

Recent Advances in Management of Pre- and Post-Weaning Diarrhea in Piglets

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Abstract

Piglet diarrhea is one of the major causes of morbidity and mortality in swine production and is associated with substantial economic losses worldwide. This review summarizes recent advances in the prevention and management of diarrhea during the pre-weaning and post-weaning periods. Important pre-weaning interventions include optimization of colostrum intake and sow nutrition, maternal vaccination against enteric pathogens, improved farrowing-house hygiene, appropriate farrowing accommodation, and the provision of probiotics or synbiotics to neonatal piglets. Gradual weaning and creep feeding may facilitate gastrointestinal adaptation, whereas diets with reduced crude protein and balanced amino acid profiles can reduce excessive protein fermentation and associated diarrhea after weaning. Several nutritional alternatives to conventional antimicrobials and pharmacological levels of zinc oxide, including organic acids, essential oils, enzymes, and postbiotics, have also been investigated for maintaining intestinal health. Microbiome-oriented interventions, including fecal microbiota transplantation, together with precision feeding, improved housing, molecular diagnostics, and digital monitoring, represent emerging approaches for disease prevention and early intervention. Overall, integrated nutritional, environmental, immunological, and management strategies are likely to provide the greatest benefits when adapted to the specific risk factors and production conditions of individual herds. Further region-specific research is required to evaluate the feasibility, efficacy, safety, and economic suitability of these approaches under Indian production conditions.

Keywords: Antimicrobial Alternatives, Feeding Strategies, Gut Health, Piglet Diarrhea, Pre-Weaning, Post-Weaning, Probiotics.

Introduction

Diarrhea is one of the major causes of morbidity and mortality in piglets during the pre-weaning and post-weaning periods and is associated with substantial economic losses in swine production. Its etiology is multifactorial and involves infectious agents, management practices, nutritional factors, immune status, and environmental stressors (Fairbrother *et al.*, 2005; Lallès *et al.*, 2007). Enterotoxigenic *Escherichia coli* (ETEC), rotavirus, *Clostridium perfringens*, porcine epidemic diarrhea virus (PEDV), and porcine deltacoronavirus are among the important infectious causes of enteric disease in piglets (Jung *et al.*, 2015; Saif *et al.*, 2019). ETEC is an important cause of neonatal diarrhoea because bacterial adhesion to the intestinal epithelium and production of enterotoxins disrupt intestinal fluid and electrolyte homeostasis (Fairbrother *et al.*, 2005). Post-weaning diarrhea is associated with the combined effects of weaning stress, abrupt dietary change, impaired intestinal barrier function, and proliferation of enteric pathogens, including ETEC and *Lawsonia intracellularis* (Lallès *et al.*, 2007; Rhouma *et al.*, 2017).

Recent management approaches have increasingly emphasized prevention through maternal immunity, improved hygiene, nutritional management, probiotics, prebiotics, organic acids, phytogenic additives, enzymes, and other alternatives to conventional antimicrobial interventions (Rhouma *et al.*, 2017; Xu *et al.*, 2020). These approaches are particularly relevant in the context of increasing concerns regarding antimicrobial resistance and the need to reduce unnecessary antimicrobial use in livestock production (Holman & Chénier, 2015). The following sections critically examine recent advances in pre-weaning and post-weaning diarrhea management, with particular emphasis on nutritional, immunological, environmental, microbiome-based, diagnostic, and precision-management approaches.

Pre-Weaning Diarrhea: Risk Factors and Recent Advances

Pre-weaning diarrhea, particularly neonatal porcine diarrhea, occurs during the first weeks of life and is influenced by multiple interacting factors, including inadequate passive immunity, low birth weight, infectious pathogens, environmental contamination, and management practices. Major pathogens include ETEC, *Clostridium perfringens*, rotavirus, and *Cystoisospora suis*. Consequently, recent preventive approaches have focused on strengthening passive immunity, improving environmental hygiene, optimizing neonatal nutrition, and modulating intestinal microbial development.

