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Formula feeding: Evidence for health, nutrition and early childhood development during the critical first 1000 days from rural China

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ABSTRACT

Infant and young child feeding is crucial to physical and mental development and long-term health. In developing settings, the widespread use of formula raises concerns regarding the growth and development of infants. However, little is known about the role that formula may play in the observed poor infant health, nutrition and development in developing areas. Using a rich panel dataset of 1802 infants aged 6–30 months collected at six months intervals from rural China, we describe the prevalence of formula feeding, identify households that are more likely to use formula, and examine the associations between formula feeding with various dimensions of infant health, nutrition and development outcomes: anthropometric measurements, infant illnesses, cognitive, psychomotor, and socio-emotional development. We found infant formula is widely used in rural China, and it is significantly associated with infant health and nutritional outcomes - formula feeding is associated with a 4.59-point increase in Hemoglobin concentration and a 13% reduction in anemia prevalence, but is also associated with a 0.11-sd decrease in weight-for-age and height-for-age Z-scores. Moreover, infants are more likely to be fed formula when their families have higher socioeconomic status, when their parents have out-migrated, and when they have no siblings. Our findings suggest that there is a need to promote age-appropriate feeding practices, with an emphasis on families who are particularly in need of guidance, to reduce over-reliance on formula, and provide support for mothers to delay their migration or create pathways for rural parents to bring their children with them when they migrate.

1. Introduction

Infant and young child feeding practices are a cornerstone of early childhood development (World Health Organization, 2014).

Abbreviations: SES, Socioeconomic Status; SD, Standard Deviation; WHO, World Health Organization; UNICEF, United Nations International Children's Emergency Fund; RMB, Renminbi; IYCF, Indicators of Infant and Young Child Feeding; Hb, Hemoglobin Concentrations; HAZ, Height-for-age Z-scores; WAZ, Weight-for-age Z-score; WHZ, weight-for-height Z-scores; BSID-I, Bayley Scales of Infant Development, First Edition; MDI, Mental Development Index; PDI, Psychomotor Development Index; ASQ, SE: Social-Emotional component of the Ages and Stages Questionnaire; 2SLS, Two-Stage Least Squares.

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Research on child nutrition emphasize the key role played by the 'critical first 1000 days' including the prenatal period and the first two years after birth, and nutritional insults in this period are difficult to reverse at later ages (Hoddinott et al., 2008; Maluccio et al., 2009; Martorell et al., 1994; Victora et al., 2008). The World Health Organization (WHO) recommends that children be exclusively breastfed for the first six months after birth and continue to breastfeed non-exclusively until age two or older (Organisation mondiale de la santé & Unicef, 2003). However, researches find that less than 40% of infants in developing countries are exclusively breastfed for the first six months after birth (Cai et al., 2012; Lauer et al., 2004) and few continue breastfeeding for the recommended duration (Lauer et al., 2004; Wang et al., 2005). Early introduction of other liquids and breast milk substitutes, such as infant formula, is responsible for low breastfeeding rate. A study by UNICEF reports a large share of infants under six months consume formula worldwide, including 37% in Latin America and 28% in East Asia (Keeley et al., 2019). Moreover, global market trends indicate the formula consumption increases at higher rates in developing settings: Between 2008 and 2013, the sales of infant formula grew by 72% in middle-income countries such as China, Brazil, Peru and Turkey, compared to 41% globally (Baker et al., 2016).

What factors might be leading families to choose formula over breastmilk? Research in high-income countries has found that socioeconomic status is positively associated with increased breastfeeding and decreased formula usage (Barton, 2001; Gibbs & Forste, 2014; Kurinij & Shiono, 1991). However, these are not representative of developing countries, where the factors underlying formula use may be significantly different. In fact, a study of factors related to formula use in 20 developing countries find that maternal education and work status are associated with higher formula usage (Yarnoff et al., 2014), suggesting a need for more regionally-specific scholarship.

The wide use of formula also raises questions regarding the links between formula use and infant health, nutrition and development. Some studies have found that formula feeding is associated with lower hemoglobin levels (Assis et al., 2004), higher rates of infant illnesses such as diarrhea (American Academy of Pediatrics, 2007; Ball & Wright, 1999; Brown et al., 1989; Coppa et al., 2006; Dewey et al., 1995), and weight gain (Gibbs & Forste, 2014; Heinig et al., 1993). In contrast, a recent study finds no significant associations between formula use and illnesses, height, or weight among children aged 6–12 months in 20 developing countries (Yarnoff et al., 2013). This inclusive nature of the literature is mainly due to the fact that previous studies have drawn on cross-sectional data rather than tracking infants over time, and thus little is known about how formula feeding may be linked to child health and nutrition as children aged.

The literature is similarly mix on the role of formula played in early childhood development. Some studies have found that formula-fed infants have significant disadvantages in cognitive, psychomotor and socio-emotional development compared to breastfed infants (Anderson et al., 1999; Bier et al., 2002; Drane & Logemann, 2000; Fewtrell et al., 2002; Morley et al., 2004). Other studies have found no significant difference in early cognitive development (American Academy of Pediatrics, 2007; O'Connor et al., 2003). However, a major limitation of existing literature is that all studies draw on samples from developed countries, thus little is known about the relationships between formula feeding and child development in developing settings, where nutritional deficiencies in early childhood lead to adverse developmental outcomes for many children (Walker et al., 2007).

Rural China provides a unique opportunity to examine formula use in a developing context. China has experienced unprecedented economic growth in recent decades, as well as a corresponding dramatically increase in formula consumption (Baker et al., 2016; Keeley et al., 2019). China's formula market accounted for nearly one-quarter of the global market in 2013 (Gira Consultancy & Research, 2018), and has been growing at an annual rate of 20% (Ubic Consulting, 2014). Studies have found more than half of infants under six months of age in China have consumed formula (Qiu et al., 2010; Tang et al., 2014), and the rate increases after six months of age (Liu et al., 2013; Tang et al., 2014).

At the same time, rural China is similar to other developing settings in terms of child health, nutrition and early childhood development. An official report shows that 30%− 50% of rural infants aged 6–12 months in China are at risk of anemic (Chinese Center for Disease Control & Prevention, 2014), which is similar to the other developing countries such as South Africa (48%) (Smuts et al., 2005) and Iran (32%) (Monajemzadeh & Zarkesh, 2009). Moreover, Wang et al. (2019) estimates that nearly half of children under age three in rural China are at risk of cognitive delay, 53% are at risk of psychomotor delay, and 30% are at risk of socio-emotional delay, all of which may be due in part to nutritional deficiencies (Wang et al., 2019). Considering that 59% of children under five in china are from rural areas, these previous findings indicate that a large share of children across China face health risks (National Bureau of Statistics of China, 2010). However, to date, no studies have examined the role that formula may play in the observed poor infant health, nutrition and early childhood development in rural China.

The overall goal of this paper is to describe formula feeding behavior in rural China and examine the associations between formula feeding practices and infant health, nutrition and development. To do so, we first describe infant and young child feeding behaviors and the prevalence of formula feeding among rural families in China. Second, we identify which types of families are more likely to use formula to feed their children. Finally, we examine the associations between formula feeding and infant health, nutrition and development outcomes.

2. Methods

2.1. Sample selection

We conducted our study from April 2013 to April 2015 in 11 counties located in Qinba mountain region, a remote rural area that has been nationally recognized as a concentrated poverty-stricken area in China (China State Council Leading Group Office of Poverty Alleviation & Development, 2012). The per capita income of rural residents in sample area was $1032 (RMB 6503) in 2013, lower than the national rural per capita income of $1412 (RMB 8896) (National Bureau of Statistics of China, 2014).

