoholic fatty liver disease, *T2DM* type 2 diabetes mellitus

comorbidities, health habit monitoring, pharmacotherapy, bariatric surgery and genetic testing and gene-targeted therapy (see following sections for a detailed description).

Formal Dietary Advice

Formal dietary advice can be easily implemented as a three-step approach [120]. In the first step, the nutritionist should inquire about the family's ongoing eating practices based on the culture of the family member, as well as their beliefs and work patterns. Based on this information, in the second step, changes in the diet, starting with just a change in proportions, should be encouraged, with the suggestion to gradually introduce more significant changes. It is essential to maintain a long-term follow-up with these patients to help with any roadblocks. Step 3 involves a long-term follow-up, which is often required for the person to lose weight and maintain weight loss. This step also requires striking a delicate balance between optimising growth without compromising essential nutrients and simultaneously avoiding any excess food consumption that may contribute to further weight gain. Micronutrients should also be optimised in addition to macronutrient balance [121].

Physical Activity Recommendations

Regular moderate to vigorous physical activity (MVPA) improves insulin sensitivity, which then modulates BMR and promotes efficient energy utilisation rather than storage. MVPA also increases muscle mass development, which is crucial for managing and preventing obesity. A healthy routine can be introduced with the initiation of at least 20 min of MVPA daily, with progression to 60 min of MVPA daily, in alignment with global guidelines (e.g. WHO, US Centers for Disease Control and Prevention [CDC]). This routine will help improve cardiorespiratory fitness, reduce adiposity and lower the levels of inflammatory markers associated with obesity [122]. Moreover, regular MVPA positively impacts mental health, self-esteem and behaviour, contributing to better adherence to long-term lifestyle modifications in children with obesity [123, 124].

Reduction in Screen Time

It is recommended that non-academic screen time be reduced to less than 120 min daily; such a reduction is crucial and supported by strong physiological evidence [125]. Excessive screen exposure leads to sedentary behaviour, reducing energy expenditure and promoting a positive energy balance that favours fat accumulation, particularly visceral adiposity [124]. Moreover, screen time—especially in the evening—disrupts circadian rhythms and suppresses melatonin secretion, impairing sleep quality. Sleep deprivation alters appetite-regulating hormones by increasing ghrelin (stimulating hunger) and decreasing leptin (promoting satiety), which drives overeating [126]. Additionally, screen time is associated with increased exposure to food advertisements and distracted eating, which enhances reward-driven caloric intake [127].

Cognitive Behavioural Therapy

While modifications in dietary and physical activity are fundamental, evidence-based behavioural change strategies are equally critical for sustained success in pediatric obesity management [128]. Cognitive behavioral therapy (CBT) is effective in addressing emotional eating, poor self-regulation and low motivation, all common characteristics of children with obesity. CBT focuses on identifying triggers for overeating, developing coping mechanisms and reinforcing positive behaviour changes [129]. Motivational therapy, goal-setting techniques and family-based interventions can significantly enhance adherence to lifestyle changes [130]. Incorporating such structured behavioural therapies into clinical practice can improve long-term weight outcomes and psychological well-being, especially in children struggling with binge eating, anxiety or low self-esteem linked to obesity.

Table 1 Drugs approved for treating childhood obesity in different geographical regions