a. Colostrum and Sow Nutrition

The colostrum consumption is of great importance (200-300 mL per piglet) during the first 24 h. Colostrum contains immunoglobulins (IgG, IgA, IgM) and growth factors; the higher the ratio of IgA/IgG in colostrum, the less piglets with diarrhea (Craig *et al.*, 2019). In one instance, sows had colostrum that was dense with IgA that led to low diarrhea and better survival rates. Mother diet may be improved to increase the quality of colostrum. Antioxidant supplementation (vitamin E, selenium), 8-carotene, omega-3 PUFAs or particular feed additives (e.g. monosodium glutamate, yeast products) of sows significantly increases colostrum Ig and antioxidant capacity (Johnston *et al.*, 2014). As an example, live yeast (e.g. *Saccharomyces cerevisiae*) in sow diets led to better piglet immunoglobulins, and β -carotene enhanced IgG/IgA in colostrum (Jiang *et al.*, 2015). Similarly, omega-3 fatty acids can enrich the milk fatty acid composition and inflammation of the gut in piglets can be reduced (Szabo *et al.*, 2025).

b. Sow Vaccination

An effective method to confer passive immunity to piglets by colostrum is through vaccination of sows that will provide antibodies against the most prevalent enteric pathogens. Enterotoxigenic *Escherichia coli* (ETEC) fimbriae (F4, F5, F6), *Clostridium perfringens* toxins and rotavirus are the most frequently used commercial vaccines and newer vaccines are multivalent or toxin-combination vaccines to offer wider protection. Indicatively, the performance of the litter produced by sows immunized with a new *E. coli*/C. *perfringens* Multivalent vaccine (Enteroporc Coli AC 8 4) in a recent field trial also showed significant improvement in terms of higher weight gain and lower diarrhea symptoms than unvaccinated controls (Arkadiusz *et al.*, 2024). In particular, vaccinated sow piglets at weaning (day 22) had about 0.33 kg more body mass and had a lower number of cases of neonatal piglet diarrhea (NPD). The vaccine contains ETEC fimbrial antigens (F4ac, F5, F6) with *C. perfringens* type A alpha toxoid and beta2 toxoid giving both fimbrial and toxin-associated protection. Evidence of supporting studies also states that maternal immunization helps in reducing morbidity and mortality of piglets due to NPD. Nevertheless, the protective effect

of vaccines depends mostly on the antigenic match of the vaccine strains and the field strains, and multivalent formulations (fimbrial antigens and enterotoxins) tend to have the highest protective effect (Ntakiyisumba *et al.*, 2022; Arkadiusz *et al.*, 2024). Besides commercial preparations, experimental subunit vaccines against porcine epidemic diarrhea virus (PEDV) and rotavirus have also produced promising results, and it is possible to further increase protection both in maternal antibody transfer and piglet immunization in the future.

c. Environmental and Hygiene Measures

The farrowing environment should have better hygiene to ensure the build-up of the pathogen is avoided. Optimized farrowing hygiene protocol (power-wash, detergent, disinfection, drying agent) was demonstrated to reduce NPD drastically: one of the studies reported no cases of diarrhea in piglets of sanitized pens and 22% in poorly cleaned pens (Halpin *et al.*, 2024). It was also through this intervention that antibiotic interventions were reduced by half and piglets grew. Major measures involve the comprehensive cleaning of crates, application of drying and disinfectant chemicals, as well as floor layouts (slatted/drainage) that minimize the fecal contact. Recent studies discuss the issue of microbial control and colonization of the gut; excessive disinfection may decrease the healthy microbes. As an example, excessive consumption of harsh disinfectants may hinder the normal flora. Thus, innovative solutions (e.g. application of useful biosecurity products that suppress pathogens but do not harm commensals) are being investigated. However, simple hygiene (cleaning of farrowing stalls, elimination of birth fluids, correct bedding) is still the most effective measure in the prevention of NPD (Halpin *et al.*, 2024).

