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## Wild Bird Nutrition in a Changing World: Dietary Ecology, Seasonal Nutrient Demands and Conservation Implications

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### ABSTRACT:

Nutrition is a central link between wild birds and the habitats on which their survival, reproduction, moult and migration depend. Bird species exploit diverse foods—including seeds, fruits, nectar, invertebrates, fish and vertebrate prey—and differ in how they acquire and process nutrients. Food quality and availability vary across seasons and landscapes, while habitat conversion, climate variability, pesticide exposure and urban food subsidies can alter diets. This review considers dietary guilds, seasonal nutritional demands, foraging ecology, gut microbiome research, contaminants and the opportunities and risks associated with supplementary feeding. Human-provided food may be useful in specific conservation or emergency contexts, but it can also provide unbalanced nutrients, concentrate birds and increase exposure to pathogens or contaminants. The nutritional consequences are species- and context-specific, so conservation interventions should be based on ecological evidence rather than a general assumption that more food is always beneficial. Research on wild avian microbiomes is expanding, yet causal links among diet, microbial function, body condition and reproductive success remain limited compared with domestic poultry. The Indian context includes wetlands, grasslands, forests, urban settlements and agricultural mosaics, each supporting different food webs and conservation priorities. Future work should combine dietary analysis, habitat assessment, non-invasive condition measures and demographic monitoring. Conservation nutrition can strengthen management when it protects natural food resources, identifies seasonal bottlenecks and evaluates interventions for both intended benefits and unintended ecological effects.

**Keywords:** Wild bird nutrition; nutritional ecology; dietary guilds; migration; gut microbiome; supplementary feeding; conservation; India

**Review scope:** This narrative review synthesizes selected peer-reviewed literature and authoritative reference works relevant to the topic. It is not presented as a systematic review; claims and recommendations should be checked against the cited original sources before journal submission.

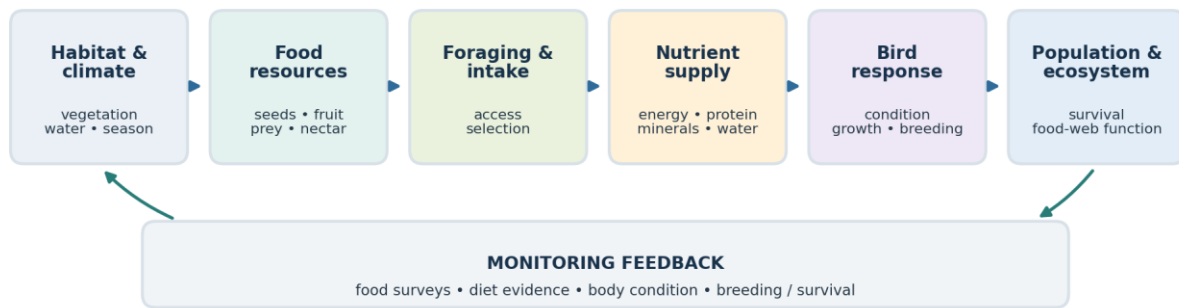
### 1. Introduction

Wild birds obtain nutrients within natural and human-modified food webs. Their diets may consist of seeds, fruits, nectar, leaves, insects, fish, carrion or live vertebrate prey, and many species shift food use as availability changes. Nutrition affects energy balance, feather maintenance, immune competence, breeding output and migration. Unlike poultry or captive birds, free-ranging individuals select their own foods across complex landscapes; actual intake is therefore difficult to quantify and cannot be inferred from the presence of a food item alone. For North America, long-term monitoring has documented substantial declines in bird abundance across multiple groups, illustrating the conservation relevance of protecting food webs and habitats (Rosenberg et al., 2019).

Conservation nutrition is an interdisciplinary approach linking nutrient availability and food quality to animal condition and population outcomes, while also recognizing the broader ecological functions of birds in ecosystems (Şekercioğlu, 2006). It does not imply that wild birds should routinely be fed by people. Instead, it asks whether environmental changes create nutritional bottlenecks, which species are affected, and whether habitat management or carefully designed interventions can improve outcomes. Current reviews emphasize that wild-bird microbiome knowledge remains less developed than domestic poultry research and requires stronger links to ecology, health and reproduction (Ottinger et al., 2024).

## WILD-BIRD NUTRITION: FROM HABITAT TO CONSERVATION OUTCOME

Conceptual pathway; links differ among taxa, seasons and ecosystems



*A food-rich site is not automatically a high-quality nutritional habitat when food quality, access or contaminant exposure is poor.*

Fig. 1. Conceptual pathway linking habitat and climate to food resources, nutrient supply, individual response and population-level conservation outcomes.

This illustration emphasizes that wild birds obtain food from a mosaic of wetlands, grasslands, field margins and woody vegetation. The scene is conceptual and should not be read as a specific Indian site or as an identification plate for individual species.

## 2. Dietary guilds and nutritional strategies

### 2.1 Seeds, grains and plant materials

Granivorous birds rely on seeds whose energy, protein, lipid, fibre and mineral composition differ among plant species and growth stages. Seed size and hardness can limit access, so beak form and feeding behaviour interact with nutrient availability. Agricultural landscapes may provide abundant grain for brief periods but fewer diverse native seeds through other seasons. Some harvested or stored grain may also be contaminated by moulds, mycotoxins or agrochemicals. Conservation therefore benefits from assessing the timing, quality and accessibility of seed resources, not simply counting seed-bearing plants.

### 2.2 Invertebrates, fruits and nectar

Invertebrates provide protein and micronutrients and may be particularly important for growing chicks, even in species that consume seeds or fruits as adults. Frugivores depend on plant phenology and the spatial distribution of fruiting species; their foraging also contributes to seed dispersal. Nectar supplies rapidly available sugars, but nectarivorous birds may obtain other nutrients from insects or complementary foods. Habitat simplification can remove key seasonal resources even when some food remains available. Native vegetation with varied flowering and fruiting times can support more continuous food supply.

### 2.3 Fish, carrion and vertebrate prey

Piscivores and raptors depend on prey abundance, size and accessibility. Their nutrient intake may change when wetlands, rivers or grasslands are modified. Predators can also be exposed to persistent contaminants accumulated through food webs, making prey quality a health issue as well as a quantity issue. Carrion-feeding species depend on the availability and safety of carcasses; changes in veterinary drug use, waste disposal or livestock management can alter their food supply. Species-specific knowledge is essential because the same landscape change can benefit one feeding guild and disadvantage another.