We followed a multistage cluster sampling design to select infants and households. First, all townships (the middle administrative level between county and village) in each counties were selected into the study, with the exception of the township in each county that housed the county seat (which is typically wealthier and more urban than other areas of the county), and townships without any villages with a population of 800 or more. In total, 174 townships were included. Next, we used official government data to compile a list of villages in selected townships and randomly selected two villages in each township. Finally, in each sample village, we obtained a list of all registered births over the past 12 months from local family planning officials, and enrolled all infants within our target age range (6 −12 months) in two waves, first in April 2013 and again in November 2013. If a village had fewer than five infants within our target age range, we randomly selected an additional village in the same township and continued to randomly selecting additional villages until five infants per township had found. Overall, our baseline sample consisted of 1802 infants in 351 rural villages across 174 townships in Qinba mountain region.

2.2. Data collection

We collected data in four survey waves, including a baseline survey in April/November 2013 and three follow-up surveys conducted at six-month intervals for each cohort of infants until April 2015. Thus, surveys were conducted when infants were 6–12 months old, 12–18 months old, 18–24 months old and 24–30 months old. In the baseline survey, 1802 children and their caregivers were successfully interviewed, while 1592, 1499, and 1490 infants in subsequent surveys, resulting in an overall attrition rate of 20.54%. Most attrition in our sample was due to family out-migration to other parts of the prefecture, or province. Importantly, both probit and BGLW tests found very limited evidence for non-random attrition.

In each survey wave, teams of trained enumerators collected detailed information on the characteristics of infants and households, as well as on infant feeding practices and indicators of infant health, nutrition and developmental. We have obtained written permissions to translate and use each questionnaire and measures from the relevant rights holder.

2.2.1. Infant and household characteristics

We collected socioeconomic and demographic data from all households. The primary caregiver was first identified in each household as the family member who was the most responsible for the infant's care (typically the infant's mother or grandmother). Enumerators then administered to the primary caregiver a detailed survey of infant characteristics, including infant's gender, whether the infant has siblings, and whether the infant was born prematurely. The age of each infant was obtained from his/her birth certificate. Enumerators also collected information on household characteristics, including maternal age, paternal migration, grandmother's health status (based on self-reported general health), and the primary caregiver's educational attainment. In addition, the survey team collected data on household owned equipment, appliances and vehicles to represent household's economic status by constructing a standardized family asset index.

2.2.2. Infant feeding practices

Each survey wave collected detailed information on infant feeding practices. Following Indicators of Infant and Young Child Feeding (IYCF), an instrument developed by WHO (World Health Organization, 2010), we collected detailed month-by-month histories of breastfeeding and formula feeding for each infant. Thus, we can identify infants who had been breastfed, formula-fed, or a mix of both over time. In addition, we recorded complementary foods infant ate the previous day based on caregiver's recall and constructed an index of dietary diversity.

2.2.3. Infant health, nutrition and development

We first collected anthropometric measurements for each infant, including hemoglobin concentration (Hb), height and weight. To assess anemia status, nurses from Xi'an Jiaotong Medical School tested Hb for all infants using a HemoCue Hb 201 + finger prick system (Hemocue, Inc, Angelholm, Sweden). We defined anemia as Hb less than 110 g/L, according to internationally accepted standards for our sample age group (World Health Organization, 2011). Nurses next measured height of each infant to a precision of 0.1 cm and weight to a precision of 0.1 kg. Physical indicators of height and weight were used to construct three standardized indicators following WHO growth charts: height-for-age Z score (HAZ), weight-for-age Z-score (WAZ), and weight-for height Z score (WHZ) (World Health Organization, 2008). Following internationally-recognized cutoffs, we considered infants to be at risk of underweight, stunted, and wasted if they were more than two standard deviations below the international mean for WAZ, HAZ, and WHZ, respectively (World Health Organization, 2008). Additionally, infants' general health at survey period were indexed by the frequency of common illnesses that infants had experienced in the past month, including diarrhea, fever, cold, cough, and indigestion.

Infant' cognitive and psychomotor development were assessed using the Bayley Scales of Infant Development (BSID-I), an internationally-recognized tool for assessing infant and toddler development, which is used extensively in psychological and health literature (Rubio-Codina et al., 2016). The BSID-I has been formally adapted to the Chinese and environment and scaled according to an urban Chinese sample (Yi et al., 1993). The BSID-I was administered by enumerators who attended a week-long formal training course, including 2.5 days of practical training in the field. The BSID-I yields two indices - the mental development index (MDI) and the psychomotor development index (PDI). Both indices were scaled to have an expected mean of 100 and a standard deviation of 16, and infants with a scaled index value below 80 were considered at risk of developmental delay (Yi, 1995).

To measure socio-emotional development, we used the Social-Emotional component of the Ages and Stages Questionnaire (ASQ: SE). ASQ:SE is an instrument administered to caregivers aims at screening for socio-emotional delay. It consists of a series of age-appropriate questions about infant behavior and caregiver-infant interactions. In our study, ASQ:SE scores were standardized to a

Table 1
Summary statistics of sample infants and households at baseline ($N = 1802$).

	Frequency (n)	Percentage (%) / Mean ± SD
Panel A: Infant Characteristics		
(1) Gender		
Male	949	52.66
Female	853	47.34
(2) Age		
6 Months	186	10.32
7 Months	300	16.65
8 Months	275	15.26
9 Months	275	15.26
10 Months	297	16.48
11 Months	315	17.48
12 Months	154	8.55
(3) Has Siblings		
Yes	373	20.7
No	1429	79.3
(4) Premature Birth		
Yes	198	10.99
No	1604	89.01
(5) Mother is Primary Caregiver		
Yes	1477	82.41
No	325	17.59
Panel B: Household Characteristics		
(6) Maternal Age		
Age $\leq$ 25	899	49.89
Age $>$ 25	903	50.11
(7) Paternal Migration		
Yes	1012	56.16
No	790	43.84
(8) Grandmother Health Status		
Healthy	761	42.23
Unhealthy	1041	57.77
(9) Primary Caregiver Education		
$\leq$ 9 years	1557	86.40
$>$ 9 years	245	13.60
(10) Asset Index	1802	-0.00 ± 1.20
Panel C: Health and Development Outcomes		
(11) Hemoglobin Concentration (g/L)	1802	109.11 ± 12.69
(12) Total Percent Anemia (Hb $<$ 110 g/L)	887	49.22
(13) Mild Anemia (100 g/L $\leq$ Hb $<$ 110 g/L)	528	29.3
(14) Moderate Anemia (70 g/L $\leq$ Hb $<$ 100 g/L)	347	19.26
(15) Severe Anemia (Hb $<$ 70 g/L)	12	0.67
(16) Underweight (WAZ <-2)	20	1.11
(17) Stunted (HAZ <-2)	67	3.72
(18) Wasted (WHZ <-2)	43	2.39
(19) Cognitively Delay (Bayley MDI $<$ 80)	243	13.49
(20) Psychomotor Delay (Bayley PDI $<$ 80)	435	24.14
(21) Socio-emotional Delay (1 =yes; 0 =no)	722	40.07
(22) Illnesses in Past Month (times)	1802	1.08 ± 0.97

Notes: Descriptive statistics of infant and household characteristics when infants were 6–12 months of age. The table shows the mean and standard deviation of infant and household characteristics for the full sample.

mean of zero according to the infant's age, and higher scores were indicative of socio-emotional development issues. We generated an indicator that equals one if the infant was deemed at risk for socio-emotional delay and zero if not.