d. Probiotics, Prebiotics, and Synbiotics in Neonatal Piglets

The gut flora and immunity can be manipulated by administration of beneficial microbes or substrates in the neonate. The first week evidence of probiotics is however inconclusive; live yeast supplements have a tendency of increasing survival in larger litters, and freeze-dried microbes need to be able to endure gastric passage. In general, prebiotic/probacterial manipulations in suckling piglets have potential to become effective adjunct in the management of NPD, but strain- and dose-specific.

i. Probiotics

Probiotics, defined as live microorganisms that confer health benefits to the host when administered in adequate amounts, have gained significant attention in swine production (Hill *et al.*, 2014; Barba-Vidal *et al.*, 2019). The most extensively studied probiotic genera in piglets include *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, *Bacillus*, and *Saccharomyces* yeasts (Saha *et al.*, 2024; López-Gálvez *et al.*, 2021). Experimental evidence demonstrates that early-life supplementation with probiotics enhances intestinal villus height, increases mucosal IgA production, and improves growth performance (Saha *et al.*, 2024). For instance, oral administration of *Lactobacillus delbrueckii* to neonatal piglets elevated serum IgG levels and reduced colonization by enterotoxigenic *Escherichia coli* (ETEC) (Hu *et al.*, 2018).

Systematic reviews further highlight that probiotics—including heat-killed strains termed “immunobiotics”—can significantly reduce diarrhea incidence by strengthening gut barrier function and promoting competitive exclusion of pathogens (Saha *et al.*, 2024; Hu *et al.*, 2018). Recent studies also indicate that synbiotics provide additional benefits by supporting microbial colonization and immune modulation (Qin *et al.*, 2022). Probiotic supplementation around weaning has been particularly effective in mitigating post-weaning diarrhea (PWD). For example, dietary inclusion of *Bacillus subtilis* KN-42 ($2\text{--}20 \times 10^9$ CFU/kg) reduced PWD incidence by approximately 50% within the first two weeks post-weaning, with efficacy comparable to neomycin treatment (Hu *et al.*, 2015). Similarly, multi-strain formulations, such as combinations of *Lactobacillus* and *Enterococcus*, have demonstrated consistent improvements in diarrhea scores and gut microbial balance (Hu *et al.*, 2015). Moreover, supplementation with *Lactiplantibacillus plantarum* and *Lactococcus lactis* markedly decreased diarrhea severity following experimental ETEC challenge in piglets (Qin *et al.*, 2022).

ii. Prebiotics

Prebiotics are defined as non-digestible feed ingredients that selectively stimulate the growth and activity of beneficial intestinal microorganisms, thereby conferring health benefits to the host. Commonly used prebiotics in animal nutrition include non-digestible oligosaccharides such as fructo-oligosaccharides (FOS), galacto-

oligosaccharides, inulin, mannan-oligosaccharides (MOS), and chito-oligosaccharides (Gibson *et al.*, 2017). These substrates resist digestion in the upper gastrointestinal tract and reach the colon, where they are fermented by commensal microbiota to produce short-chain fatty acids, supporting intestinal barrier function and overall gut health.

Evidence regarding the efficacy of prebiotics in piglets remains variable. Several trials report reductions in post-weaning diarrhea and improvements in intestinal morphology, whereas others demonstrate negligible effects, particularly under conditions where control groups remain healthy. For example, dietary supplementation with chito-oligosaccharides at 0.01–0.04% (100–400 mg/kg) significantly reduced the incidence of post-weaning diarrhea and increased small intestinal villus height (Liu *et al.*, 2008). Similarly, MOS and FOS, administered either to sows during gestation/lactation or directly to piglets, have been shown to modestly elevate colostral IgM levels and promote the proliferation of beneficial gut microbes, thereby enhancing mucosal immunity and intestinal health (Gibson *et al.*, 2017).

iii. Symbiotics

Symbiotics are combinations of probiotics and prebiotics formulated to achieve additive or synergistic effects on host health. According to the International Scientific Association for Probiotics and Prebiotics (ISAPP), a symbiotic is defined as “a mixture comprising live microorganisms and substrate(s) selectively utilized by host microorganisms” (Swanson *et al.*, 2020). Two main categories are recognized: complementary symbiotics, in which the prebiotic component is intended to support the growth of indigenous gut microbes, and synergistic symbiotics, in which the prebiotic is specifically selected to enhance the activity of the co-administered probiotic (Swanson *et al.*, 2020).