Table 1. Broad dietary guilds and their nutritional-ecology considerations.

| Guild / feeding strategy | Common food types               | Nutritional/ecological issue                                      | Conservation consideration                                           |
|--------------------------|---------------------------------|-------------------------------------------------------------------|----------------------------------------------------------------------|
| Granivores               | Seeds and grains                | Seed size, shell access, seasonal supply and nutrient composition | Maintain native seed-producing plants and field margins              |
| Insectivores             | Insects and other invertebrates | Prey availability can be critical during chick growth             | Protect invertebrate resources and reduce harmful pesticide exposure |

| Guild / feeding strategy    | Common food types                  | Nutritional/ecological issue                                 | Conservation consideration                               |
|-----------------------------|------------------------------------|--------------------------------------------------------------|----------------------------------------------------------|
| <b>Frugivores</b>           | Fruits and berries                 | Fruit availability varies with plant phenology               | Maintain diverse native fruiting plants                  |
| <b>Nectarivores</b>         | Nectar plus insects or other foods | Rapid energy supply must be paired with other nutrients      | Protect flowering plants and seasonal nectar sources     |
| <b>Piscivores / raptors</b> | Fish or vertebrate prey            | Prey fluctuations and contaminant transfer through food webs | Protect aquatic prey and monitor persistent contaminants |

### 3. Seasonal demands: breeding, moult and migration

Nutritional requirements vary across the annual cycle. Before breeding, adequate energy reserves and body condition may influence whether birds initiate reproduction and how they allocate resources. During chick rearing, parents may require plentiful prey with the right size and nutrient composition. Feather growth during moult requires protein and other nutrients, while migration demands energy storage, efficient metabolism and access to refuelling habitat. Seasonal changes can create a mismatch between the timing of food peaks and the needs of birds, particularly when climate change shifts flowering, insect emergence or wetland hydroperiods (Davies and Deviche, 2014; McWilliams et al., 2004).

**Table 2. Life-history stages and possible nutritional bottlenecks in wild birds.**

| Stage                      | Potential demand or constraint                  | Habitat/food response                              | Useful measures                                  |
|----------------------------|-------------------------------------------------|----------------------------------------------------|--------------------------------------------------|
| <b>Pre-breeding</b>        | Energy reserves and condition for reproduction  | Food-rich habitats and suitable nutrient diversity | Body condition, diet and lay timing              |
| <b>Chick rearing</b>       | High demand for suitable prey or food types     | Availability of accessible, age-appropriate food   | Nestling growth, provisioning rate and fledging  |
| <b>Moult</b>               | Resources for feather synthesis and maintenance | Sustained food access and reduced disturbance      | Moult timing, feather quality and body condition |
| <b>Migration</b>           | Energy storage and refuelling opportunities     | Stopover habitat and predictable natural food webs | Stopover use, fuel stores and migration timing   |
| <b>Winter / dry season</b> | Thermoregulation and reduced food availability  | Shelter and natural food continuity                | Survival, local abundance and food availability  |

### 4. Habitat change, climate and food-web quality

Land conversion, intensive agriculture, pesticide use, drainage of wetlands, fire regimes, invasive species and urban expansion can change both food quantity and quality. Extreme heat or drought can reduce invertebrate activity and water availability; intense rainfall can alter prey accessibility and nesting conditions. Agricultural fields may provide seasonal food pulses but offer limited continuity and diversity. Conservation planning should therefore identify the food resources required by particular species at sensitive life stages and protect the habitats that sustain those resources.

A landscape should not be judged nutritionally beneficial only because birds are frequently observed there. Birds may aggregate around a temporary food source while showing poor condition, altered behaviour or increased exposure to hazards. Food-web monitoring, body-condition data and demographic indicators provide a stronger basis for evaluation. The objective is to maintain ecological processes and reliable natural food availability rather than maximize the local concentration of birds.

## 5. Gut microbiome, diet and nutritional ecology

### 5.1 Diet–microbiome relationships

The avian gut microbiome can influence nutrient processing, immune interactions and host physiology, while diet and foraging behaviour influence microbial communities. In wild birds, diets may change rapidly with season, migration and habitat, creating opportunities to investigate microbial flexibility. However, evidence is uneven across bird groups. Microbiome patterns should not be interpreted as direct measures of nutrition unless they are paired with dietary, physiological or fitness data (Ottinger et al., 2024).

### 5.2 Foraging behaviour and microbial exposure

Foraging behaviours such as feeding on soil, insects, carcasses or faecal material may shape microbial exposure as well as nutrient intake. A recent review discussed coprophagic foraging as a possible route for acquisition of microbes and resources, while also recognizing exposure to pathogens, pollutants or antimicrobial-resistant organisms in some contexts (Dunbar et al., 2024). These pathways are likely to vary across species and environments; laboratory and captive-bird findings should not be assumed to describe all free-living birds.

### 5.3 Research methods and limits

Faecal metabarcoding can identify prey DNA, stable isotopes can support inference about food sources, and microbial sequencing can describe community patterns. Each method answers a different question. DNA detection is not a direct measurement of nutrient absorption; isotope values depend on suitable baselines; and microbial composition alone does not establish function. Integrating methods with observations of body condition, reproductive success, survival and habitat conditions is necessary to move from descriptive data to conservation decisions.

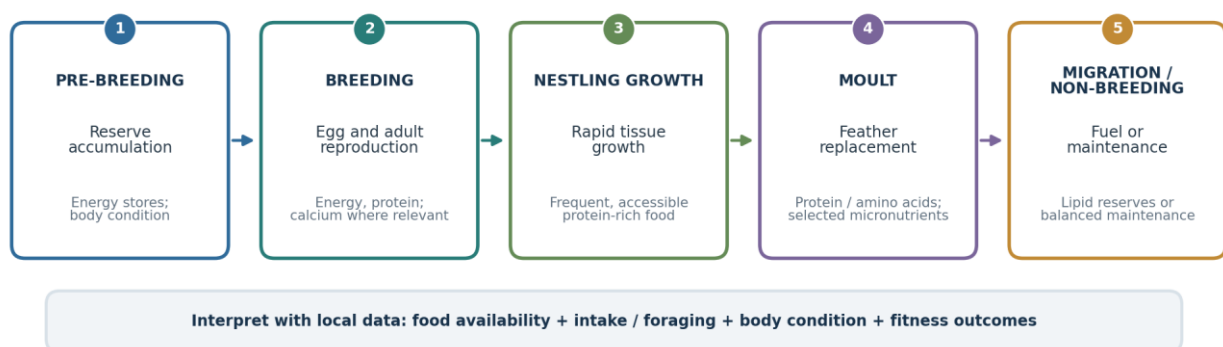
## 6. Supplementary feeding: benefits, risks and safeguards

Supplementary feeding occurs in backyard gardens, tourism settings, rehabilitation, emergency response and targeted conservation programmes. It may provide resources during a defined shortage, but the effect depends on the target species, food composition, timing, amount and delivery method. Food that is energy-rich but nutritionally unbalanced may change body condition without meeting broader requirements. Feeding stations can aggregate birds, increase competition and expose individuals to contaminated surfaces or food. A global wildlife review found that supplemental feeding often increased contact opportunities and pathogen accumulation, while outcomes differed according to the purpose and design of feeding (Murray et al., 2016; Robb et al., 2008).

