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Precision Feeding Should Begin With the Animal Rather Than the Diet: A Phenotype-to-Nutrient Decision Model Integrating Metabolic Demand, Disease State, Intake Capacity, Digestive Constraints, Behavior, and Feeding Environment

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ABSTRACT

Precision feeding is commonly framed as increasingly accurate diet formulation and delivery, yet this framing can reverse the decision sequence. Nutrient requirements arise from the animal's changing physiological state, while the feasibility of meeting those requirements depends on disease status, voluntary intake, digestive capacity, feeding behavior, feed form, and environmental conditions. This article develops an original non-empirical nutritional decision model that begins with the animal phenotype and treats diet selection as a conditional response rather than the starting point. Evidence across dairy cattle, pigs, poultry, and small ruminants is used to distinguish metabolic demand from intake capacity, formulated nutrient concentration from realized nutrient availability, and intrinsic animal state from behavior expressed under management constraints. The proposed model organizes feeding decisions around sequential characterization of physiological demand, disease-associated modification, intake feasibility, digestive and behavioral constraints, environmental context, and only then diet selection, followed by reassessment when the animal state changes. This architecture does not imply that phenotype can be measured without error, that individualized feeding is always superior to group feeding, or that one set of thresholds can transfer across species and production systems. Its principal value is analytical: it makes explicit where calculated nutrient targets may become biologically or practically infeasible and where apparently adequate diets may fail to match the animal receiving them. Prospective testing, external validation, species-specific calibration, and evaluation of decision utility are required before the model can support implementation claims.

Keywords: Precision feeding, Animal phenotype, Nutrient requirements, Voluntary intake, Digestive constraints, Feeding behavior

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Introduction

Precision feeding has often advanced through better formulation, delivery technology, and prediction of nutrient requirements. Its underlying logic, however, is more fundamental: nutrient supply should be matched to the requirements of an animal whose needs vary across individuals and over time [1, 2]. Precision-feeding research in pigs shows why population-average provision can produce systematic over- or undersupply when requirement trajectories differ, whereas dairy optimization work demonstrates that the mathematically preferred diet for an individual need not be identical to the group solution [3]. Precision feeding can also alter modeled environmental burdens, but those gains depend on production-system assumptions and cannot be treated as automatic consequences of individualization [4].

The argument developed here is therefore not that ration formulation is secondary in importance, but that it is secondary in decision order. A diet cannot be judged nutritionally appropriate without first defining the animal state to which it is applied. That state includes production demand, physiological transition, disease-associated modification, voluntary intake capacity, digestive and absorptive constraints, feeding behavior, and environmental opportunity. These domains are analytically distinct because they may fail in different directions: metabolic need can rise while intake falls; formulated nutrient density can remain constant while digestive availability changes; and a theoretically suitable ration can remain inaccessible because of competition or management. The article proposes a phenotype-to-nutrient decision model that preserves these distinctions and treats reassessment as necessary when the underlying animal state changes.

Limitations of diet-first precision feeding

A diet-first approach begins with a ration, ingredient matrix, or nutrient specification and then asks which animals should receive it. This can be efficient when animals are sufficiently homogeneous, but it risks making the feed formulation the reference state and the animal the adjustment term. Precision-feeding theory instead implies that heterogeneity in nutrient demand is the initiating problem, not a deviation from an otherwise fixed diet. Mathematical optimization reinforces this point because the preferred solution changes with animal-specific requirements, economic assumptions, and the objective being optimized [3].

The principal limitation is therefore not that group diets are inherently inappropriate. It is that diet adequacy is conditional. A ration that satisfies an average predicted requirement may oversupply one animal, fail to meet another animal’s effective demand, or become infeasible when intake or digestion changes. Moreover, production, economic, welfare, and environmental objectives need not identify the same “best” feeding decision. The proposed model consequently avoids defining precision as maximal individualization. It defines precision as explicit alignment between measured or estimated animal state, an evidence-bounded nutrient target, and a feasible delivery strategy. Where animal heterogeneity is small, measurements are unreliable, or delivery systems cannot individualize safely, a group-level strategy may remain the more defensible operational choice.