Experimental studies in pigs have reported mixed outcomes. For example, administration of *Lactiplantibacillus plantarum* in combination with 10 g/kg lactulose improved intestinal parameters, including increased villus height and elevated butyrate production, but failed to significantly reduce diarrhea following an ETEC challenge (Guerra-Ordaz *et al.*, 2014). Overall, symbiotics appear to provide modest improvements in gut health and intestinal morphology; however, evidence of true synergistic interactions, where combined effects exceed the sum of the individual components, remains limited in pigs.

e. Milk Replacers and Supplemental Feeding

Piglets with poor growth or those whose litter produces insufficient milk are fed on commercial milk replacers or supplements. The contemporary replacers contain hydrolyzed proteins (e.g. whey peptides) in the form of easy-to-digest food, as well as added immunoglobulins or plant immunostimulants. A frequent additive is spray-dried porcine plasma (SDP) which is highly concentrated in IgG. It has been found that SDP in feed liquid enhances gut immunity and may decrease diarrhea (Zimmerman, 1987; Gatnau & Zimmerman, 1990). As a case in point, addition of SDP (438) in milk diets augmented piglet growth and also minimized PWD in early-weaned populations (Coffey and Cromwell, 2001; van Dijk *et al.*, 2001; Torrallardona, 2010). The immunoglobulins present in SDP aid the intestinal host defense. Other supplements (e.g. colostrum powder, bovine IgG, yeast nucleotide extracts) have the same effect by enhancing nutrient consumption and immunity in weak piglets. These interventions are particularly useful in large litters or in the case of fostering that is required. To conclude, NPD can be alleviated by the adequate liquid nutrition provided to the vulnerable neonates by using improved milk formulas or plasma-supplements (Pérez-Bosque *et al.*, 2016).

Post-Weaning Diarrhea: Risk Factors and Recent Advances

The diarrhea (PWD) usually happens 5–14 days post-weaning. Enteric infections (primarily ETEC, Salmonella, Lawsonia, Brachyspira) are predisposed by weaning stress (fasting, change of environment), immature immunity, as well as the alteration of the diet (lactose-starch, high fermentable protein). Important new approaches are concerned with dietary composition, intestinal microbiota and the environment.

a. Feeding Strategies

Mitigations include gradual weaning and abrupt weaning and creep feeding. Weaning takes weeks in nature piglets,

whereas in modern weaning, weaning takes place in 3-4 weeks, which is sudden (Fu *et al.*, 1990; Poonsuk and Zimmerman, 2018). Some studies have indicated that more time (or prolonged lactation) spent by the sow or gradual separation of the sow would lead to better gut adaptation. Feeding solid or gruel diets before weaning pre-emies Readies the gut. As an example, pre-weaning pigs fed a liquid diet of gruel consumed more and gained additional weight up to 10 percent on the first day after weaning (Boston *et al.*, 2022). Boston *et al.* (2022) determined that the weaning ADG was raised by 53% when creep liquids were used over the dry-feed control. Such feeds stimulate the release of the digestive enzymes and assistance in villus structure which lessen the shock of change of diet. Also, the diet after weaning is improved: low crude protein (CP) diets containing equal proportions of amino acids reduce the undigested protein fermentation (a contributor to PWD). In a recent study, CP (with AA supplements) reduction immediately after weaning resulted in the prevention of PWD and enhanced growth (Langley *et al.*, 2025). Ingredients rich in fiber and resistant starch are also investigated to enhance SCFA-producing bacteria and gastrointestinal health. Feed type (pelleted or mash) has less effect on intake, but has a smaller effect on diarrhea; very finely ground or pelletized feeds may aggravate gastric ulcers thus optimization of feed form (moderate hardness of pellets, size of particle) is recommended.