A responsible plan begins with a clear objective and an assessment of whether habitat management could address the problem more effectively. If feeding is justified, the food should be species-appropriate, hygienic and provided in a way that avoids unnecessary crowding. Surfaces and containers require regular cleaning, and feeding should be reconsidered during disease outbreaks or when adverse effects appear. Supplementary feeding should not become a substitute for protecting native vegetation, wetlands, grasslands or the natural prey base.

### ANNUAL-CYCLE NUTRITIONAL PRIORITIES IN WILD BIRDS

Qualitative synthesis only; timing and intensity depend on species, latitude and local ecology



Life stage alone does not define a universal nutrient requirement; diets and physiology differ substantially among taxa.

Fig. 2. Qualitative annual-cycle nutritional priorities from pre-breeding through breeding, nestling growth, moult and migration or non-breeding. Timing and intensity vary among species and local environments.

The annual-cycle wheel highlights how the nutritional bottleneck can shift from reserve accumulation before breeding to chick provisioning, feather replacement or migration refuelling. Not every species experiences these stages in the same order, and resident tropical birds may not follow the same pattern as long-distance migrants.

**Table 3. Potential effects of supplementary feeding and management safeguards.**

| Potential effect                | Mechanism                                                   | Risk-reduction measure                                     | Monitoring endpoint                             |
|---------------------------------|-------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------|
| Improved short-term food access | Adds energy during defined shortage                         | Confirm target-species need and food suitability           | Body condition or survival response             |
| Nutrient imbalance              | Food may be high in energy but deficient in other nutrients | Use species-specific guidance; avoid processed human foods | Condition, behaviour and diet composition       |
| Disease transmission            | Bird aggregation and contaminated feeding surfaces          | Hygiene, lower density, pause feeding during outbreaks     | Illness, mortality and feeder contamination     |
| Behavioural/ecological change   | Altered dispersal, migration or dependency                  | Use time-limited plans and evaluate alternatives           | Site fidelity, crowding and population response |
| Contaminant exposure            | Mould, toxins or polluted food materials                    | Source food carefully and store it safely                  | Food quality and incident surveillance          |

## 7. Contaminants, disease and food safety

Food resources can expose birds to pesticides, heavy metals, veterinary drug residues, plastics, mycotoxins and harmful microorganisms. Risks depend on concentration, exposure duration, species and life stage. Predatory species may accumulate contaminants through prey, while scavengers can encounter hazardous residues in carrion. Urban food waste can provide calories but may be unsuitable in composition or contaminated. Nutritional stress and contaminant exposure can interact, so conservation monitoring should consider both food quality and environmental toxicology. Observed illness or unusual mortality should prompt relevant wildlife and veterinary authorities to assess both infectious and non-infectious causes.

## 8. Conservation applications in Indian landscapes

India supports wild birds across wetlands, coasts, grasslands, forests, deserts, agricultural fields and rapidly expanding urban areas. Each landscape has its own seasonal food resources and threats. Wetland conservation supports fish and invertebrate food webs; grassland management can maintain seed and insect resources for grassland birds; native tree and shrub diversity can provide fruits, nectar and nesting habitat; and pesticide-risk reduction may support insectivores. Management should consider threatened and migratory species as well as common urban birds, rather than applying a uniform feeding recommendation across taxa.

In urban areas, public feeding practices can be culturally important but may lead to dense bird aggregation and poor food hygiene. Educational guidance should distinguish between protecting a natural food source and routinely supplying human food. Rehabilitation centres require controlled diets based on species, age and clinical state, with release goals that support normal foraging rather than dependency. Local studies can identify which interventions improve body condition or survival and which merely increase congregation.

## 9. Research gaps and priorities

Key gaps include species-specific nutrient requirements for free-ranging birds, methods to estimate actual nutrient intake, links between diet quality and fitness, and long-term consequences of supplementary feeding. Studies are needed across under-represented regions and taxa, including migratory waterbirds, grassland birds, scavengers and urban species. Research designs should pair diet and microbial methods with environmental measures, reproductive outcomes, survival and contaminant exposure. Clear reporting of season, habitat, sampling protocol and species identity will improve comparison among studies.

**Table 4. Methods used to study nutrition in free-ranging birds.**

| Method                                          | What it can indicate                   | Strength                               | Limitation                                                |
|-------------------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------------------------|
| <b>Direct observation / feeding records</b>     | Foraging choices and provisioning      | Non-invasive and ecological context    | Difficult to quantify nutrients consumed                  |
| <b>Faecal diet analysis / DNA metabarcoding</b> | Taxa or prey represented in diet       | Can detect cryptic food items          | Detection does not directly measure nutrient absorption   |
| <b>Stable-isotope analysis</b>                  | Integrated food-web or habitat signals | Useful for broad diet-source inference | Requires appropriate baselines and careful interpretation |
| <b>Body-condition and demographic data</b>      | Potential nutrition outcomes           | Connects research to fitness measures  | Condition is influenced by disease and other stressors    |
| <b>Microbiome profiling</b>                     | Microbial community patterns           | Can generate mechanistic hypotheses    | Causality and function require additional evidence        |

## 10. Nutritional physiology: interpreting dietary quality, not just food quantity

### 10.1 Energy balance and seasonal constraints

Birds have high mass-specific metabolic rates, and energy demand changes with body size, temperature, flight, reproductive activity and exposure to weather. A food source may supply substantial calories yet fail to provide the nutrients required for feather formation, egg production or chick growth. Conversely, a diverse habitat may offer balanced food but make resources difficult to access during a short seasonal window. Conservation nutrition therefore considers the amount of food, the nutrient composition of the food, the energetic cost of acquiring it and the time available for foraging. These variables are especially important in small-bodied species facing cold nights or rapidly changing weather.

Energy balance also interacts with predation risk and disturbance. A bird feeding in an exposed area may obtain food quickly but spend more energy scanning or escaping. A habitat fragment may contain abundant insects yet have too little nesting cover or safe access. Observations of high bird density around a resource should not automatically be interpreted as a positive nutritional outcome. Body condition, reproductive success, survival and movement patterns are needed to understand whether the resource improves fitness or merely attracts birds temporarily (Davies and Deviche, 2014; McWilliams et al., 2004).