2.3. Statistical approach

To identify correlations between formula feeding and infant and household characteristics, we estimated the following linear probability model:

$$FormulaFeeding_{it} = \beta_0 + \beta_1 X_{it} + \varepsilon_{it} \quad (1)$$

where $FormulaFeeding_{it}$ is the formula feeding status of infant i in wave t, which equals one if the infant was formula fed at survey time and zero if not, and X_{it} is a vector of infant and household characteristics. $\varepsilon_{it}$is an error term clustered at village level. We calculated heteroskedasticity-robust standard errors in all regressions to improve efficiency.

To study the associations between formula feeding and our outcomes of interest, we conduct a multivariate analysis controlling for infant fixed effects as follows:

Table 2
Descriptive statistics of feeding behaviors in infant aged 6–30 months in rural China ($N = 6383$).

	6–12 Months		12–18 Months		18–24 Months		24–30 Months	
	Number (1)	Percent (%) (2)	Number (3)	Percent (%) (4)	Number (5)	Percent (%) (6)	Number (7)	Percent (%) (8)
(1) Any Breastfeeding	1049	58.21	343	21.54	78	5.20	35	2.35
(1.1) Exclusive Breastfeeding	6	0.33	0	0	0	0	0	0
(1.2) Breastfeeding with Food but without Formula	779	43.23	240	15.08	49	3.27	18	1.21
(1.3) Breastfeeding with Food and Formula	264	14.65	103	6.47	29	1.93	17	1.14
(2) Formula-feeding with Food	733	40.68	1033	64.89	1086	72.45	907	60.87
(3) Food Alone	20	1.11	216	13.57	335	22.35	548	36.78
(4) Total	1802	100	1592	100	1499	100	1490	100

Notes: No sample infants consumed formula alone, and none were fed only breastmilk and formula (without complementary food) between the ages of 6–30 months.

$$Outcome_{it} = \alpha_1 + \beta_1 HadFormula_{it} + \beta_2 X_{it} + \omega_t + s_{it} + \eta_i + \varepsilon_{it} \quad (2)$$

where $Outcome_{it}$ represents the outcome of interest for infant i in survey wave t; $HadFormula_{it}$ is a dummy variable, which equals one if the infant i had ever been formula fed at survey wave t and zero otherwise; $X_{it}$is a vector of infant and household characteristics and cohort fixed effects; $\omega_t$represents survey wave indicators; s_{it} is enumerator fixed effects designed to capture measurement error; η_i represents infant fixed effects; and ε_{it} is an error term clustered at the village level, thus accounting for correlation within villages as well as serial correlation over time (Bertrand et al., 2004).

3. Results

3.1. Sample description

Table 1 presents the descriptive statistics of infant and household characteristics at baseline (when infants were 6–12 months). As shown in panel A, of the 1802 infants, slightly over half (53%) were male – a ratio that reflects the overall gender imbalance in China (National Bureau of Statistics of China, 2014). Around 79% were only children, and 11% were born prematurely. The mother was the primary caregiver for 82% of infants. As demonstrated in in panel B, the majority (86%) of caregivers had completed 9 years of schooling or less. Half (50%) of mothers were over 25 years of age, 44% of the fathers had out-migrated, and 42% of grandmothers reported themselves as healthy.

Panel C shows infant health, nutrition and developmental outcomes at baseline. Infants in our sample were at high risk of anemia, psychomotor delays and socio-emotional delays. In baseline survey, 887 of the 1802 infants had Hb below 110 g/L, resulting in an overall anemia prevalence of 49%. The prevalence of mild anemia and moderate anemia were 29% and 19%, respectively. In addition, approximately 24% of sample infants were at risk of psychomotor delay, and almost 40% of infants were at risk of socio-emotional delay. For both psychomotor and socio-emotional delay, the prevalence of children at risk is higher than 15%, a commonly found prevalence rate in a healthy population. In contrast, the share of infants at risk for cognitive delay in our sample was normal (13%). We also found normal rates of stunting, wasting, and being underweight. Finally, on average, every infant in the sample was ill at least once in the past month.

3.2. Infant feeding behaviors

Table 2 presents the share of infants who were breastfed, formula-fed, and fed complementary food in each of the four survey waves. At 6–12 months, the total share of formula-fed infants was 55%, including 41% who did not consume breast milk and 14% who consumed breastmilk (both consume complementary food). Meanwhile, a similar percentage of 58% of infants consumed some breastmilk. In contrast, only six infants (0.33%) were exclusively breastfed between 6 and 12 months of age, and only 1% of infants in this age range consumed complementary food alone.

As the infants grew older, the rate of breast milk consumption decreased significantly, while the rates of formula and complementary feeding increased. At the age of 12–18 months, the percentage of infants who consumed any breastmilk decreased from 58% to approximately 22%, meaning that 36% of infants weaned in this six-month time span. At the same time, the percentage of infants who ate formula with food rose by 24% points (from 41% to 65%), and the percentage of infants who ate food alone rose by 12% points (from 1% to 13%). At 18–24 months, another 16% of sample infants had weaned, and only 5% of infants still consumed breast milk. The majority (72%) of infants was consuming formula with solid food at this time, and 22% were eating food alone. By 24–30 months, the share of infants eating food alone increased to 37%, while the share of those consuming formula with food decreased to 61%, a trend that would likely continue as children grow.

Table 3
Correlates of formula feeding behaviors in infant aged 6–30 months in rural China.

Dependent Variables: Formula-fed (1 =yes; 0 =no)	6–12 Months (1)	12–18 Months (2)	18–24 Months (3)	24–30 Months (4)
Panel A: Infant Characteristics				
(1) Age (months)	0.00	0.02 **	-0.02 **	-0.03 **
	(0.01)	(0.01)	(0.01)	(0.01)
(2) Gender (1 =female)	-0.01	0.03	0.01	-0.01
	(0.02)	(0.02)	(0.02)	(0.03)
(3) Has Siblings (1 =yes)	-0.06 *	-0.08 *	-0.04	0.02
	(0.03)	(0.03)	(0.03)	(0.03)
(4) Premature Birth (1 =yes)	0.12 **	0.02	0.04	0.06
	(0.03)	(0.04)	(0.03)	(0.04)
(5) Mother is Primary Caregiver (1 =yes)	-0.46 **	-0.03	-0.12 **	-0.08 **
	(0.02)	(0.03)	(0.02)	(0.03)
(6) Dietary Diversity (score)	0.07 **	0.06 * *	0.06 **	0.07 * *
	(0.01)	(0.01)	(0.01)	(0.01)
Panel B: Household Characteristics				
(7) Maternal Age 25 (1 = >25 years)	-0.00	0.00	0.03	0.02
	(0.02)	(0.02)	(0.03)	(0.03)
(8) Parental Migration (1 =yes)	0.05 *	0.14 * *	0.05 *	0.05 *
	(0.02)	(0.02)	(0.02)	(0.03)
(9) Grandmother is Healthy (1 =yes)	-0.02	-0.01	0.00	0.02
	(0.02)	(0.02)	(0.02)	(0.03)
(10) Primary Caregiver Education (1 = >9 years)	0.10 **	0.07 *	0.07 *	0.04
	(0.03)	(0.04)	(0.03)	(0.04)
(11) Asset Index	0.02 *	0.02 *	0.02 *	0.03 *
	(0.01)	(0.01)	(0.01)	(0.01)
(12) Constant	0.67 **	0.11	0.98 **	0.96 **
	(0.06)	(0.11)	(0.14)	(0.21)
(13) Observations	1802	1592	1499	1490

Notes: The result presents coefficients and village cluster robust standard errors (in parentheses) from our linear probability model, where the dependent variable equals 1 if the infant was formula fed at the time of the survey time and 0 if not. All regressions control for recruitment cohort. * indicates significant at 5%; ** indicates significant at 1%.