Animal phenotype as the starting state

Phenotype is used here as a decision state rather than as a purely genetic descriptor. Dry matter intake in Holstein cows varies with measurable phenotypic and genomic characteristics, demonstrating that intake capacity is not adequately represented by ration composition alone [5]. Individual gestating sows at nominally similar stages also show substantial variation in predicted nutrient requirements when body state and gestational trajectories are incorporated [6]. These findings support a starting assessment that is animal-specific, but they do not imply that estimated requirements are biological constants or that phenotype can be measured without error.

The phenotype relevant to feeding also includes the animal as expressed within its environment. In lactating dairy cows, parity composition and social interactions are associated with feeding patterns and feed efficiency, indicating that realized intake behavior partly reflects social context rather than intrinsic demand alone [7]. The proposed decision state therefore separates at least three questions: what the animal appears to require metabolically, what it can currently consume and utilize, and what the housing or feeding system allows it to obtain. This distinction prevents behavioral suppression, feeder competition, or measurement noise from being misclassified as a lower nutrient requirement. It also makes phenotype revisable: repeated observations can change the interpretation of the same animal as physiology, production, health, or management conditions evolve.

Life stage and production demand

Life stage changes both the magnitude and composition of nutrient demand. In transition dairy cows, controlled variation in pre- and postpartum metabolizable protein supply produced stage-dependent effects on intake, production, and metabolic markers [8]. The implication is not that one direction of protein adjustment is universally preferable, but that a nutrient target cannot be detached from the physiological interval in which it is applied. Late gestation, early lactation, growth, maintenance, reproduction, and recovery represent different demand structures rather than interchangeable points on a single intake scale.

Physiological state can also change materially in the absence of overt disease. Liver and adipose inflammatory tone shifts across the transition from late pregnancy to early lactation even in cows undergoing an apparently healthy transition [9]. A model that treats "healthy" as metabolically static would therefore erase biologically meaningful adaptation. Evidence from broiler breeders further shows that individual precision allocation can alter flock uniformity under a reproductive production system [10], supporting the broader relevance of within-stage heterogeneity while remaining species specific.

Accordingly, life stage is treated here as an organizing variable, not a sufficient prescription. The proposed model requires production demand to be interpreted alongside current body state, intake, digestive capacity, and environmental conditions before nutrient delivery is selected.

Metabolic and physiological requirements

Calculated requirements provide an indispensable reference, but they should be interpreted as state-dependent estimates. Individual gestating-sow models show that animals progressing through the same broad reproductive stage can diverge in predicted requirements [6]. Transition-cow experiments similarly demonstrate that nutritional response depends on whether supply is evaluated before or after parturition [8]. These findings support the principle that metabolic demand should be indexed to time, physiological state, and production function rather than represented as a fixed scalar.

The distinction matters because production output and physiological adaptation may not change on the same timescale. Tissue-level changes during a healthy transition show that major metabolic reorganization can occur even when disease is not diagnosed [9]. Consequently, apparently stable production does not prove stable nutrient demand, and changing biomarkers do not by themselves establish pathology. The proposed model therefore treats requirement estimation as one layer of the feeding decision, not the final decision itself.

This structure also limits overinterpretation. Requirement equations can organize expected demand, but the resulting target remains conditional on whether the animal can ingest, digest, absorb, and behaviorally access the diet capable of supplying it. Precision feeding begins to fail when a calculated requirement is treated as equivalent to deliverable nutrition. The next decision layers address precisely those constraints.

Disease-associated nutritional modification

Disease or gastrointestinal disruption can change the meaning of a previously appropriate nutrient target. Experimental hindgut acidosis in lactating dairy cows altered inflammatory, metabolic, and productive responses despite a high-fiber feeding context [11]. Such challenge evidence supports the principle that disturbed gastrointestinal state can modify nutritional response, but it does not establish a universal therapeutic diet or permit direct transfer from an induced condition to spontaneous disease.

A second category is physiological vulnerability without confirmed disease. Transition-cow welfare scholarship emphasizes that nutrition, comfort, behavior, and management interact during periods of high biological demand [12]. This distinction is important because reduced intake or altered behavior during a vulnerable state should not automatically be labelled disease. At herd level, associations between transition management, dietary factors, biomarkers, health, and production further show that nutrition-health relationships occur within management systems rather than in isolation [13]. Observational associations, however, remain vulnerable to confounding and should not be converted into causal prescriptions.

Table 1 compares three sources of nutritional mismatch that can look similar at the feeder but require different interpretations of demand, tolerance, and deliverability.