### 10.2 Protein, lipids, calcium and micronutrients

Protein provides amino acids for tissue growth, enzyme synthesis, feather production and reproduction. Insect prey can be an important source during chick rearing, but the value of prey depends on species, life stage, size and nutrient composition. Lipids are energy-dense and may be important for migrants accumulating fuel, while essential fatty-acid availability can influence membranes and developmental processes. Calcium is required for eggshell formation and skeletal development, and the availability of calcium-rich foods can become a constraint in some habitats. These broad functions must be interpreted species by species because birds differ in digestive morphology, diet selection and physiological strategy.

Nutritional limitation is often a balance problem rather than a simple shortage of calories. A seed-rich diet may provide energy but may be insufficient for some needs during rapid growth if suitable animal prey or other nutrients are limited. Likewise, a high-protein food item does not guarantee adequate calcium, trace minerals or essential fatty acids. Wild birds select mixtures of foods, and diet diversity can buffer variation, but diversity alone is not a guarantee of adequacy. Research should measure the composition of consumed foods and the nutrients actually acquired rather than infer adequacy from broad categories such as “insectivore” or “granivore.”

### 10.3 Morphology, digestive capacity and food handling

Bill shape, gape size, leg length, tongue structure and digestive-tract morphology affect which foods are accessible and how efficiently they are processed. Seed-eaters may be limited by seed hardness and handling time, while waders depend on prey distribution and substrate. Frugivores can vary in fruit selection according to size, pulp composition and seed dispersal effects. Species that use carrion or aquatic prey encounter distinct nutrient and contaminant profiles. These adaptations influence how habitat management should be designed: plantings and restorations are most useful when they provide food species can actually use at the relevant season and in an accessible structure.

Dietary traits can also vary within a species according to age, sex, migration status or local conditions. A generalist may switch foods rapidly when a preferred resource declines; a specialist may be more vulnerable to the loss of a narrow prey base. Field classifications should therefore be flexible. Stomach-content samples, direct observations, faecal analysis and DNA-based methods provide complementary information, but each has biases. The nutritional interpretation of a prey list should include prey size, edible portion, handling cost and timing as well as taxonomic identity.

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## **11. Annual-cycle nutrition: breeding, moult and migration**

### ***11.1 Pre-breeding condition and egg formation***

Reproduction increases demands for energy, protein, lipids and selected minerals, but the timing of breeding often tracks predictable food availability. Photoperiod can provide a seasonal cue, while rainfall, temperature and prey emergence influence whether the food needed for eggs and nestlings is available. A mismatch between breeding phenology and prey availability can increase adult workload or reduce chick provisioning. For conservation, protecting habitat only during one month may be insufficient if adults need to build reserves, establish territories or recover from migration before reproduction begins (Davies and Deviche, 2014).

Egg formation involves substantial allocation of nutrients from maternal reserves and current food intake. The size and quality of the egg can reflect maternal condition, diet and environmental constraints, though relationships differ across species. Calcium availability is especially relevant for eggshell formation, while protein and lipid supply support embryo development and other reproductive functions. Supplemental food may influence breeding in some circumstances, but it can also alter population density and competition. Any conservation intervention should determine whether food is truly limiting and whether improving habitat quality is likely to provide a more sustainable solution.

### ***11.2 Nestling growth and prey availability***

Nestlings have high growth demands and may depend on food types that differ from the adult diet. Adult birds that eat seeds or fruits may feed their chicks insects or other animal prey because of differences in nutrient needs, digestibility or prey handling. The systematic review and meta-analysis by Twining and colleagues (2023) found a positive relationship between insect food availability and songbird reproductive success, while also showing complexity in the relationship between chick body condition and reproductive output. The practical message is that prey abundance can matter, but its effects are not uniform across all species, landscapes or reproductive stages.

Agricultural management can influence nestling food through changes in insect abundance, vegetation structure and pesticide exposure. A field margin that provides insects at the time nestlings need them may be more valuable than a visually green field with little accessible prey. Timing matters: a resource that peaks before or after the nesting period may not meet the relevant demand. Monitoring should record prey availability alongside provisioning rate, chick growth, fledging success and weather. This helps distinguish whether poor breeding outcomes reflect food limitation, nest predation, disturbance, disease or multiple interacting pressures.

### ***11.3 Moult and migration fuel management***

Feather replacement requires protein and energy, and the timing of moult can overlap with breeding or migration depending on species. Birds may prioritize different functions at different times, and poor food availability can lengthen or disrupt the process. Migratory species face the challenge of accumulating energy reserves without impairing flight capacity. Lipid storage, protein sparing, gut capacity and fuel deposition rate vary across species and migration strategies. Food-rich stopover habitats can be particularly important because birds must refuel within limited time while avoiding predators and disturbance (McWilliams et al., 2004).

For migrants, the quality and spatial arrangement of habitat may matter as much as the total area. If wetlands, mudflats, grasslands or forest patches are separated by long unsuitable gaps, birds may expend more energy reaching them. Conservation planning should consider seasonal connectivity, disturbance, water levels and prey availability at stopover sites. Climate-related shifts in rainfall and food phenology can create new mismatches, including when a site remains geographically available but food peaks at a different time. More long-term studies are needed to connect changes in stopover nutrition to survival and population trends.

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## **12. Conservation nutrition across Indian landscapes**

### ***12.1 Wetlands, coasts and aquatic food webs***

Wetland and coastal birds depend on prey that responds to hydrology, water quality, substrate and season. Drainage, altered river flow, pollution and shoreline construction can reduce accessible invertebrates, fish or other food, even when water remains present. Waterbird management should therefore assess feeding depth, prey availability, vegetation and disturbance rather than count birds alone. Seasonal water-level management may influence access to benthic organisms and fish, while contamination can transfer through prey. In restoration plans, the nutritional value of a wetland is linked to its ecological processes, not just the amount of open water visible in a satellite image.

India's wetlands support resident and migratory birds, but nutritional constraints differ by site. Shallow-feeding waders may need exposed mudflat at particular depths, while diving birds require suitable prey and water clarity. A one-size-fits-all vegetation or water-level target may help one guild and disadvantage another. The appropriate assessment combines habitat mapping with prey sampling, feeding observations, disturbance records and seasonal bird counts. This is a reason to connect wetland conservation with food-web science rather than treating aquatic vegetation, water spread and bird abundance as isolated indicators.