3.3. Correlates of formula feeding

Table 3 presents correlations between formula feeding and infants and families characteristics. Our data show that of all the factors linked to infant formula intake, socioeconomic status was the most strongly correlated. Households with higher asset indices, as well as households in which fathers had out-migrated were more likely to feed their infants formula. These correlations are positive and significant across all age groups. Moreover, infants who had more diverse diets were also more like to be fed formula at all age. Several other variables also linked with formula feeding, though only across certain age groups. When the mother was not the primary caregiver, the infant was significantly more likely to be formula fed at 6–12 months, 18–24 months and 24–30 months. Additionally, when the primary caregiver had over nine years of education, they were significantly more likely to feed their infant formula at 6–12 months, 12–18 months, and 18–24 months. Finally, infants who had siblings were less likely to fed formula at the age of 6–12 and 12–18 months, and premature infants were more likely to be formula fed at the age of 6–12 months.

3.4. Formula feeding and infant health, nutrition and development

In this sub-section, we compare the health, nutrition and development outcomes of formula-fed infants and infants who were never formula fed. Table 4 presents the results of our bivariate analysis. Across all four time-periods, formula-fed infants had higher hemoglobin concentrations than non-formula-fed infants, as well as lower anemia rates. Additionally, starting from 12 to 18 months, formula-fed infants also had superior outcomes in terms of WAZ, HAZ and WHZ scores when compared to infants who were never formula-fed. In contrast, the results show that at 6–12 months, formula-fed infants had lower psychomotor development, lower socio-emotional development, and higher rates illness compared to infants who had never consumed formula. However, the relationship with psychomotor development reversed at 12–18 and 18–24 months, and all three relationships eventually became insignificant. There was no significant difference in cognitive development across any age groups between formula-fed infants and infants who had never been formula-fed.

Table 5 presents the results of multivariate analysis to check the robustness of the above findings. Column 1 presents the associations between formula feeding and our outcomes of interest without controls; Column 2 presents the results while controlling for infant and household characteristics; and Column 3 additionally controls for child fixed effects. In all three specifications, formula feeding was associated with significantly higher hemoglobin concentrations and lower rates of anemia. In our most preferred specification (Column 3), formula feeding was associated with a 4.59-point increase in hemoglobin concentrations and a 13% reduction in anemia prevalence.

In contrast, the relation of formula feeding to other health and developmental outcomes varies across the three specifications. The

Table 4
Bivariate associations between formula feeding and early childhood health, nutrition and development outcomes ($N = 6383$).

Has Infant been Formula-fed:		6–12 Months			12–18 Months			18–24 Months			24–30 Months		
		Yes	No	Difference *P*-Value	Yes	No	Difference *P*-Value	Yes	No	Difference *P*-Value	Yes	No	Difference *P*-Value
		(1)	(2)	(1) - (2)	(3)	(4)	(3) - (4)	(5)	(6)	(5) - (6)	(7)	(8)	(7) - (8)
	% (n)	55.33 (997)	44.67 (805)	-	77.39 (1232)	22.61 (360)	-	88.13 (1321)	11.87 (178)	-	89.66 (1336)	10.34 (154)	-
(1) Hb Concentrations (g/L)	Mean ± SD	112.23 ± 11.85	105.25 ± 12.64	0.00	116.86 ± 12.37	110.65 ± 12.24	0.00	118.93 ± 11.92	113.06 ± 13.74	0.00	118.71 ± 12.94	115.84 ± 11.51	0.01
(2) Anemia (Hb below 110 g/L)	% (n)	38.62 (385)	62.36 (502)	0.00	24.76 (305)	39.17 (141)	0.00	18.77 (248)	33.15 (59)	0.00	21.18 (283)	27.27 (42)	0.08
(3) Bayley MDI	Mean ± SD	96.78 ± 16.77	96.85 ± 17.04	0.94	94.77 ± 18.44	93.98 ± 16.85	0.47	84.83 ± 19.34	85.25 ± 18.01	0.78	81.19 ± 22.08	77.99 ± 20.41	0.09
(4) Bayley PDI	Mean ± SD	89.35 ± 17.26	91.02 ± 17.45	0.04	96.52 ± 23.60	91.11 ± 23.32	0.00	104.28 ± 19.73	99.97 ± 18.10	0.01	103.04 ± 19.36	101.06 ± 20.27	0.23
(5) Socio-emotional Score	Mean ± SD	-0.07 ± 26.95	-2.86 ± 25.20	0.03	5.11 ± 28.20	4.39 ± 24.67	0.66	7.99 ± 31.46	6.27 ± 31.84	0.49	17.54 ± 37.94	19.95 ± 38.69	0.46
(6) WAZ Score	Mean ± SD	0.39 ± 0.95	0.32 ± 1.02	0.12	0.14 ± 0.88	-0.07 ± 0.85	0.00	0.03 ± 0.89	-0.25 ± 0.98	0.00	0.04 ± 0.88	-0.19 ± 0.89	0.00
(7) HAZ Score	Mean ± SD	0.10 ± 1.17	0.07 ± 1.16	0.62	-0.20 ± 1.13	-0.34 ± 1.11	0.03	-0.22 ± 1.11	-0.44 ± 1.13	0.02	-0.07 ± 1.06	-0.36 ± 1.02	0.00
(8) WHZ Score	Mean ± SD	0.42 ± 1.09	0.34 ± 1.19	0.14	0.32 ± 0.99	0.15 ± 1.09	0.01	0.21 ± 0.10	-0.02 ± 1.11	0.00	0.07 ± 1.02	0.00 ± 1.05	0.47
(9) Illnesses in Past Month (times)	Mean ± SD	1.12 ± 0.98	1.02 ± 0.96	0.02	1.14 ± 1.11	1.04 ± 0.89	0.12	0.96 ± 0.93	0.99 ± 0.83	0.67	0.85 ± 0.97	0.77 ± 0.86	0.32

Notes: Times ill in past month shows how many times the child had been ill with diarrhea, fever, cold, cough or indigestion in the past month.

Table 5
Multivariate associations between formula feeding and child health, nutrition and development outcomes.