Drug	Indication	Mechanism of action	Dosage	Clinical use	Impact on weight loss	Contra-indications	Approval status in some high-burden regions/country
Orlistat	Age ≥ 12 years with BMI ≥ 95th percentile + comorbidity	Gastrointestinal lipase inhibitor: inhibits fat absorption	120 mg orally, three times daily	Approved for long-term management; as an adjunct to a reduced-calorie diet and increased physical activity	Reduces BMI by approximately 1.3 kg/m^2	Chronic malabsorption, cholestasis, pregnancy	USA: yes EU: no India: no
Phentermine	Age ≥ 16 years with BMI ≥ 95th percentile + comorbidity	Nor-epinephrine reuptake inhibitor: appetite suppressant	7.5 mg-37.5 mg orally	Combination approved for adolescents; phentermine alone for teens	Effective for short-term use; significant weight loss in adolescents	Cardiovascular disease, hyperthyroidism, glaucoma, MAOI use	USA: approved for short-term use (12 weeks) EU: no India: no
Liraglutide	Age ≥ 12 years with BMI ≥ 95th percentile and weight-related comorbidities	GLP-1 receptor agonist: decreases gastric emptying and acts as an appetite suppressant	2.4–3 mg/day subcutaneously	Dose escalation gradually to 3.0 mg/day	Demonstrated BMI reduction in adolescents	Personal/family history of MTC, pancreatitis, pregnancy	USA: approved for obesity with or without T2D in children (aged ≥ 12 years) EU: yes India: no
Semaglutide	Age ≥ 12 years with obesity	GLP-1 receptor agonist: decreases gastric emptying and reduces appetite	2.4 mg/week, subcutaneously	Part of GLP-1 receptor agonists; central action in reducing appetite	Significant BMI reduction, up to 16% in clinical trials	Same as liraglutide	USA: approved for obesity with or without T2D in children (age ≥ 12 years) EU: yes (age ≥ 12 years) India: no
Setmelanotide	Age ≥ 6 years with rare genetic obesity (POMC, PCSK1, LEPR deficiency)	MC4R agonist: treats genetic obesity by restoring impaired activity		Approved for chronic weight management in patients with POMC, LEPR, PCSK1 deficiency, and Bardet-Biedl syndrome	For children aged 2–5 years: BMI reduction can reach 26% at 52 weeks For children aged ≥ 6 years: 80% of participants with POMC deficiency achieved at least 10% weight loss at 52 weeks	Non-genetic obesity	USA: yes (age ≥ 6 years) EU: yes India: no
Topiramate	Not FDA approved for pediatric obesity	Carbonic anhydrase inhibitor: centrally suppresses appetite and reduces binge eating episodes	25–100 mg orally, twice daily			Pregnancy, glaucoma, MAOI use	USA: approved for binge eating disorder (age ≥ 18 years) EU: no India: no
Naltrexone/bupropion	Not approved for paediatric obesity	Naltrexone: opioid antagonist Bupropion: dopamine and noradrenaline reuptake inhibitor		Used off-label for appetite suppression		Seizure disorders, uncontrolled hypertension, opioid use	USA: no EU: no India: no

BMI Body mass index, *EU* European Union, *FDA* US Food and Drug Administration, *GLP-1* glucagon-like peptide-1, *LEPR* leptin receptor, *MAOI* monoamine oxidase inhibitor, *MC4R* melanocortin 4 receptor, *MTC* medullary thyroid carcinoma, *POMC* pro-opiomelanocortin, *PCSK1* proprotein convertase subtilisin/kexin type 1 *T2D* type 2 diabetes

Management with Co-Existing Comorbidities

Children with severe obesity are at an increased risk for developing metabolic complications due to a complex interplay of insulin resistance, adipose tissue dysfunction and chronic low-grade inflammation. These children are particularly susceptible to comorbidities such as type 2 diabetes mellitus (T2DM), dyslipidemia and NAFLD, with these conditions often manifesting during late childhood or adolescence [131]. Obesity also contributes to the exacerbation of existing childhood diseases. Therefore, the therapeutic approach must extend beyond weight reduction to include targeted metabolic control. Routine biochemical assessment for glycaemic status, lipid profile, fasting insulin and liver enzymes can be provide valuable insights.

The management should involve a low glycaemic index and a high-fibre diet rich in micronutrients and omega-3 fatty acids to improve insulin sensitivity and lipid metabolism, as well as appropriate pharmacotherapy if necessary. Likewise, a gradual weight loss of 7–10% of body weight in children with obesity and NAFLD has been shown to reduce hepatic steatosis and inflammation; vitamin E may be used in non-diabetic children with biopsy-proven non-alcoholic steatohepatitis under guidance [132]. A multidisciplinary team, including paediatric endocrinologists, dietitians and hepatologists, must provide individualised care, ensure regular monitoring and achieve long-term cardiometabolic health outcomes.