b. Nutritional Additives

An extensive range of feed additives is in the research as alternative antibiotics to control PWD. The acids (organic acids, formic, lactic, citric acids) reduce the gut pH and suppress the pathogens. They decrease the severity of diarrhea in drinking water or feed citric acid supplementation reduced the number of ETEC and stool water content (Nhara *et al.*, 2024). Antimicrobial and anti-inflammatory properties belong to essential oils and plant extracts (carvacrol, thymol, capsaicin and tannins). The meta-analyses show that essential oil blends can be used to enhance the growth and reduce cases of diarrhea in weaned pigs. In trials, the scoring of diarrhea decreased in a review that contained citric acid and essential oils (Nhara *et al.*, 2024). Enzymes (phytase, protease, carbohydrases) enhance the digestibility of nutrients; the partially anti post-wean gut disturbance is reduced by reducing undigested protein. Yeast derivatives (mannan-oligosaccharides, -glucans) have immunomodulatory effects - e.g -glucans in *Saccharomyces* sensitize macrophages and goblet cells, are useful in the prevention of enteric pathogens. There is a new phenomenon of postbiotics (killed microbial metabolites): heat-inactivated *Lactobacillus plantarum* or *Pediococcus* feeds raised fecal *Lactobacillus* bacterial counts and feed conversion in piglets (Pupa *et al.*, 2021). It is worth noting that alternatives to ZnO are of high priority: such options as zinc nanoparticles (in vitro effective against *E. coli*) (Baholet *et al.*, 2022), copper or other trace minerals, and combinations (organic acids + oil blends) are possible. These have some potential, but there are still no reliable field results and safety data available

i. Organic Acids and Fatty Acids

Organic acids also known as acidifiers are frequently added to the weaner diets due to their antimicrobial and digestive properties (Rhouma *et al.*, 2017). Commonly known acids are formic, lactic, propionic, citric, fumaric and benzoic acids that reduce the gastrointestinal pH, suppress pathogenic bacteria and provide an easy source of energy to enterocytes. The reviews all find that organic acids have potential in the treatment of intestinal disease and enhanced performance of piglets, with formic acid and its salts exhibiting the most consistent effects in the reduction of the severity and duration of *Escherichia coli* F4-induced diarrhea (Luise *et al.*, 2020). Nevertheless, a lot of the evidence that exists is indirect because many studies have not been explicitly developed to assess the outcomes of diarrhea. In recent years, organic acid combinations with medium-chain fatty acids (MCFAs; C612, usually produced by coconut oil) have become of interest. MCFAs are very effective in antibacterial action and provide fast energy to the intestinal epithelial cells (Xu *et al.*, 2018). Challenge studies have shown that dietary blends of short-chain organic acids and MCFAs at 0.2 to 0.4 per cent of feed have a major impact in diarrhea reduction in *E. coli*-challenged weaners (Lei *et al.*, 2017). Moreover, such blends in a large-scale trial reduced the quantity of pens requiring diarrhea treatment to the same level as 2500 ppm medicinal zinc oxide (Li *et al.*, 2018).

ii. Specific Amino Acids

Some amino acids do not only contribute to protein synthesis, but also directly maintain gut immunity and repair the gut barrier. Of particular importance is threonine, tryptophan, arginine, glutamine, methionine, and cysteine as essential to intestinal integrity, which increases when under weaning stress or infection (Lopez-Galvez *et al.*, 2020; Liao, 2021). Threonine in particular is significant, with 28-35 per cent of the mucin amino acids and is a primary substrate of mucus secretion (Zhang *et al.*, 2019). The addition of threonine beyond the NRC recommendations to

weaner diets (e.g. + 2.5 g/kg) has a life-long significant positive effect on mucin production and goblet cell density (NRC, 2012). Mucosal resilience and height of the villus are also shown to improve after the additional threonine *E. coli* challenge with recent trials. These results show that excess threonine can strengthen the bowel barrier in weaning and perhaps prevent diarrhea, but the consequences of excess threonine on post-weaning diarrhea (PWD) have yet to be fully substantiated (Canibe *et al.*, 2022).