		OLS/Logit	OLS/Logit	FE
		(1)	(2)	(3)
(1) Hemoglobin Concentration (g/L)		6.04 **	5.29 **	4.59 **
		(0.44)	(0.45)	(0.60)
	N	6383	6383	6383
(2) Anemia (Hb below 110 g/L)		-0.78 **	-0.70 **	-0.72 **
		(0.07)	(0.08)	(0.15)
	N	6383	6363	4262
(3) Bayley Mental Development Index (MDI)		0.56	-0.09	-0.09
		(0.65)	(0.64)	(0.88)
	N	6383	6383	6383
(4) Bayley Psychomotor Development Index (PDI)		1.68 *	1.03	-1.31
		(0.74)	(0.77)	(0.97)
	N	6383	6383	6383
(5) Socio-emotional Score		1.36	1.73	0.15
		(1.10)	(1.09)	(1.48)
	N	6383	6383	6383
(6) Weight for Age Z-Score (WAZ)		0.16 **	0.08	-0.11 **
		(0.05)	(0.05)	(0.03)
	N	6383	6383	6383
(7) Height for Age Z-Score (HAZ)		0.12 *	0.04	-0.11 **
		(0.05)	(0.05)	(0.04)
	N	6383	6383	6383
(8) Weight for Height Z-Score (WHZ)		0.13 **	0.08	-0.06
		(0.05)	(0.05)	(0.05)
	N	6383	6383	6383
(9) Times Ill in Past Month		0.08 *	0.10 **	0.06
		(0.03)	(0.03)	(0.05)
	N	6383	6383	6383
(10) Wave Dummies		Yes	Yes	Yes
(11) Controls			Yes	Yes
(12) Child Fixed Effects				Yes

Notes: Table shows coefficients and standard errors on a variable indicating formula feeding in a logit regression with anemia indicator and OLS regressions with several development and health outcomes on the left as dependent variables. Column (1) shows the coefficient on formula feeding in an OLS or logit regression pooling data across waves and controlling for survey wave dummies. Column (2) shows coefficients from pooled OLS or logit regressions additionally controlling for baseline controls and dietary diversity. Column (3) additionally controls for child fixed effects. All regressions with Bayley MDI, PDI and socio-emotional scores as dependent variables additionally control for tester fixed effects, and regressions with health and nutrition outcomes as dependent variables additionally control for nurse fixed effect. Standard errors are clustered at the village level. N is the total number of observations in each regression. * indicates significance 5%; ** indicates significance at 1%.

Table 6
First-stage estimation of formula feeding.

Dependent variable: Formula feeding (1 =yes)	
(1) leave-one-out prevalence of formula feeding in the same village	0.65 **
	(0.11)
(2) Infant Characteristics	Yes
(3) Household Characteristics	Yes
(4) Observations	6383

Notes: Statistics show coefficients and robust standard errors (in parentheses) from first-stage regression, where formula feeding decisions are regressed on the leave-one-out prevalence of formula feeding in the same village and infant and household characteristics. Standard errors are clustered at the village level. * indicates significance 5%; ** indicates significance at 1%.

results presented in Column 1 show that infants who had been formula fed had higher psychomotor development levels and higher WAZ, HAZ, and WHZ scores compared to non-formula-fed infants. However, infants who had been formula fed were significantly more likely to be ill in the past month. After controlling for additional infant and household characteristics (Column 2), the associations between formula feeding and increased number of illnesses remained significant; however, the associations between formula feeding and psychomotor development, WAZ, HAZ and WHZ were no longer statistically significant. Finally, after accounting for time-invariant heterogeneity using child fixed effects (Column 3), formula feeding was associated with a 0.11-sd decrease in WAZ and HAZ, but the results shown no statistically significant associations between formula feeding and number of illnesses, cognitive, psychomotor or socio-emotional development outcomes in our sample.

Table 7
Impacts of formula feeding: 2SLS estimates.

(1) Hemoglobin Concentration (g/L)		5.08 *
		(2.51)
	N	6383
(2) Anemia (Hb below 110 g/L)		-1.35 **
		(0.45)
	N	4262
(3) Bayley Mental Development Index (MDI)		-2.08
		(3.06)
	N	6383
(4) Bayley Psychomotor Development Index (PDI)		-1.68
		(3.67)
	N	6383
(5) Socio-emotional Score		0.51
		(2.10)
	N	6383
(6) Weight for Age Z-Score (WAZ)		-0.26 *
		(0.11)
	N	6383
(7) Height for Age Z-Score (HAZ)		-0.55 **
		(0.17)
	N	6383
(8) Weight for Height Z-Score (WHZ)		0.16
		(0.17)
	N	6383
(9) Times Ill in Past Month		0.08
		(0.22)
Observations	*N*	6383

Notes: Table shows coefficients and standard errors on predicted formula feeding form the first-stage regression in a logit regression with anemia indicator and OLS regressions with several development and health outcomes on the left as dependent variables. All regressions control for age, dietary diversity and child fixed effects. N is the total number of observations in each regression. * indicates significance 5%; ** indicates significance at 1%.

3.5. Robustness checks

Since there may exist unobserved factors, such as home environment, that could influence both the decision of formula feeding and the infant's health, nutrition, and development, formula feeding decisions are endogenous. In this subsection, we conducted several robustness checks, including the use of instrumental variable, pseudo treatment test, and pseudo outcome test.

3.5.1. Instrumental variable

Intuitively, infants' health, nutrition, or development, are unrelated to the presence of formula feeding among other infants in the same village; however, peer influence may induce the mother to feed their infant formula. Therefore, we constructed the leave-one-out prevalence of formula feeding in the same village as an IV for the formula feeding decision, and conducted a two-stage least squares (2SLS) regression. The result of the first-stage regression is shown in Table 6, where formula feeding decisions are regressed on the leave-one-out prevalence of formula feeding in the same village and infant and household characteristics. The estimated result confirmed that the leave-one-out prevalence of formula feeding in the same village is a significant predictor of formula feeding decision - when formula feeding was more prevalent in the village, mothers were more likely to feed their infants formula.

We then use the predicted formula feeding decisions from the first stage regression to estimate the impact of formula feeding on infants' health, nutrition, and development. The results are shown in Table 7. The estimated coefficients further validated the results from our multivariate analysis with fixed effect in Table 5 (column 3). The estimated coefficients indicated that formula feeding led to a 5.08-point increase in hemoglobin concentrations, a 14% reduction in anemia prevalence, as well as a 0.26-sd decrease in WAZ and a 0.55-sd decrease in HAZ. As 2SLS regression estimates the local average treatment effect, the estimated coefficients are typically larger than those in our multivariate analysis using OLS.

3.5.2. Placebo test

As previously noted, the decision to use infant formula was not random, which may lead to inherent differences. Thus, we conducted pseudo treatment tests and pseudo outcome tests to verify our results. First, to conduct the pseudo treatment tests, we randomly assigned our sample into a "pseudo formula feeding group" and a "pseudo non-formula feeding group" using random numbers generated by computers. We then performed the pseudo treatment test 100 times using the same model in Eq. (2). Table 8 shows the results of the pseudo treatment test, which suggested there was no significant effect on any of our outcomes. And the distributions of the placebo effect for all outcomes were close to zero. Second, we used the hours spent on watching TV collected during the fourth survey wave as a pseudo outcome to conduct the pseudo outcome test. Since formula feeding does not appear to affect the hours spent on watching TV, we expected that the estimated effect of formula feeding on the pseudo outcome would be insignificant. Table 9 shows

Table 8
Pseudo treatment test.