Health Habit Monitoring

Digital health technologies, including mobile health habit monitoring apps and artificial intelligence (AI)-driven tools, are emerging as valuable adjuncts in managing childhood obesity [133]. These apps enable real-time tracking of dietary intake, physical activity, sleep patterns and screen time, thereby promoting self-awareness and adherence to healthy behaviours. Integration with wearable devices allows for continuous monitoring and personalised feedback [134]. Moreover, AI algorithms can analyse individual data, such as age, growth trajectory, metabolic parameters and food preferences, to generate personalised nutrition plans tailored to the child's specific needs [135]. Such AI-driven interventions help optimise caloric balance, ensure micronutrient adequacy and adapt recommendations dynamically based on progress and compliance. These technologies empower both clinicians and families, fostering sustainable lifestyle changes and improving long-term obesity outcomes in pediatric populations.

Pharmacotherapy

As Fig. 3 suggests, pharmacotherapy should be considered only if no weight reduction has been noted following a formal lifestyle intervention. Several pharmacological agents have been approved for managing childhood obesity in select regions, with significant geographical variation in approval status (Table 1). The approval status of the available pharmacotherapy options to manage childhood obesity in different parts of the world is due to concerns over safety and lack of efficacy data in children [124]. Currently, no anti-obesity medication is approved for use in Indian children and adolescents. Orlistat and phentermine are approved in the USA for adolescents aged ≥ 12 and ≥ 16 years, respectively, but not in the European Union (EU). Liraglutide and semaglutide, both glucagon-like peptide-1 (GLP-1) receptor agonists, achieve a notable BMI reduction and are approved in the USA and EU (age ≥ 12 years) for obesity with or without type 2 diabetes. Setmelanotide, an MC4R agonist, is approved for rare genetic obesity in children aged ≥ 6 years in the USA and EU. Other drugs, such as topiramate and naltrexone/bupropion, are used off-label but have not been approved by the US Food and Drug Administration (FDA) for paediatric obesity.

Bariatric Surgery

Indications for bariatric surgery in children are similar to those in adults and should be only considered following a formal lifestyle intervention and a trial of anti-obesity medications. However, a significant difference between these

Table 2 Three broad components of approaches for population-based obesity prevention

Structures within the government	Population-wide policies and initiatives	Community-based interventions
1. Leadership	1. Policies influencing food environments: i. marketing of unhealthy foods and non-alcoholic beverages to children ii. nutrition labelling iii. food taxes and subsidies iv. fruit and vegetable initiatives	1. Increased fruit and vegetable consumption
2. "Health-in-all" policies	2. Physical activity policies	2. Reduced consumption of beverages high in sugar (e.g. "soft" drinks)
3. Dedicated funding for health promotion	3. Social marketing campaigns	3. Reduced consumption of foods high in fat, saturated fat, salt and sugar
4. NCD monitoring systems		4. Decreased television viewing and other screen-based activities
5. Workforce capacity		5. Increased competitive and non-competitive sports participation
6. Networks and partnerships		6. Increased active transport to schools
7. Standards and guidelines		

NCD Non-communicable disease

two patient populations is that children should have at least reached Tanner stage 4 with near adult height before embarking on surgery [124].

Genetic Testing and Gene-Targeted Therapy

Genetic testing should only be done in a specific group of young-onset severe obesity with a family history of consanguinity or young-onset morbid obesity in the family. The presence of hyperphagia, developmental delay and other malformations may also provide a clinical clue to the underlying genetic defect [136]. Gene-targeted therapies like bremelanotide (MC4R agonist) are in different stages of clinical trials and may be valuable tools for those who harbour a specific mutation [137].

Preventive Approaches to Childhood Obesity

The best course of action is preventing a child from gaining excess body weight. The American Academy of Paediatrics (AAP) believes that obesity prevention is as important a public health priority as treatment. A literature review has suggested various approaches that need to be kept in mind while dealing with managing childhood obesity. These approaches can be broadly divided into individual and population-based approaches (Table 2; Fig. 4).