Table 1. Similar reductions in intake or performance separated by gastrointestinal, physiological, and management origins

Diagnostic feature	Gastrointestinal disruption	Physiological vulnerability	Management-conditioned mismatch
What has changed	Digestive state, tolerance, passage, or utilization	The animal is in a high-demand or transitional state with unstable capacity	Access, grouping, feeding routine, or another system condition alters the response
Why intake or performance may fall	Previously suitable supply is consumed or utilized differently	Demand can rise while intake, behavior, or comfort becomes unstable	The ration may be adequate on paper but inaccessible or poorly matched to management

Evidence available in the manuscript	Inflammatory, metabolic, digestive, and productive response to gastrointestinal challenge	Transition-stage intake, behavior, metabolic adaptation, and welfare indicators	Farm practices considered with biomarker, health, intake, or production patterns
Feeding implication	Reconsider delivery feasibility and tolerance before increasing nutrient density	Treat the target as provisional and repeat state assessment through the transition	Test the management or access explanation before reformulating the diet
Inference to avoid	An induced challenge is not a universal therapeutic-diet rule	Vulnerability is not equivalent to disease	Observational association does not establish that management caused the mismatch

Voluntary intake capacity

A nutrient target is actionable only if the animal can consume enough feed to approach it. Phenotypic variation in dry matter intake demonstrates that intake capacity differs among animals even within a production class [5]. During the transition period, intake can also move independently of theoretical production demand, and gastrointestinal disruption can further alter the relationship between diet offered and nutrients effectively obtained [11]. The proposed model therefore treats voluntary intake capacity as a feasibility constraint rather than merely another outcome variable.

Observed intake, however, is not synonymous with unconstrained appetite. Social grouping and feeding interactions can modify feeding patterns [7], while herd-management conditions can also shape the context in which intake and health signals are expressed [13]. A low observed intake may consequently reflect physiological limitation, disease, competition, feed access, environmental stress, normal adaptation, or combinations of these factors.

This distinction changes the feeding question. Instead of asking only whether nutrient concentration should be increased, the model first asks why the animal is not obtaining the calculated supply. Greater dietary density may be rational when intake capacity is genuinely limiting, but it can be inappropriate if the principal constraint is access, digestive tolerance, or a transient state that requires reassessment rather than escalation. Intake is therefore both a delivery constraint and a state variable whose interpretation must remain conditional.

Digestive and absorptive constraints

Formulated nutrient content does not guarantee equivalent physiological availability. In finishing pigs, changing insoluble-fibre particle size and soluble-fibre gelation altered digesta passage through the gastrointestinal tract, demonstrating that physical feed properties can modify digestive kinetics independently of nominal nutrient concentration [14]. In dairy cows, monensin and live-cell yeast supplementation altered selected measures of feeding behavior, nutrient digestibility, or lactation response, indicating that realized utilization can change within a broader ration context [15]. These findings support the distinction between nutrients formulated, nutrients consumed, and nutrients physiologically available.

Ruminant evidence also shows why physical structure matters. In Alpine goats, both the level and source of physically effective fibre affected intake, nutrient utilization, ruminal fermentation, heat production, and milk responses [16]. Those results cannot be converted into universal fibre thresholds across cattle, goats, pigs, or poultry, because gastrointestinal anatomy and fermentation impose different constraints.

The proposed model therefore places digestive feasibility after estimation of demand but before final diet selection. When passage rate, fermentation, absorptive function, gastrointestinal disturbance, or physical feed form limits utilization, simply increasing calculated nutrient concentration may not solve the mismatch. The key decision is whether the constraint changes the feasible nutrient target, the delivery form, or both. This preserves a necessary separation between biochemical formulation and biological exposure.

Feeding behavior

Feeding behavior determines whether a theoretically appropriate diet is actually encountered and consumed. Under feed competition, dairy cows differ in how feeding patterns and milk production change, and those responses are associated with behavioral phenotype [17]. This finding supports treating behavior as part of the expressed feeding state rather than as a direct measure of metabolic requirement. A cow that withdraws under competition and a cow with low physiological appetite may show similar intake, yet they pose different nutritional problems.

Social preference further complicates interpretation. Lactating cows can differ in their use of feed bins shared with cows of the same or different parity, with relationships to feeding behavior and efficiency [18]. In broiler breeders, relaxing feed restriction changes feeding and feed-seeking behavior alongside reproductive performance, illustrating that motivation, access, and production objectives need not move together [19]. These studies do not justify universal behavioral thresholds, but they show that observed intake is partly shaped by feeding opportunity.