### ***12.2 Grasslands, agricultural mosaics and forest systems***

Grasslands and open agricultural habitats can support seed-eating birds and insectivores, but food availability depends on plant diversity, cropping pattern, harvest timing, grazing, pesticide use and the persistence of field edges. Conversion of diverse grassland to uniform plantations or intensive cropland can remove nesting cover and reduce the continuity of natural food resources. For insectivorous birds, access to invertebrate prey during breeding is particularly important; pesticide exposure and reduced prey diversity can alter both food quantity and food safety. Conservation measures should protect suitable vegetation structure while retaining safe areas for feeding and nesting.

Forested landscapes provide fruits, nectar, foliage-dwelling insects and vertebrate prey, with strong seasonal variation. Native plant assemblages may sustain a broader sequence of fruiting and flowering than simplified vegetation, but food resources must be evaluated for local bird communities. Habitat restoration should not introduce non-native plants solely because they attract birds at feeders or produce large fruits. The ecological value of plantings includes food timing, nutritional composition, nesting habitat and effects on native plant regeneration. Monitoring should assess whether birds consume the resources and whether there are associated benefits in condition or reproduction.

### ***12.3 Urban settings and culturally driven feeding***

Urban areas provide lawns, gardens, food waste, insects around lights, and deliberately offered food. Such resources can subsidize some species but may favour generalists, increase competition and alter natural foraging. Bread, salty snacks and highly processed human foods are not suitable universal foods for wild birds. Uncontrolled food waste also creates opportunities for pests and can expose birds to plastics, salt or contaminants. Urban policies should distinguish habitat enhancement—such as native planting, water management and pesticide reduction—from concentrated provisioning that may create hygiene problems.

In India, public feeding can have cultural and religious significance. Conservation communication should be respectful while explaining when and how feeding creates a risk. Where feeding is continued, advice should be species-aware, avoid processed foods, maintain clean sites, remove spoiled material and prevent crowding. In some locations, a managed feeding programme may have a clear welfare purpose, such as temporary rehabilitation, but it requires monitoring and professional guidance. In other cases, protecting native vegetation and natural food availability is likely to benefit more species while reducing disease transmission and dependence on people.

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## **13. Supplementary feeding: deciding when, how and whether**

### ***13.1 Define the conservation objective first***

Supplementary feeding may be used for emergency response, rehabilitation, research, tourism or routine backyard enjoyment. These purposes have different standards for success and acceptable risks. A conservation programme should specify whether it aims to prevent short-term starvation, support a threatened population, improve breeding success or simply provide public viewing opportunities. The target species, season, population context and alternative habitat actions should be stated before feed is introduced. Without a defined objective, feeding may be maintained indefinitely even when evidence of benefit is weak or negative effects emerge.

A baseline assessment should record natural food availability, bird condition, population density, disease risks and existing human food sources. The programme should also identify a stop or modification rule, such as evidence of crowding, aggression, poor condition or repeated pathogen transmission. Murray et al. (2016) reviewed evidence across wildlife provisioning contexts and emphasized that predictable food can benefit animals but may also alter contact patterns, stress, contaminant exposure and disease dynamics. Their conclusions support risk management rather than a universal instruction to feed or never feed.

### ***13.2 Food composition, hygiene and seasonal design***

A supplementary food must be appropriate to the target species, not merely convenient or inexpensive. The formulation should consider energy density, protein, minerals, particle size, digestibility and likely consumption alongside natural food. Food should be fresh, protected from weather and contamination, and offered in amounts that can be consumed without prolonged accumulation. Water points and feeding stations require cleaning; mouldy or wet material should be removed, and waste should not attract rodents. Site design should reduce crowding and allow individuals to feed without being trapped or exposed to predators.

Seasonal feeding may have unintended consequences if it alters migration timing, breeding density, dependency on human provision or competitive relationships among species. Long-term food subsidies can promote the growth of some generalist populations while leaving specialists disadvantaged.

They can also change where birds aggregate, increasing pathogen transmission or predation risk. Evaluation should compare outcomes against areas or periods without intervention when feasible. Simple counts at feeders are inadequate as the only endpoint; the programme should track health, condition, reproduction, survival or the defined conservation metric.

### ***13.3 Disease and behaviour safeguards***

Dense gathering at a feeding site can increase direct or indirect contact among individuals and between species. Wet organic matter, shared surfaces and contaminated water may enable pathogen persistence. Feeding sites can also change aggression, territoriality and social hierarchy, with subordinate birds obtaining less food. A well-intended intervention may therefore improve resource access for some individuals while increasing risk for others. The design should consider feeding dispersion, cleanable surfaces, dry storage, frequency of cleaning and rapid removal of sick or dead birds according to wildlife-health protocols.

Where mass mortality, neurological signs, respiratory signs or unusual clustering occurs, feeding should be reviewed immediately and wildlife or veterinary authorities consulted. Moving feeders or distributing food more widely may reduce some forms of crowding, but no single measure is adequate for every pathogen or species. Feeding guidance should follow local disease advice and legal requirements. Public messaging should avoid unsupported claims that any specific seed or supplement will prevent disease; good habitat, hygiene and appropriate species management are more defensible foundations.

## **14. Methods, evidence quality and research priorities**

### ***14.1 Measuring diet in free-ranging birds***

Diet can be studied through direct observation, camera traps, nest-provisioning observations, faecal metabarcoding, DNA barcoding of prey, stable-isotope analysis and, in selected contexts, digestive-tract contents. Each method has different strengths. Direct observation captures feeding behaviour but misses small prey and nocturnal events; DNA methods identify taxa but may not quantify biomass accurately; stable isotopes integrate diet over a tissue-specific time window but generally do not provide a precise item list. A stronger study can combine methods and explicitly describe their limitations. Nutritional conclusions should not overstate what a taxonomic diet profile can reveal about energy or nutrient intake.

Faecal samples can provide both diet and microbiome data, creating opportunities to investigate reciprocal relationships between food choice and microbial communities. Uehling and Houtz (2025) highlight that diet-microbiome research in wild birds is growing, but many causal questions remain unresolved. Sample collection should consider age, season, location, recent diet, captivity or handling, antibiotics and storage conditions. The presence of a microbial taxon does not necessarily establish its function, and microbiome differences may reflect environmental exposure or host behaviour rather than a direct nutritional effect.

### ***14.2 Linking food to demographic outcomes***

A rigorous conservation study should connect food quantity and quality to measures closer to fitness, such as body condition, egg production, nestling growth, fledging success, juvenile survival or annual population change. Associations need careful interpretation because habitat quality, predation, weather, disease and disturbance can affect both food availability and reproductive outcome. Longitudinal and multi-site studies can help separate these factors. Where randomized interventions are not feasible, matched sites, before-after comparisons and transparent statistical models can strengthen inference, but limitations should remain explicit.