iii. Essential Oils

Essential oils (EOs) are aromatic compounds of plants, including thymol, carvacrol and cinnamaldehyde, which have a wide range of antimicrobial and antioxidant effects (Omonijo *et al.*, 2018). They interfere with the bacterial membrane with their hydrophobic molecules, and can also prevent quorum sensing or toxin production (Bouyahya *et al.*, 2019). EO supplementation has had promising effects in piglets against post-weaning diarrhea (PWD). Two studies in the non-challenge category indicated that EO blends reduced the PWD incidence and enhanced its growth (Resende *et al.*, 2020). The results of the ETEC challenge models showed fewer benefits, but two experiments, one using an EO mix and one an individual compound, showed a reduction in the diarrhea rates in *E. coli* F4/F18-challenged piglets (Choi *et al.*, 2020). As an example, thymol and cinnamaldehyde (0.2-0.3%), which are microencapsulated, reduced the diarrhea scores and enhanced the weight gain observed in post-weaning pigs (Rodrigue *et al.*, 2020).

iv. Antimicrobial Polypeptides (Peptides)

Antimicrobial peptides (AMPs) are short, cationic polypeptides (6–100 amino acids) that form part of innate immunity across species (Ciesinski *et al.*, 2018). In livestock, synthetic and recombinant AMPs—often termed host-defense peptides—are being explored as antibiotic alternatives. Their primary mechanism involves disrupting bacterial membranes via lipid binding, which makes resistance uncommon, while additional effects include modulation of host immunity through enhanced IgA and reduced inflammatory cytokines (Zhang *et al.*, 2021).

Recent piglet studies highlight their anti-diarrheal potential. The synthetic peptide WK3, an analog of porcine cathelicidin, reduced diarrhea incidence, improved average daily gain, and increased villus height when injected at 2 mg/kg in *E. coli* F4-challenged weaners, while also downregulating inflammatory genes (TLR4, IL-1 α) and enhancing antioxidant activity (Zhang *et al.*, 2021). When fed at 50 mg/kg, WK3 similarly improved weight gain and reduced cecal *Enterobacteriaceae* (Cao *et al.*, 2021). Another AMP, cathelicidin-BF from frog skin, administered at 0.6 mg/kg post-weaning, decreased diarrheal scores and proinflammatory cytokines (IL-6, TNF- α), while increasing IgA and tight-junction proteins (Feng *et al.*, 2020).

v. Supplementation of Enzymes

Antimicrobials are frequently employed to prevent or treat post-weaning diarrhea (PWD) in piglets; however, repeated use can promote bacterial resistance (Forsberg *et al.*, 2006). β -Mannan, an antinutritive fiber present in soybean meal and other common feedstuffs, is considered unsuitable for young piglets due to its immunostimulatory effects on the innate immune system (Ferrel *et al.*, 2014). Undigested β -mannan can ferment in the hindgut, supporting the proliferation of pathogenic bacteria and exacerbating PWD. Supplementation with β -mannanase has been shown to reduce PWD incidence and the reliance on antibiotics, even when diets include increased levels of soybean meal (Vangroenweghe *et al.*, 2021).

Bromelain, a proteolytic enzyme extracted from *Ananas comosus*, has also demonstrated protective effects against PWD and associated production losses under commercial conditions (Chandler & Mynott, 1998). Bromelain prevents adhesion of F4 *Escherichia coli* (ETEC) to enterocytes by cleaving bacterial receptors on the small intestine (Mynott *et al.*, 1996) and inhibits ETEC-induced fluid secretion through modulation of cyclic nucleotide and calcium-dependent signaling pathways (Mynott *et al.*, 1997). Together, these feed additives represent promising non-antibiotic strategies for reducing diarrhea and improving intestinal health in weaned piglets.