Population-Based Approach

Regarding the containment of this emerging public health issue, it is pertinent to mention that the determinants of obesity are complex and varied, and it is essential to recognise that

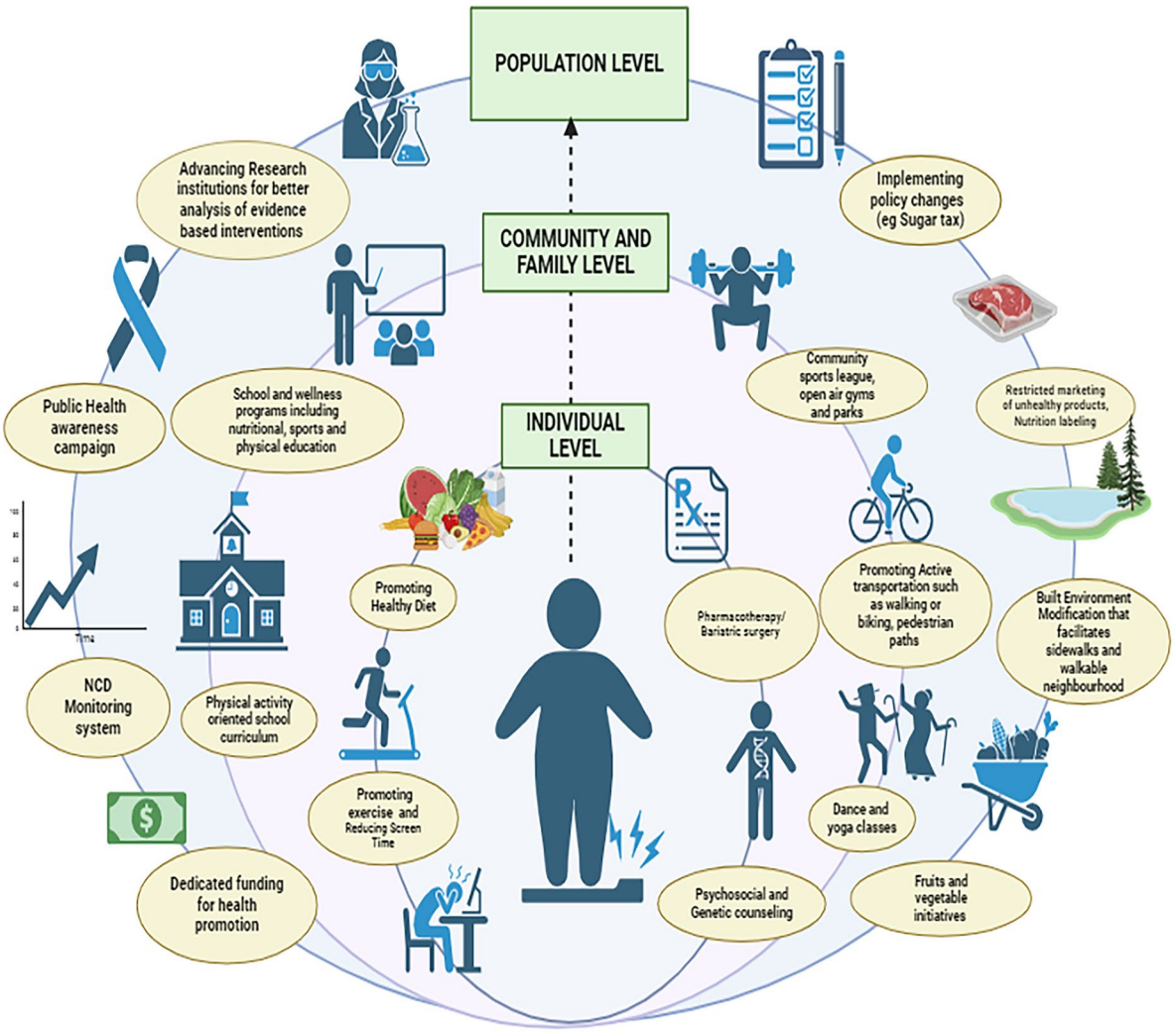


Fig. 4 Approaches to managing childhood obesity at different levels

no single intervention is likely to prevent childhood obesity. Actions to prevent childhood obesity must be taken in multiple settings, including various approaches and involving various stakeholders. Sustained interventions are likely to be required at several levels, such as at an individual level in schools and community settings to effect behavioural change and changes in such sectors as agriculture, food manufacturing, education, transportation and urban planning. Each intervention may have minimal effects when assessed in isolation but can constitute significant components of an overall strategy. Childhood obesity prevention efforts need to be tightly integrated with other efforts to control all significant NCD risk factors. NCD risk factors are embedded in the framework of society and influenced by many areas of national policy [138]. For many LMICs, actions for obesity prevention need to be integrated with the related issues of food security and undernutrition. Finally, interventions for childhood obesity prevention need to be part of existing plans and programmes that aim to improve diets and physical activity. Interventions that utilise specific settings should also strive for integration.