The relationship between individual condition and population growth is not always straightforward. Birds in poor habitats may compensate by laying more eggs, working harder or dispersing; a good year may increase reproduction but also increase competition later. The meta-analysis by Twining and colleagues (2023) illustrates that food availability can be associated with reproductive success while condition and reproductive output may trade off. Conservation decisions should therefore use multiple indicators and avoid equating one favourable measure with an overall population benefit.

### ***14.3 A practical monitoring framework***

An applied monitoring framework can be organized around five domains: resource availability, nutrient quality, bird use, health and demographic response. At a wetland, this might include water depth and prey density, feeding observations, bird condition and breeding outcomes. In an agricultural system, it could include insect abundance, pesticide management, nest provisioning and fledgling success. In urban settings, monitoring may focus on feeder hygiene, disease events and the balance between supplementary food and natural habitat. Indicators should be low-cost enough to repeat and selected before interventions begin.

Data standards are important if findings are to be compared across regions. Studies should report season, habitat, species, sample size, food measurement method, diet analysis, body-condition measure and any feeding intervention. Negative or null outcomes deserve publication because they help identify circumstances where feeding or restoration does not work. Indian research priorities include multi-season studies at wetlands and grasslands, quantification of pesticide-linked food changes, evaluation of native urban plantings and culturally sensitive guidance for bird feeding. Conservation nutrition is strongest when ecological data and animal outcomes inform adaptive habitat decisions.

## 15. Species-specific synthesis: applying nutrition concepts without overgeneralization

### 15.1 *Granivores and seed availability*

Seed-eating birds are influenced by seed size, hardness, nutrient composition, harvest practices and access to the ground or vegetation where seeds accumulate. Crop harvest can create a short pulse of food, but the resource may disappear rapidly or expose birds to machinery, pesticides and disturbance. Seed-rich habitats may still be deficient in suitable nesting cover or water. Management should therefore evaluate both resource quality and temporal continuity. For threatened species with narrow habitat requirements, local field studies are needed before recommending seed supplementation or particular plantings.

Supplementary seed mixes should not be assumed nutritionally complete for every species. Different seed types vary in fat, protein, fibre and micronutrients; birds also differ in whether they can crack, husk or digest a given seed. Concentrated feeding can disproportionately benefit common generalists and promote interspecific aggression. Habitat restoration that retains native seed-producing plants can provide a more diverse resource base, but the timing of seed availability and its use by target species should be documented. The relevant outcome is not simply the number of birds at a feeding patch but survival, condition and breeding performance where these can be measured.

### 15.2 *Insectivores and the timing of prey pulses*

Insectivorous birds depend on invertebrates whose abundance and accessibility vary with temperature, rainfall, vegetation and management. Some prey emerge in brief pulses, making the timing of reproduction critical. A habitat that supports a high annual mean of insects may still fail to provide adequate prey during the period when chicks need it. Measuring prey at the relevant height and microhabitat is therefore important; sweeping vegetation or counting insects in a different habitat stratum may not reflect what birds can capture. Prey size and nutritional composition can also influence the usable food supply.

In agricultural landscapes, pesticide exposure and habitat simplification may act together by reducing prey and changing the safety of the remaining food. Integrated pest management, native field margins and retention of structurally diverse vegetation may improve the ecological basis for insect availability, though outcomes depend on crop, region and farming practice. Conservation studies should measure prey, parental provisioning and chick survival together where possible. Nutritional evidence is strongest when resource changes can be linked to demographic response rather than inferred from bird abundance alone (Twining et al., 2023).

### 15.3 *Frugivores, nectarivores and food-plant phenology*

Fruit and nectar availability depend on plant species, flowering or fruiting phenology, rainfall and climate. Foraging birds may rely on a sequence of species that provide resources at different times; simplification of native vegetation can create seasonal gaps even when total plant cover appears adequate. Fruit chemistry, size, pulp composition and seed traits influence which birds use a plant and how it affects dispersal. Planting decisions should therefore be grounded in local ecology and should avoid assuming that a single prolific non-native species is the best conservation resource. Nectar is rich in readily available sugars but does not supply all nutrients needed by birds. Nectarivores may consume insects, pollen-associated materials or other foods to meet requirements beyond carbohydrate energy. Artificial nectar can be inappropriate if concentration, hygiene or feeder design is unsuitable for the target species. In natural systems, maintaining a diversity of native flowering plants may be more resilient than relying on a single mass-flowering resource. Monitoring should include plant phenology, bird use, diet composition and potential ecological effects on native species.

## 16. Ethical considerations and conservation intervention evaluation

### 16.1 *Avoiding unintended ecological effects*

Conservation actions may benefit one species while harming others. Feeding can raise local density, promote aggression or disease transmission, alter predator behaviour and influence community composition. Planting a non-native food plant might benefit one generalist yet displace native vegetation or change seed dispersal patterns. Nutritional interventions should therefore be evaluated as ecological interventions with trade-offs, not as isolated ways to deliver calories. A risk assessment should identify intended beneficiaries, non-target species, likely pathways of harm and practical indicators for detecting unwanted outcomes.

The precautionary approach does not mean that all intervention is prohibited. Rescue, rehabilitation or emergency feeding may be appropriate when clearly justified and carried out with suitable veterinary and wildlife expertise. The key is to have a defined objective, a time frame, monitoring and an exit strategy. Habitat protection often produces broader benefits because it sustains natural food webs, nesting cover and refuge simultaneously. Where supplementary feeding is proposed, evidence should show why it is necessary and why lower-risk habitat actions alone are insufficient.

### 16.2 *Biosecurity and welfare in managed feeding sites*

A feeding site should be designed to limit contamination and avoid forcing birds to gather in a small, predictable space. Food storage must prevent moisture, mould and pest access; feeders need routine cleaning; spilled food should be removed; and sick or dead birds should be managed under local

wildlife-health guidance. The risk is not identical across pathogens or taxa, so decisions about suspension, cleaning or relocation should be informed by disease advice. Murray et al. (2016) emphasize that provisioning can alter both nutritional state and pathogen transmission mechanisms, supporting context-specific safeguards.

Welfare considerations include access for subordinate individuals, risk of entrapment, exposure to predators, aggression, and changes in normal foraging or movement. A programme should assess which individuals actually consume the food and whether condition improves across the target population. It should also avoid creating long-term dependency where this is not an intentional and justified management objective. Transparent public communication can explain that keeping a feeding area clean, using species-appropriate food and protecting habitat may be more beneficial than simply increasing the quantity of human-provided food.