c. Microbiome Modulation

The microbiome of the gut is the first to understand and manipulate. Transplantation of fecal microbiota of healthy donors can restore a protective flora. The FMT (which was frequently used in combination with probiotics) seemed

to partially reduce PWD: piglets fed by healthy adults on FMT scored lower in diarrhea and higher in weight gain (Su *et al.*, 2021; Xiang *et al.*, 2020). As an example, prenatal FMT with *Clostridium butyricum* and *Saccharomyces boulardii* reduced weaning weight and reduced cases of diarrhea by a significant margin (Xiang *et al.*, 2020). Such methods achieve this by enhancing microbial diversity and short-chain fatty acid beneficial producers. The next generation probiotics (e.g. *Akkermansia muciniphila*, *Faecalibacterium prausnitzii*) are also being investigated; *Akkermansia* deactivation prevented the ETEC challenge, whereas *F. prausnitzii* vesicles relieved PEDV in piglets (Xing *et al.*, 2025). Additionally, there are fermentable prebiotics that are used orally as feed to selectively increase beneficial bacteria (such as *Bifidobacteria*). Overall, microbiome-targeted interventions are potentially effective and need additional confirmation before continued implementation.

d. Water Quality and Housing Management

Good housing and clean water also help to reduce PWD. The ability of organic acids to lower the load of pathogens in the gut is encouraged by acidifying drinking water. There are studies (though not numerous among piglets) that indicate that water acidifiers increase the antioxidant state and decrease weaning diarrhea (White *et al.*, 1969; Baholet *et al.*, 2022). It is necessary to have uncontaminated water available always. Housing: proper temperature (piglets require 28-32°C at weaning), humidity, draft-free pens, prevent cold stress, which in turn inhibits immunity and causes diarrhea. Good ventilation eliminates ammonia concentration and respiratory distress that may be predisposing factors to enteric disease. By mishandling and mixing the litters during weaning, the psychological stress is minimized. Altogether, the gut resilience after weaning is supported with the help of holistic environmental management (clean water, thermal comfort, bedding, and enrichment to reduce stress) (Halpin *et al.*, 2024).

e. Immune-Based Approaches

Immune-based approaches after weaning include functional feed ingredients, immunomodulatory microbial products, nucleotides, yeast-derived components, plant bioactives, and experimental vaccines. These interventions aim to strengthen mucosal immunity, regulate inflammatory responses, and improve intestinal barrier function. Spray-dried plasma has been extensively investigated as an immunologically active dietary ingredient in weaned pigs, with evidence supporting beneficial effects on feed intake, growth performance, and intestinal health (van Dijk *et al.*, 2001; Torrallardona, 2010; Pérez-Bosque *et al.*, 2016). Because the nutritional and immunological functions of plasma have already been discussed in Section 1.5, the present section focuses on the broader concept of post-weaning immune modulation rather than repeating the detailed plasma literature. Yeast-derived products, nucleotides, plant-derived immunomodulators, and experimental vaccines represent additional approaches. However, many of these interventions remain dependent on specific formulations and experimental conditions, and further field validation is required before routine implementation.

Diagnostic Advances

Rapid and correct diagnosis of enteric disease is very important. Value-added technologies such as molecular diagnostics (PCR/qPCR panels, multiplex assays) to identify feces or tissue pathogenic agents have been improved recently. ETEC virulence genes (F4, F18 fimbriae, heat-labile toxin, STa, STb, etc) can be verified in hours by Multiplex PCR (Bosworth & Casey, 1997; Madoroba *et al.*, 2009; Moon *et al.*, 1999). Indicatively, De Lorenzo *et al.*, (2018) optimized multiplex PCR on the fixed tissues to diagnose ETEC colibacillosis in piglets (Van Reeth *et al.*, 2012). There are similar panels of rotavirus, coronavirus, *Clostridium*, and parasites. Gut health Biomarkers of gut health are being studied: serum or fecal calprotectin and lactoferrin are associated with intestinal inflammation, and may enable early detection of enteritis, but veterinary validation is in progress. Advanced technologies of precision livestock farming (sensors, cameras, RFID) can identify the initial symptoms of disease. As an example, feed/water intake or piglet vocalizations have been automatically monitored to predict diarrhea development (Thomas *et al.*, 2021). Isolating (or huddling, which is an indicator of sickness) piglets can be detected with thermal imaging or video tracking prior to the developing diarrhea. Although these digital tools are yet to be fully developed, they will offer proactive management of the herd.