Table 3 Pre-natal and post-natal factors affecting the pre-disposition to childhood obesity

Pre-natal factors	Post-natal factors during infancy
1. Genetic predisposition: family history of obesity, genetic mutations (e.g. FTO, MC4R genes)	1. Genetic influences on feeding behavior: inherited tendencies toward emotional eating or preference for high-calorie foods
2. Maternal smoking during pregnancy: increases risk of low birth weight followed by rapid postnatal catch-up growth, predisposing to obesity	2. Rapid weight gain in infancy: early-life accelerated weight gain linked to increased obesity risk
3. Maternal weight gain during pregnancy: excessive weight gain increases the likelihood of obesity in offspring	3. Infant feeding practices: formula feeding versus breastfeeding and early introduction of solid foods
4. Maternal blood sugar levels: gestational diabetes leading to fetal hyperinsulinaemia and increased fat storage	4. Sleep patterns: short sleep duration linked to disrupted appetite-regulating hormones (ghrelin and leptin)
5. Maternal nutrition and diet: high intake of sugar, fat, and processed foods influencing foetal adipogenesis	5. Microbiome development: early-life exposure to antibiotics affecting gut microbiota composition linked to obesity
6. Epigenetic modifications: maternal diet and stress affecting foetal DNA methylation and gene expression associated with obesity	6. Parental feeding behaviour: overfeeding, restrictive feeding practices, and lack of responsive feeding
7. Hormonal influence: in-utero exposure to glucocorticoids affecting metabolic programming and fat distribution	7. Physical activity levels: limited physical activity opportunities influencing early movement patterns
8. Environmental exposures: exposure to endocrine-disrupting chemicals (e.g., BPA, phthalates) influencing fat storage	8. Socioeconomic factors: parental education, income and access to nutritious foods affecting feeding practices
9. Maternal mental health: prenatal stress, anxiety, and depression affecting fetal HPA axis development, increasing obesity risk	9. Psychosocial environment: parental stress, anxiety and depression impacting feeding practices and emotional eating
10. Intrauterine growth restriction: low birth weight with rapid postnatal catch-up growth increasing obesity risk	10. Cultural influences and feeding norms: cultural beliefs and norms influencing dietary patterns and feeding practices
11. Maternal physical activity and sedentary behavior: sedentary lifestyle leading to excessive weight gain and metabolic changes in the fetus	11. Feeding style and parent–child interaction: authoritative vs. permissive feeding styles affecting appetite regulation and eating behaviours
12. Paternal influence: paternal obesity and lifestyle factors influencing offspring obesity risk through epigenetic modifications	12. Digital media exposure: screen time and exposure to food advertising influencing dietary preferences and sedentary behaviour
	13. Social support and parenting practices: availability of social support networks, parental modelling, and parenting practices influencing feeding and physical activity levels

Table 3 continued

Pre-natal factors	Post-natal factors during infancy
	14. Infant temperament and self-regulation: difficult temperament or poor self-regulation skills predisposing to emotional eating and obesity

BPA Bisphenol A, *FTO* Fat mass and obesity-associated, *HPA* hypothalamic-pituitary-adrenal, *MC4R* melanocortin 4 receptor

In many cases, schools, for example, have been able to integrate behaviour modification education into their existing curriculum. Approaches for population-based obesity prevention can be divided into three broad components (Table 3):

a. Structures within the government. Such structures will support childhood obesity prevention policies and interventions.
b. Population-wide policies and initiatives. These involve the development of an enabling environment. Such policies and initiatives direct policy actions and help create environments that support healthy diets and physical activity.
c. Community-based interventions. These are multicomponent interventions and programmes, typically applied across multiple settings, tailored to the local environment and implemented locally.