### ***16.3 Evaluating success with multiple outcomes***

A good evaluation includes a before-and-after measure and, where feasible, a comparable unmodified site or group. Indicators should be chosen before the intervention: use by target species, condition, reproductive success, disease incidence, natural foraging, predation and non-target effects may all matter. A high count immediately after feeding is not enough to demonstrate improved conservation status. Monitoring should continue long enough to detect whether the intervention changes survival or reproduction and whether effects persist after food is removed. Negative outcomes should lead to modification or discontinuation rather than continued provisioning by habit.

Interpretation requires care because population changes can be driven by regional weather, habitat change, migration or broader demographic trends. Multi-site replication, standardized effort and transparent reporting strengthen conclusions. Where rare or sensitive species are involved, study design must minimize disturbance and follow applicable permits. Combining ecological, nutritional and veterinary evidence can help determine whether observed changes arise from food supply, disease, habitat structure or a combination. Such evaluation turns practical conservation actions into evidence that can inform future management.

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## **17. Communication, policy and future research in India**

### ***17.1 Integrating habitat, agriculture and community practice***

India's bird habitats include wetlands, coasts, forests, grasslands, deserts, farms, orchards and dense urban neighbourhoods. Nutrition-related conservation actions must fit this landscape diversity. In agricultural areas, retention of native field margins and careful pesticide management can support prey and seed resources; in wetlands, hydrology and prey availability require attention; in cities, native vegetation and safe water may be more valuable than unregulated food provision. Effective action depends on the season and the target ecological guild, so broad slogans such as “feed birds” or “never feed birds” are inadequate.

Community engagement is crucial because many food sources and feeding practices are managed by households, temples, parks, farmers or tourism operators. Guidance should explain what is known, what remains uncertain and what local changes can reduce risk. A respectful, evidence-led approach is more likely to be adopted than one that dismisses cultural practices. Collaboration among ecologists, veterinarians, nutritionists, agricultural extension workers and local communities can improve both the scientific relevance and public legitimacy of conservation nutrition programmes.

### ***17.2 Data integration and emerging methods***

Environmental DNA and DNA metabarcoding can broaden the ability to identify diet items, while remote sensing maps vegetation, flooding and habitat connectivity. Stable isotopes provide complementary evidence about resource sources and trophic position, and automated acoustic or camera systems can document activity and behaviour. These methods are useful only when they are matched to a clear research question and supported by appropriate sampling. Molecular detections may be biased by digestion and reference databases, while satellite habitat measures cannot directly show whether a nutrient-rich food is accessible or being consumed.

Future work should combine diet composition with nutrient content, food availability, individual condition and demographic outcomes. Standardized sample storage, metadata, seasonal coverage and transparent analysis pipelines can make findings comparable across regions. Microbiome studies should connect taxonomic observations with function and host outcomes. In India, priority datasets could cover seasonal food availability at major wetlands and grasslands, insect prey in agricultural mosaics, native plant phenology in urban and forest systems, and the risks and benefits of supplementary feeding across bird guilds.

### ***17.3 A research agenda that supports decisions***

A useful research agenda should prioritize questions that can change management: when is food actually limiting, which nutrient or prey category is scarce, which habitat action addresses that constraint, and what indicator will demonstrate improvement? Studies should distinguish natural food restoration from artificial provision and document whether benefits persist after intervention. They should also quantify adverse effects such as disease, competition, contaminants and ecological displacement. Where evidence is sparse, pilot interventions with clear stop rules are preferable to large-scale permanent feeding based only on anecdote.

The overarching challenge is to build a bridge between nutrition and conservation outcomes. Body condition can provide a fast signal, but breeding success and survival provide stronger demographic information; diet DNA can identify prey, but does not by itself give nutrient balance; and food abundance can be high while access or timing remains limiting. A multi-evidence framework is needed to avoid overconfident conclusions. When habitat management, nutrition measures and demographic monitoring are designed together, conservation nutrition can help explain why some landscapes sustain bird populations and others fail despite apparently abundant food.

**Table 7. India-oriented habitat–food-web matrix for wild-bird conservation nutrition; guild examples are illustrative, not exhaustive.**

| Indian habitat / context              | Natural food-web base                                            | Nutrition-sensitive pressure                              | Useful field signal / response                                     |
|---------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------------|
| <b>Wetland and coast</b>              | Aquatic invertebrates, fish, molluscs, seeds and emergent plants | Hydrological change, pollution and prey-depth shifts      | Water depth, prey density, feeding behaviour and water quality     |
| <b>Grassland and dryland</b>          | Grass seeds, insects and small vertebrate prey                   | Grazing/fire change, drought and simplified vegetation    | Seed and insect availability; retain habitat heterogeneity         |
| <b>Agricultural mosaic</b>            | Crop grains, weed seeds, field-margin plants and invertebrates   | Harvest pulses, pesticide exposure and loss of margins    | Compare crop stage, insect activity and bird condition             |
| <b>Native woodland / scrub</b>        | Fruits, nectar, foliage-associated insects and seeds             | Gaps in flowering/fruitle sequence and canopy loss        | Record native plant phenology and foraging use                     |
| <b>Urban garden / park</b>            | Insects, native fruits, seeds and human-provided food            | Unbalanced food, crowded feeding points and contamination | Improve native planting and hygiene; monitor community composition |
| <b>Mountain / cold-season habitat</b> | Seasonal berries, seeds, insects and localized prey              | Short growing season and weather-driven access limits     | Record phenology, snow/weather conditions and body condition       |

Interpretation: habitat examples are broad ecological categories. Confirm which resources are actually used by the target species and season before drawing nutritional conclusions.

**Table 8. Seasonal resource pulses and likely nutritional bottlenecks in Indian landscapes; timing must be checked locally.**

| Season / event (locally variable)         | Potential resource pulse or gap                                                 | Bird groups potentially affected                                | Monitoring focus                                           |
|-------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------|
| <b>Pre-monsoon dry period</b>             | Drying wetlands, reduced surface activity of some prey and scarce green growth  | Water-associated insectivores, waders and some small passerines | Water persistence, prey sampling and foraging time         |
| <b>Monsoon onset and peak</b>             | Rain-driven insect emergence and changing accessibility of ground foods         | Insectivores and breeding birds provisioning chicks             | Prey abundance, nest provisioning and rainfall timing      |
| <b>Post-monsoon / winter arrival</b>      | Seasonal influx of migrants and changing wetland/grassland food supply          | Migratory waders, waterbirds and insectivores                   | Stopover use, prey density, disturbance and body condition |
| <b>Harvest and stubble period</b>         | Temporary grain/weed-seed pulse followed by rapid removal or field disturbance  | Granivores and opportunistic feeders                            | Crop stage, seed access, field operations and food safety  |
| <b>Breeding window (species-specific)</b> | High nutrient demand and potential mismatch between chick demand and prey peaks | Nestlings and adults provisioning young                         | Food size/quality, visit rate, chick growth and fledging   |

Interpretation: Indian seasonal patterns differ by region, rainfall, altitude and species. This table is a monitoring prompt, not a uniform national calendar.