		OLS/Logit	OLS/Logit	FE
		(1)	(2)	(3)
(1) Hemoglobin Concentration (g/L)		-0.29	-0.23	-0.27
		(0.31)	(0.30)	(0.32)
	N	6383	6383	6383
(2) Anemia (Hb below 110 g/L)		0.02	0.00	0.04
		(0.06)	(0.06)	(0.08)
	N	6383	6363	4262
(3) Bayley Mental Development Index (MDI)		0.10	0.23	0.04
		(0.45)	(0.44)	(0.44)
	N	6383	6383	6383
(4) Bayley Psychomotor Development Index (PDI)		-0.24	-0.09	-0.21
		(0.53)	(0.54)	(0.55)
	N	6383	6383	6383
(5) Socio-emotional Score		0.23	0.51	0.33
		(0.77)	(0.74)	(0.76)
	N	6383	6383	6383
(6) Weight for Age Z-Score (WAZ)		-0.01	-0.01	-0.01
		(0.02)	(0.02)	(0.01)
	N	6383	6383	6383
(7) Height for Age Z-Score (HAZ)		0.01	0.00	-0.02
		(0.03)	(0.03)	(0.02)
	N	6383	6383	6383
(8) Weight for Height Z-Score (WHZ)		-0.02	-0.01	0.01
		(0.03)	(0.03)	(0.02)
	N	6383	6383	6383
(9) Times Ill in Past Month		0.04	0.04	0.00
		(0.03)	(0.03)	(0.03)
Observations	*N*	6383	6383	6383

Notes: Table shows coefficients and standard errors on a pseudo treatment variable generated by computer in a logit regression with anemia indicator and OLS regressions with several development and health outcomes on the left as dependent variables. Column (1) shows the coefficient on pseudo treatment variable in an OLS or logit regression pooling data across waves and controlling for survey wave dummies. Column (2) shows coefficients from pooled OLS or logit regressions additionally controlling for baseline controls and dietary diversity. Column (3) additionally controls for child fixed effects. All regressions with Bayley MDI, PDI and socio-emotional scores as dependent variables additionally control for tester fixed effects, and regressions with health and nutrition outcomes as dependent variables additionally control for nurse fixed effect. Standard errors are clustered at the village level. N is the total number of observations in each regression. * indicates significance 5%; * * indicates significance at 1%.

Table 9
Pseudo outcomes test: wave 4.

Dependent variable: Hours spent on watching TV		
(1) Formula-fed (1 =yes; 0 =no)	0.15	0.11
	(0.09)	(0.09)
(2) Infant characteristics		YES
(3) Household characteristics		YES
(4) Observations	1490	1490

Notes: Table shows coefficients and standard errors (in parentheses) on formula feeding in an OLS regression with hours spent on watching TV as dependent variables. Standard errors are clustered at the village level. * indicates significance 5%; ** indicates significance at 1%.

the result of the pseudo outcome test, which there was no effect of formula feeding on hours spent on watching TV.

3.6. Heterogeneity analysis

To further test the robustness of our main results and explore the potential heterogeneity of the impacts of formula feeding, we studied how the effects of formula feeding on infants' health, nutrition, and development outcomes vary by premature birth and household asset, respectively. The results are reported in Table 10, which revealed similar results as in Table 5 and reconfirmed the significant impacts of formula feeding on infants' health and nutrition outcomes. The results in panel A suggested that although premature birth was associated with low hemoglobin concentrations and a higher prevalence of anemia rate, formula feeding has significant positive impacts on hemoglobin concentration and anemia for infants who born premature. Formula feeding also had negative impacts on cognitive development and WAZ for infants who born premature. The result in panel B indicated that household assets generally had positive impacts on the majority of infant outcomes, with formula feeding reinforcing the positive impacts on hemoglobin concentrations and cognitive development among infants form wealthier households.

Table 10
Heterogeneity Analysis.

	Hemoglobin Concentration (g/L)	Anemia (Hb below 110 g/L)	Bayley Mental Development Index (MDI)	Bayley Psychomotor Development Index (PDI)	Socio-emotional Score	Weight for Age Z-Score (WAZ)	Height for Age Z-Score (HAZ)	Weight for Height Z-Score (WHZ)	Times Ill in Past Month
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: premature birth									
Has infant been formula-fed	4.59 * *	-0.70 * *	0.32	0.44	1.42	-0.04	-0.04	0.04	0.10 * *
	(0.43)	(0.09)	(0.63)	(0.74)	(1.09)	(0.03)	(0.04)	(0.04)	(0.03)
Formula feed * premature	6.43 * *	-0.85 * *	-3.48 *	0.37	-0.76	-0.19 *	-0.09	-0.13	-0.03
	(1.54)	(0.27)	(1.73)	(2.19)	(2.90)	(0.09)	(0.11)	(0.12)	(0.10)
Premature (1 =yes; 0 =no)	-4.20 * *	0.50 *	1.41	-2.49	1.04	0.14	-0.00	0.15	0.02
	(1.41)	(0.24)	(1.70)	(1.99)	(2.50)	(0.10)	(0.12)	(0.12)	(0.09)
Panel B: household asset									
Has infant been formula-fed	5.26 * *	-0.79 * *	0.10	0.49	1.32	-0.05 *	-0.04	0.03	0.09 * *
	(0.43)	(0.09)	(0.60)	(0.723)	(1.01)	(0.03)	(0.04)	(0.04)	(0.03)
Formula feed * asset Index	0.74 *	-0.05	1.26 * *	0.23	-0.28	0.01	0.01	-0.01	-0.01
	(0.36)	(0.07)	(0.49)	(0.47)	(0.79)	(0.02)	(0.02)	(0.03)	(0.03)
Asset Index	0.75 *	0.06	1.65 * *	1.90 * *	-1.24	0.07 * *	0.11 * *	0.03	0.01
	(0.33)	(0.06)	(0.45)	(0.45)	(0.65)	(0.02)	(0.03)	(0.03)	(0.02)
Observations	6383	6363	6383	6383	6383	6383	6383	6383	6383

Notes: Statistics show coefficients and robust standard errors (in parentheses) from our regression models. Standard errors are clustered at the village level. * indicates significance 5%; * * indicates significance at 1%

4. Discussion and conclusion

Appropriate feeding ensures an adequate provision of nutrients beginning in the early stages of life, which is crucial to ensuring good physical and mental development and long-term health. Despite the proliferation of evidence demonstrating the lifelong health benefits of exclusive and continued breastfeeding for children, fairly too few children are breastfed as recommended (World Health Organization, 2022). The growth in infant formula sales and widespread use of formula raise concerns about health risks introduced by inappropriate feeding in early age. Drawing on panel data from 1802 infants and families collected over four survey waves, this study providing evidence on the role that formula plays in the observed poor infant health, nutrition and early childhood development in developing areas.

We find infant formula is widely used in rural China - more than half of the infants in each age group are formula fed. This represents a much greater prevalence than other developing countries, where studies find about 17% of infant age 6–12 months are formula fed and even fewer children are fed formula after 12 months of age (Yarnoff et al., 2014). We also observe that the breastfeeding rate declines significantly as infant age - the continued breastfeeding rate after 18 months is about 5%, which is consistent with the findings of other studies conducted in rural areas of China (Guo et al., 2013; Liu et al., 2013). However, the observed breastfeeding rates are much lower than those found in other developing countries, where about 68–76% of children are breastfed (Lauer et al., 2004; Yarnoff et al., 2014).

Although formula feeding is common overall among our sample, some families are more likely to feed their infants formula than others. We find that higher socioeconomic status is significantly associated with increased formula feeding. Families with higher asset index values are significantly more likely to feed their infants formula. Similarly, infants whose primary caregivers have more than nine years of education and infants whose parents have out-migrated (linked to higher household income) are also more likely to be formula-fed. These results stand in contrast to Barton (2001), which find that higher income and higher levels of maternal education in the U.S. are related to lower levels of formula use and higher levels of exclusive breastfeeding (Barton, 2001). However, our results are consistent with a study in 20 developing countries by which find that a wealthier and more educated woman are more likely formula feed their children (Yarnoff et al., 2014).