Pre-Natal and Post-Natal Through this approach, prevention should begin before childbirth, with an emphasis on healthy maternal weight, breastfeeding, appropriate weight gain in infancy and parental role modelling of healthy behaviours. Several risk factors that have been identified as possible determinants of later-life obesity act within the first 1000 days of life (i.e. from conception to age 2 years). Of these, the most common risk factors that affect a child's health in later life are listed in Table 2. The feeding practices of breastfeeding mothers may differ from those who use formula. Mothers who breastfeed may be more responsive to their child's hunger cues and may be less likely to restrict feeding and diminish their child's ability to self-regulate food intake. At age 3 years, BMI *z*-scores are lower in children who were exclusively breastfed for at least 6 months. Finally, we consider the influence of the nutritional exposure of children from age 6 to 24 months on the risk of obesity. This particular time of the child's life offers unique challenges, mainly due to the transition from breast/formula feeding to a complementary early solid diet. Reviewing the literature, rapid weight gain is the most frequently analysed risk factor for obesity in this specific period. Even though definitions vary, a significant association has been confirmed between higher infant weight gain and weight status in later ages. Botton et al. reported that weight growth velocity at 3 months of age is associated with the higher body weight in adolescence (odds ratio [OR] for a 1-SD increase 1.52; 95% CI 1.04–2.22) [139].

Preschool Parents with obesity or those who have restrictive feeding practices are significantly more likely to have preschool children with overweight/obesity. Furthermore, mothers who use food as a reward or in response to emotions, as well as those who restrict intake based on weight or fat content of food, are more likely to have children with disordered eating (i.e. overeating or emotional eating) and higher BMI *z*-scores [140]. Anticipatory guidance toward feeding practices may help change preschoolers' food preferences, such as including more fruits in the diet and avoiding "junk food". Such guidance may also help to prevent other obesogenic behaviours, such as emotional eating and poor hunger/satiety cues [141].

School-Age and Older The role of diet and physical activity strategies in preventing childhood obesity has been studied extensively. Various studies on the effects of interventions on school-age children using different strategies

have reported little effect of such strategies on reducing the prevalence of overweight and obesity, showing only that the effects of the strategies can only maintain children's BMI over time. The most substantial evidence is provided through a recent Cochrane review by Brown et al., which included 153 RCTs [142]. Most of these studies were based in high-income and upper-middle-income countries, with the majority of studies [80] targeting children aged 6 to 12 years. It should be noted here that the BMI score a widely accepted tool to assess whether a child is overweight. Here, we calculate a score based on their height and how much they weigh and then relate this to the weight and height of many children their age in their country.

Children Aged 0–5 Years There is moderate-certainty evidence that combined interventions of diet + physical activity, when compared with controls, reduce BMI; neither diet nor physical activity interventions alone compared with controls reduced BMI. This means that interventions that include diet and physical activity can reduce the risk of obesity (BMI *z*-score and BMI) in young children aged 0 to 5 years.

Children Aged 6 to 12 Years and 13 to 18 Years It was concluded that interventions that only focus on physical activity can reduce the risk of obesity (BMI) in children aged 6 to 12 years and adolescents aged 13 to 18 years. In these age groups, there is no evidence that interventions that only focus on diet are effective, and some evidence that diet combined with physical activity interventions may be effective.

Actionable Interventions and Policy Recommendations

This review highlights the role of important actionable interventions and policy recommendations structured into evidence-based, practical interventions that specifically focus on the individual, community, healthcare and policy levels to prevent and manage childhood obesity effectively while aligning with the WHO guidelines and global best practices.

1. During early childhood (pre-natal and post-natal period), major interventions should target the promotion of maternal nutrition programs by implementing structured nutritional guidance for pregnant women to reduce risks of gestational diabetes and foetal macrosomia, both of which are linked to childhood obesity. At the same time, it is essential to encourage breastfeeding through support programs that help promote breastfeeding exclusively for the first 6 months, as recommended by WHO, as breastfeeding is crucial for decreasing the risk of childhood obesity. At the same time, parents should be made aware of healthy weaning foods and portion control to avoid overfeeding in infancy, as well as the importance of regular monitoring of the growth trajectories through community-based primary health care clinics or specialised growth monitoring clinics at higher centres to keep a check on excessive weight gain in the initial stages of life.
2. As the child grows, the role of school-based interventions in keeping a check on BMI cannot be ignored. Various interventions have been found to be effective. For example, implementing healthy school meal policies has been reported to ensure balanced, nutritious meals in school cafeterias that align with the national or sub-national nutrition guidelines. Introducing age-appropriate nutrition literacy programmes and teaching children about healthy food choices can help them further minimise the consumption of calorie-dense foods. Every attempt to mandate at least 60 min of structured physical activity daily should be made, aligning with global recommendations.
3. Apart from schools, we also recommend involving the family and community to further our efforts. Expanding parental