**Table 9. Decision matrix for supplementary feeding: evidence required, default action and stop rules.**

| Situation                              | Evidence to check first                                                         | Default management position                                         | Safeguard / stop rule                                        |
|----------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------|
| Natural foods appear adequate          | Habitat condition, natural foraging and bird body condition                     | Prefer habitat protection over routine feeding                      | Do not add food solely to attract birds                      |
| Short, documented emergency shortage   | Cause, duration, target species and expected benefit                            | Consider a time-limited, species-appropriate intervention           | Predefine exit criteria and monitor response                 |
| Rehabilitation or veterinary care      | Individual condition and professional assessment                                | Use expert-designed feeding for the specific species and life stage | Avoid transferring captive diets to free-ranging populations |
| High-density public or tourist feeding | Crowding, aggression, food type, contamination and local ecological effects     | Reduce concentration and prioritize habitat-based alternatives      | Pause if disease, injury or poor-quality food is observed    |
| Disease cluster or unusual mortality   | Wildlife-health advice, water/food contamination and contact patterns           | Suspend congregation-based feeding pending guidance                 | Follow relevant wildlife authority / veterinary advice       |
| Suspected toxic or mouldy food         | Source traceability, visible spoilage and contaminant testing where appropriate | Remove suspect material and notify responsible authorities          | Do not replace with another unassessed food source           |

Interpretation: feeding should be an evidence-led, monitored intervention. Disease events or suspected contamination should trigger expert advice rather than routine continuation.

**Table 10. Habitat-first intervention logic for common field constraints.**

| Observed constraint          | Evidence to collect                                  | Lower-risk first response                              | Outcome to monitor                         |
|------------------------------|------------------------------------------------------|--------------------------------------------------------|--------------------------------------------|
| Low chick provisioning       | Prey availability, adult feeding rate, weather       | Protect prey-rich habitat and reduce disturbance       | Provisioning and fledging success          |
| Seasonal food gap            | Plant phenology, seed/insect availability, movement  | Restore diverse native food resources                  | Seasonal use and body condition            |
| Urban crowding at feeders    | Food quality, disease events, species composition    | Improve site hygiene and habitat, reassess need        | Health, aggression and natural foraging    |
| Wetland bird decline         | Water depth, prey density, pollution and disturbance | Restore hydrology and food-web processes               | Prey use, condition and seasonal abundance |
| Suspected food contamination | Feed / prey source, toxicology, event history        | Remove suspect source and consult wildlife authorities | Exposure reduction and health outcomes     |

Interpretation: choose indicators before implementing the intervention and review outcomes alongside safety, welfare and economics.

**Table 11. Minimum reporting framework for studies of wild-bird nutrition.**

| Domain              | Minimum information                                       | Why it is necessary                               |
|---------------------|-----------------------------------------------------------|---------------------------------------------------|
| Species and context | Species, age class if known, site, season and habitat     | Enables ecological interpretation                 |
| Diet methods        | Observation, metabarcoding, isotope or other method       | Methods differ in taxonomic and quantitative bias |
| Food environment    | Availability, timing, accessibility and quality           | Separates resource presence from usable intake    |
| Host outcomes       | Condition, breeding, survival or defined proxy            | Connects diet to biological relevance             |
| Confounding factors | Weather, predators, disturbance, disease, land management | Reduces over-attribution to nutrition alone       |

Interpretation: choose indicators before implementing the intervention and review outcomes alongside safety, welfare and economics.

### EVIDENCE-INTEGRATION FRAMEWORK FOR CONSERVATION NUTRITION

Use independent evidence streams before attributing population change to nutrition

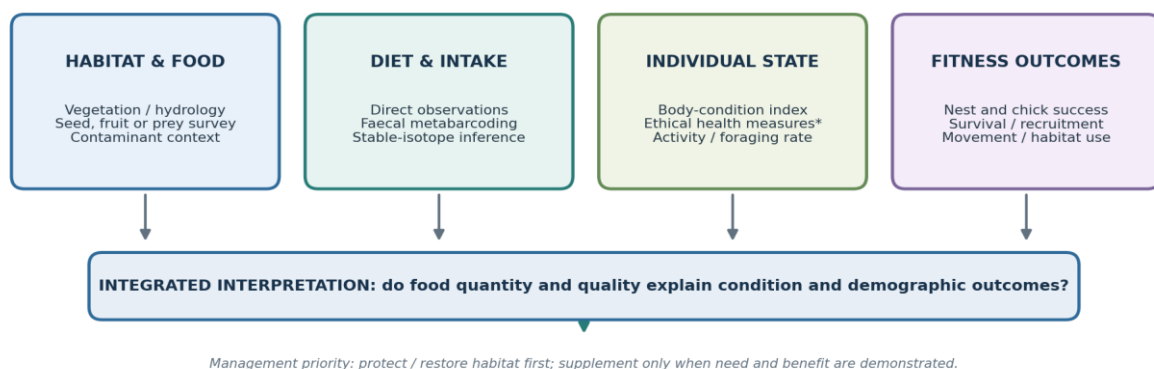


**Fig. 3. Evidence-integration framework for conservation nutrition, combining habitat and food surveys, diet and intake evidence, individual condition and demographic outcomes.**

Figure 3 is intended as a field interpretation aid: it links broad habitat types with resource categories and measurable signals. It does not imply that all species in a habitat share one diet or respond identically to management.

## Conclusions

Wild bird nutrition is best understood as a property of ecological food webs shaped by habitat, season, species traits and human activities. Protecting natural food resources is usually the first-line conservation strategy. Supplementary feeding may have a role in selected situations, but it must be species-appropriate, hygienic, limited, monitored and justified by a clear objective. Gut microbiome methods and dietary molecular tools offer new opportunities, yet should be linked to host and population outcomes before being used to prescribe interventions. In India, conservation nutrition can contribute by identifying seasonal resource bottlenecks and guiding habitat management across wetlands, grasslands, forests and urban landscapes. funding was received for preparation of this review. Please amend this statement if funding supported the work.

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