Comparative Evaluation of Interventions

Indian vs Global: A good number of such interventions have been confirmed in intensive systems (EU/USA). Some of the strategies would be difficult in the context of India (large fraction small herd, hot climate, limited cold-chain).

An illustration of this is the complex feed additives or vaccines may not be used to its full potential because of the cost or its availability. Nevertheless, simple interventions (colostrum management, hygiene and low-cost probiotics) can be generalized. ETEC and *C. perfringens* are confirmed to be the primary causes of some studies in India (Nirupama *et al.*, 2018; (Mittal *et al.*, 2018), and the resistance to antibiotics is very high, which makes the use of alternative methods necessary. Therefore, the global advances that are to be translated must be adjusted to the local level of production, economics, and the profile of pathogens.

Challenges and Limitations

These advances present challenges in their implementation. Farmers with smallholder farms and backyard farms (typical in India/Asia/Africa) frequently do not have the resources to use advanced feed or vaccines. Education and extension is necessary to promote the best practices (colostrum feeding, clean farrowing, proper weaning). The alternatives are encouraged by regulatory limitations (antibiotic restrictions, ZnO phase-out), yet the approved alternatives can be constrained. Management practices are also highly varied: what works in one herd (e.g. liquid feed, all-in-all-out hygiene) would not be practicable in another. Unification of the protocols is not easy. Moreover, there are a lot of new products (probiotics, enzymes, phytogenics, vaccines) that are not always demonstrated in the field conditions; their effectiveness may be variable. To point out one example, the effects of probiotics are strain- and dose-dependent. The improvements in new diagnostic tools (biomarkers, sensors) are promising but they need to be invested in and validated. Lastly, there is the evolution of pathogens (ETEC antigen shifts) and therefore vaccines have to keep changing. In general, these challenges need to be addressed by means of education, infrastructure, and research specific to regions.

Future Prospects

The trends of the future are towards precision and biotechnology solutions. Multi-omics (metagenomics, metabolomics, proteomics) will determine microbial and metabolic responses of healthy and diarrheic gut to allow customized interventions. To illustrate, microbiome profiling may inform the choice of a probiotic or it may predict danger prior to the occurrence of an illness. Another frontier is nanotechnology: nanoparticle feed additives (e.g. zinc, silver nanoparticles) have a high potential of displaying the same antibacterial properties at reduced doses (Baholet *et al.*, 2022). Early work is promising that zinc nanoparticles can replicate the effect of ZnO, with reduced environmental impact (Baholet *et al.*, 2022), but needs a better understanding of the impact on gut flora. There are also highly sophisticated vaccines (e.g. nanoparticle-delivered antigens, mRNA vaccines in pigs) in development to cause strong mucosal immunity to a variety of pathogens. The automated feeders (precision feeding systems that feed pigs with tailored diets) may change the nutrition in real time, according to the growth or risk condition of pigs. Finally, additional field trials (especially of Indian herds) with longer time scales would be required to confirm new strategies in local fields. This involves research on local probiotic strains, low feed solutions, and cost benefit of alternatives on small farms.

Conclusions

In pre- and post- weaning diarrhea in piglets, multifactorial, integrated management is the most efficient. The high incidence of diseases can be significantly mitigated by providing high passive immunity (colostrum, vaccination), nutritional (creep feed, balanced diets), and hygienic environment. There are alternative ways of using probiotics, organic acids and targeted vaccines as alternatives to traditional antimicrobials, but they should be combined. The approaches have to be specific to the risk factors of each herd. Although there are significant progresses that have been achieved across the world, there is a need of more region-specific research (e.g. in India) to ensure that such interventions are adjusted to different production systems and climate. As the industry struggles toward a more sustainable, antibiotic-free production system, further research and development of gut health management efforts is needed in solving piglet welfare and profitability in the industry (Baholet *et al.*, 2022; (Ntakiyisumba *et al.*, 2022).

Contribution by Authors

All the authors contributed equally to writing the manuscript. The final manuscript was read by all authors and consented to publication.

Conflict of Interests

There is no conflict of interest.

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