These findings suggest a difference in the relationship of socioeconomic status to formula feeding in developing versus developed settings. This may be due to higher opportunity costs of breastfeeding for wealthier and better-educated women in developing settings. Yarnoff et al. (2014) find that although women with higher education levels have more knowledge of infant feeding, they are also likely to work outside home, and the consequent increased income may outweigh the financial cost of formula (Yarnoff et al., 2014). Evidence suggests that rural Chinese mothers face a similar opportunity cost to breastfeeding as women in other developing settings: it is common for rural mothers to out-migrate to urban areas for better jobs, and many families consider parental out-migration an economic necessity (Chang et al., 2019; Yue et al., 2020). Formula may therefore represent a convenient alternative to households that can afford it. Indeed, this is consistent with our data – infants are more likely to fed formula in families where the mother is not the primary caregiver.

In addition to socio-demographic factors that influence formula feeding, dietary diversity is also significantly associated with increased formula feeding. Although we cannot provide direct evidence of the reasons behind this finding, it may reflect the role of socioeconomic status in infant feeding. Considering that family asset value is positively correlated with formula feeding, relatively better socioeconomic status may allow families to afford a greater diversity of foods for their infants. Appendix file 1 provides a description of infant dietary diversity and its association with formula consumed. We find that formula-fed infants have significantly greater dietary diversity than infants who are not fed formula (Appendix: Table 1). However, among the subsample of infants who consume formula, infants who are not breastfed consume more formula than infants who also breastfed (Appendix: Figure 1), and the quantity of formula intake is negatively correlated with dietary diversity (Appendix: Table 2). In other words, infants consume more formula when they are not breastfed, and infants who consumed more formula had less diverse diets than infants who consumed less. This suggests that caregivers may be over-relying on formula as a substitute for both breastmilk and a diverse diet of solid foods.

We also find that formula feeding is significantly associated with infant health and nutrition in development settings. Using in-depth panel data, we are able to track infants across time and address the issues of endogeneity by controlling for child fixed-effect. To address the endogeneity problem and reveal the causal effect, we constructed the leave-one-out prevalence of formula feeding in the same village as an IV to estimate the effect of formula feeding on the children's outcomes. Firstly, we find formula feeding is robustly and consistently associated with significantly higher hemoglobin concentrations and lower rates of anemia, even after controlling for infant and household characteristics and child fixed effects or using the IV estimate. Similar results have been reported in other studies surveyed in rural China (Luo et al., 2014; Wang et al., 2009). This result is not surprising, as most infant formulas are fortified with iron and other micronutrients. However, the positive relationship between socioeconomic status and formula usage found in our sample suggests that infants from poorer families may not have enough iron-fortified food and may be at a higher risk for anemia. This is also a significant finding, considering that nearly half of infants aged 6–12 month in our sample are at risk of anemia, which is a common trend in rural China (Dong et al., 2013; Wang et al., 2013; Yue et al., 2016). The WHO recommends that in communities where the prevalence of iron deficiency anemia exceeds 40%, all infants should receive iron supplementation (World Health Organization, 2001). Although our results show that formula feeding has a positive association with anemia reduction, using infant formula should not be promoted in view of the benefits of breastfeeding, and it is not a cost-effective solution (Morley et al., 2004). Therefore, iron supplementation could instead take the form of iron-rich foods or micronutrient supplements, rather than infant formula.

Secondly, although formula feeding is associated with decreased anemia among sample infants, formula-fed infants show a greater number of illnesses compared to infants who have never formula-fed. This finding is consistent with previous studies, which have

Table A.1
Dietary diversity among sample infants by age in rural China (N = 6383).

Dietary Diversity		6–12 Months	12–18 Months	18–24 Months	24–30 Months
(1) Full Sample		3.00	4.23	4.63	4.63
	N	1802	1592	1499	1490
(2) Formula-fed infants		3.23	4.41	4.76	4.84
	N	997	1136	1115	924
(3) Non-formula-fed Infants		2.72	3.80	4.24	4.29
	N	805	456	384	566
(3.1) Exclusive Breastfeeding or breastfeeding with food		2.71	3.52	3.90	4.28
	N	785	240	49	18
(3.2) Food Alone		3.01	4.11	4.29	4.29
	N	20	216	335	548
(6) Difference (2) - (3) *(P-value)*		0.00	0.00	0.00	0.00
(7) Difference (2) - (3.1) *(P-value)*		0.00	0.00	0.00	0.06
(8) Difference (2) - (3.2) *(P-value)*		0.40	0.00	0.00	0.00

Notes: For the initial baseline survey in April of 2013, dietary diversity is measured by the number of the following food categories fed to the child in the past week. The following surveys (conducted in October of 2013, April of 2014, October of 2014, and April of 2015) measure dietary diversity as the number of food categories fed to the child the previous day. Food categories include: 1. grains, roots and tubers; 2. legumes and nuts; 3. dairy products; 4. flesh foods (meat, fish, poultry and liver/organ meats) 5. eggs; 6. vitamin-A rich fruits and vegetables; 7. other fruits and vegetables. N is the total number of observations in each category.

Table A.2
Relationship between dietary diversity and formula quantity ($N = 3634$).

Dependent Variables: Get Minimum Diet Diversity (1 =yes; 0 =no)	OLS	OLS	FE
	(1)	(2)	(3)
(1) Liters of Formula Intake	-0.07 *	-0.05	-0.06 *
	(0.03)	(0.03)	(0.03)
(2) Age (month)		0.02 **	0.02 **
		(0.00)	(0.00)
(3) Gender (1 =female)		0.01	0.00
		(0.02)	(0.02)
(4) Has Siblings (1 =yes)		-0.02	-0.00
		(0.02)	(0.02)
(5) Premature Birth (1 =yes)		0.01	0.02
		(0.02)	(0.02)
(6) Mother is the Primary Caregiver (1 =yes)		0.05 **	0.04 *
		(0.02)	(0.02)
(7) Maternal Age 25 (1 => 25 years)			0.02
			(0.01)
(8) Paternal Migration (1 =yes)			0.00
			(0.01)
(9) Grandmother is Healthy (1 =healthy)			0.02
			(0.01)
(10) Primary Caregiver Education (1 =>9 years)			0.12 **
			(0.02)
(11) Asset Index			0.03 **
			(0.01)
			(0.02)
(12) Wave Dummies	Yes	Yes	Yes
(13) Constant	0.52 **	0.30 **	0.27 **
	(0.03)	(0.05)	(0.05)
(14) Observations	3634	3634	3634

Notes: Statistics show coefficients and village cluster robust standard errors (in parentheses) from our linear probability model, where the dependent variable equals to 1 if dietary diversity equals 4 or more. All regressions control for recruitment cohort. * indicates significant at 5%; * * indicates significant at 1%.

found bottle feeding to be linked with increased risk of gastrointestinal illness compared to breastfeeding, possibly because the iron content of formulas can promote the growth of illness-causing bacteria (Angulo et al., 2008; Baltimore et al., 1978; Koopman et al., 1985). However, in our sample, the association between formula feeding and illnesses becomes insignificant after adding child fixed effects, which contradicts previous studies, and more research are need to better understand this finding.