awareness on healthy meal planning, portion control, and reducing the use of ultra-processed foods at home is crucial. Parents significantly affect a child's exposure to risk factors as the latter tries to imitate the former. Every opportunity to connect with the parents should be utilised to sensitise them to the importance of reducing sedentary behavior and screen time and of promoting the WHO-recommended screen time limits (≤ 1 h/day for toddlers, ≤ 2 h/day for older children). The family should be encouraged to prefer home-cooked meals over processed foods.

4. We strongly recommend strengthening the healthcare system for obesity prevention and management. Integrating BMI-for-age and waist circumference monitoring into routine paediatric check-ups allows early detection of obesity risk. Additionally, screening for metabolic risk factors, such as insulin resistance, fatty liver and HTN, is essential for preventing complications. Providing mental health support through psychological counselling and behavioural therapy helps manage emotional eating and body image issues, which are upcoming issues. Establishing multidisciplinary obesity clinics with paediatricians, dietitians, psychologists and physical activity specialists ensures comprehensive care and effective management.
5. Economic and policy-level reforms like increased taxation on sugar-sweetened beverages and processed foods, similar to policies in Mexico and Singapore, are known to reduce consumption and encourage healthier eating. Enforcing regulations on food marketing to children can limit exposure to unhealthy promotions. To increase access to nutritious foods, subsidies for fresh fruits, vegetables and whole grains should be provided. Like the traffic light system, front-of-pack labelling can help consumers make informed choices.
6. Urban and environmental planning helps target the obesogenic environment. Community-based fitness initiatives also help control the obesogenic environment by developing accessible public play areas, walking trails and safe cycling infrastructure, and encouraging outdoor activities. Investing in walkable neighbourhoods and safe play areas, including parks, pedestrian pathways and cycling tracks, promotes physical activity and reduces sedentary behaviour. Integrating structured physical activities into schools and workplaces supports active lifestyles for both children and parents. Ensuring supermarket access in underserved areas prevents food deserts and encourages healthier eating.
7. Lastly, utilising technology like digital health education programmes delivered through mobile apps and SMS reminders effectively promotes healthy eating and active lifestyles. AI-based personalised nutrition and exercise plans are promising and allow tailored recommendations. Social media regulations restricting targeted advertising of unhealthy foods and mukbang videos help protect children from harmful marketing and create a healthier digital environment.

CONCLUSIONS

Childhood obesity is a complex and growing public health challenge with significant implications for individual and societal well-being. This review underscores the escalating burden of childhood obesity globally, highlighting disparities across regions and socioeconomic groups. The multifactorial causes of childhood obesity, including hereditary, environmental, behavioural, cultural and socioeconomic factors, interact throughout different developmental stages, necessitating a comprehensive life course approach. Additionally, molecular and metabolic alterations play a pivotal role in obesity's persistence into adulthood, emphasising the need for early interventions. Effective prevention and management require a multilevel strategy encompassing healthcare system strengthening, economic and policy reforms, urban and environmental planning and leverage of digital technology. Integrating routine obesity

screening, metabolic risk assessments and mental health support within paediatric care is essential. Policy-level interventions, including taxation on sugar-sweetened beverages, food marketing regulations and subsidies for healthy foods create supportive environments for healthier choices. Urban planning and community-based initiatives encourage active lifestyles, while digital health education and AI-based personalised interventions offer innovative solutions. This review provides a robust framework for actionable interventions aligned with WHO guidelines and global best practices. By targeting multiple life stages and societal levels, these strategies aim to curb the rising trend of childhood obesity, mitigate associated health risks and promote long-term health. Continued research and policy integration are crucial for achieving sustainable outcomes and reducing the global burden of childhood obesity.

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Declarations

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