Thirdly, we find similar variations in the correlations between formula feeding and child anthropometric outcomes. Our multivariate analysis controlling for child fixed effects suggests that formula feeding is significantly negatively associated with WAZ and HAZ scores. HAZ measures cumulative nutritional investments and illnesses over time, whereas WAZ is thought to reflect more immediate dietary intake (World Health Organization, 2008). Given that formula-fed infants have greater dietary diversity on average,

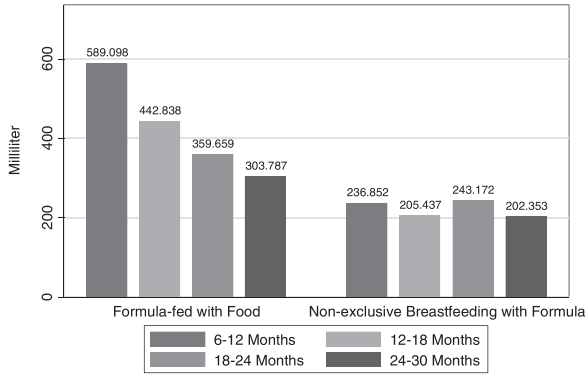

Fig. A1. The quantity of formula milk intake the previous day (Milliliter).

the negative relationships between formula feeding, HAZ and WAZ are even more troubling. One possible reason may be that formula-fed infants are more frequently ill, which may result in the stunting of their physical development (Wang, 2008).

Finally, we find overall no significant association between formula feeding and psychomotor, cognitive or socio-emotional development among sample infants. However, it is important to note that despite the lack of correlations to formula feeding, the results find a high share of sample infants to be at risk for psychomotor and socio-emotional delays, consistent with the low developmental levels for infants observed in other studies in China's rural areas (Luo et al., 2014; Yue et al., 2020).

Our study faces two limitations that should be addressed in future research. First, as our survey is limited to one rural region in northwestern China, we cannot claim that our results are representative of rural China as a whole. The widespread use of infant formula and its correlations with infant health, nutrition, and development outcomes may vary in other areas; therefore, further studies conducted in different areas of China and other developing areas are recommended. Second, there are many factors related to early childhood development beyond infant feeding, such as interactive parenting inputs. Future research should examine the effects of both parenting inputs and nutritional inputs to determine the relative importance of each factor in health, nutrition and early childhood development.

Despite these limitations, our paper has several key strengths. First, this is the only panel study to document formula feeding prevalence and examine the socioeconomic and demographic factors associated with formula feeding in a developing setting. Second, our research is the first to offer a comprehensive examination of the role of formula feeding played in various dimensions of infant health, nutrition and early childhood development in developing areas, while addressing issues of endogeneity using child fixed effects. Moreover, this is the first study to examine the associations between formula and infant cognitive and psychomotor development in a developing context, which provides a strong basis for future research in rural China and other developing settings.

Based on the results of this paper, we offer two policy recommendations. First, we recommend that actions needed to promote age-appropriate feeding practices among rural families in order to improve infant health and nutrition. This can be done through home visiting education programs that assess infant nutritional status and inform caregivers of the nutritional needs of their children (Gilmore & McAuliffe, 2013; Peacock et al., 2013). In particular, such programs should focus on families who are particularly in need of guidance for infant feeding practices to reduce over-reliance on formula, including poor families, families in which mothers have out-migrated or intend to out-migrate, the primary caregivers have low educational attainment and families with firstborn children. Second, because formula feeding is closely related to maternal migration in China, we recommend that China's central government work with provincial and local governments to provide support and encouragement for mothers to delay their migration until the child is more than two years old. Alternatively, we recommend that China's central and local governments work together to create pathways for rural parents to bring their children with them when they migrate.

DeclarationsEthics approval and consent to participate

All participating caregivers gave their oral consent for both their own and their infant's involvement in the study. Ethical approval for all procedures was obtained from the Stanford University Institutional Review Board (IRB) (Protocol ID 25734), and from the Sichuan University Ethical Review Board (Protocol ID 2013005–01).

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CRediT authorship contribution statement

AY, MC, ZY, and YS developed the study concept and design; AY, MC, ZY, CG, QS and YS oversaw fieldwork and data collection; MC, ZY and CG, QS analyzed the data; AY, MC, ZY, CG, QS and YS interpreted the results; AY, MC and ZY drafted the article. All authors were involved in critical revisions of the manuscript and approved the final version for publication.

Declaration of Competing Interest

The authors declare that they have no competing interests. The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Data Availability

Data will be made available on request.

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Consent for publication

My manuscript does not contain data from any individual person.

Appendix

Appendix file 1. Infant dietary diversity and formula intake.

This document provides a description of infant dietary diversity and its association with formula consumed. Appendix: Table A1 presents dietary diversity scores for the full sample and compares the dietary diversity of formula-fed and non-formula-fed infants in each age group. The data shows that infants who were fed formula had significantly greater dietary diversity than infants who were not fed formula (including exclusively breastfed infants, infants breastfed with food, and infants who ate food alone). Across the four age groups, formula-fed infants scored at least 0.5 points higher in dietary diversity than non-formula fed infants. Moreover, although all infants had the greatest increase in dietary diversity between 6 and 12 months and 12–18 months of age (consistent with the fact that 36% were weaned in this period), those infants who were fed formula had greater increase in dietary diversity (3.23 at 6–12 months to 4.41 at 12–18 months) compared to infants who were not fed formula (2.72 at 6–12 months to 3.80 at 12–18 months). Throughout the next two time periods (18–24 months and 24–30 months), formula-fed infants continued to have more diverse diets than non-formula-fed infants. When we compare infants who consumed breastmilk without formula (with or without consuming solid food) to those infants who ate solid food alone, the data show that although infants who ate food alone had greater dietary diversity before 24 months, this difference ultimately diminished by 24–30 months. In fact, for those infants who were fed food alone, there was no increase in dietary diversity after 18 months of age.

Although formula-fed infants show greater dietary diversity than non-formula-fed infants, among formula-fed infants, the data show variations in dietary diversity by the quantity of formula consumed. The following analysis focuses specifically on the subsample of formula-fed infants. Specifically, we first summarize the quantity of formula milk infants drank the previous day for each group and then examine whether there is relationship between the quantity of formula consumed and infant dietary diversity.

The quantity of formula milk consumed the previous day is displayed in Appendix: Figure 1. The data show that formula-fed infants who also breastfed consistently consumed less formula than infants who did not consume breastmilk across all time periods. Specifically, we found that at the age of 6–12 and 12–18 months, formula-fed infants who did not consume breast milk drank 589 and 443 milliliters of formula milk, respectively. Both are more than twice the amount of formula consumed by 6–12 month-old and 12–18 month-old formula-fed infants who had also consumed breast milk in the previous day (237 milliliters and 205 milliliters, respectively). The difference in daily formula intake between the two sub-groups eventually narrowed with age, with only about a 100 mL difference remaining at 24–30 months. At 18–24 months, we do observe a 38 milliliter increase in formula intake for infants who also consume breastmilk. However, this increased formula intake is still not enough to close the gap between subgroups: at 18–24 months, non-breastfeeding infants still consumed about 100 mL more than infants who consumed breastmilk.

Additionally, we found a negative relationship between the quantity of formula consumed and infant dietary diversity. Following IYCF standards recommendation that infants should consume a minimum of four food groups per day, the indicator for minimum dietary diversity is set to equal one if an infant's diet incorporated four or more food groups in the previous day and zero if the infant's diet incorporated fewer than four food groups. Appendix: Table A2 presents correlations between the quantity of formula intake and if

infants meet minimum dietary diversity standards. The data show that, of infants that were consuming formula, there was a negative association between the quantity of formula intake and dietary diversity. This means that the more formula the primary caregiver fed to her/his infant, the less likely that infant would receive a sufficiently diverse diet of complementary foods. In addition, the results also show that formula-fed infants were more likely to meet the minimum dietary diversity standard if their mother was the primary caregiver, if the mother was older than 25, if the primary caregiver had over nine years of education, and if the family had a higher household asset index Fig. A1.

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World Health Organization Scope and Impact of digital Marketing Strategies for promoting breastmilk substitutes 2022.

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