Table 2 links each feeding pattern to the least disruptive contextual change that can test whether access or imposed allocation contributes to the apparent undersupply.

Table 2. Contextual manipulations that distinguish behavioral access from metabolic undersupply

Observed feeding pattern	Contextual manipulation	Finding that supports a contextual contribution	What remains unresolved
Competition-sensitive intake	Reduce competition or improve feeder access before changing nutrient density	Intake pattern improves when displacement or restricted access is reduced	Pain, disease, appetite, and digestive limitation may still contribute
Socially patterned feeding	Change grouping, parity mix, or access topology	Bin choice or feeding-event pattern changes reproducibly after regrouping	Preference does not identify metabolic requirement
Restriction-driven feed seeking	Reassess allocation intensity as reproductive stage or production goal changes	Feed-seeking or consumption pace changes when allocation changes	Motivation, performance, and welfare consequences may diverge

Feed form and nutrient availability

Feed form modifies the relationship between formulated composition and biological exposure. In pigs, fibre particle size and soluble-fibre gelation alter gastrointestinal passage [14], while in goats the level and source of physically effective fibre affect intake, fermentation, nutrient utilization, and production responses [16]. These findings arise from different digestive systems and cannot be combined into a universal physical specification, but together they establish that the matrix in which nutrients are delivered is not nutritionally neutral.

If a predicted deficit is addressed only by increasing nutrient concentration, the response may fail when the limiting step is passage, rumen function, digestibility, or intake capacity. Changing physical form can also alter utilization without changing the nominal target. Evidence that additives can modify digestibility and feeding responses in dairy cows further shows that realized availability is conditional on digestive context [15].

Accordingly, the proposed model treats feed form as a delivery variable evaluated after the animal's digestive feasibility has been characterized. The question is not simply which ration contains the required nutrients, but which available form can plausibly deliver them under the animal's current gastrointestinal state. This prevents calculated supply from being mistaken for absorbed or metabolically usable supply.

Environmental and management effects

Environmental load can change both the amount of feed consumed and the physiology through which nutrients are used. Meta-analytic evidence in dairy cattle shows that heat stress is associated with reductions in dry matter intake, milk yield, and feed efficiency, although effect magnitude varies across thermal and experimental conditions [20]. Environmental state should therefore modify interpretation of the same diet rather than being treated as an external afterthought.

Heat effects are not necessarily reducible to lower intake. In a pair-fed experiment, heat-stressed cows showed gastrointestinal and production responses that were not fully reproduced by feed restriction alone [21]. This distinction matters because simply replacing calories lost through hypophagia may not address the entire physiological consequence of thermal exposure. Likewise, dietary cation-anion difference and buffering strategies tested under mild heat stress produced endpoint-dependent responses [22], showing that nutritional interventions can themselves be environment-conditioned.

The proposed model separates environment-mediated reductions in intake opportunity from direct physiological modification. Management also determines whether cooling, feeder access, grouping, and ration delivery keep a theoretically suitable diet feasible. No universal thermal threshold is proposed; environmental state instead modifies both demand and deliverability.

A phenotype-to-nutrient decision model

The proposed phenotype-to-nutrient model reverses the usual ordering of questions. It begins by characterizing the animal's current state, including production demand, physiological transition, disease or vulnerability, and observed intake phenotype. Requirement estimates are then interpreted through noncompensatory constraints: inadequate intake capacity, digestive limitation, behavioral access, or environmental stress cannot be assumed to cancel one another, and a favorable value in one domain cannot automatically compensate for failure in another.

The next step is adjudication. The model asks whether the calculated nutrient target remains biologically feasible, whether delivery must be modified, or whether the target requires temporary reinterpretation. Individual optimization shows that preferred diet solutions depend on state and objective [3], while management-context evidence cautions against interpreting nutritional response outside its system [13]. Heat-stress evidence further supports separating intake-mediated from direct environmental pathways [21].

Reassessment is integral. A feeding decision remains provisional because physiological state, access, intake trajectory, and digestive tolerance can change. **Figure 1** compresses this logic by separating evidence-supported input domains from the proposed adjudication and feedback relationships. **Table 3** then records the model's evidence boundaries so that a reader can distinguish what may guide a decision from what still requires validation.

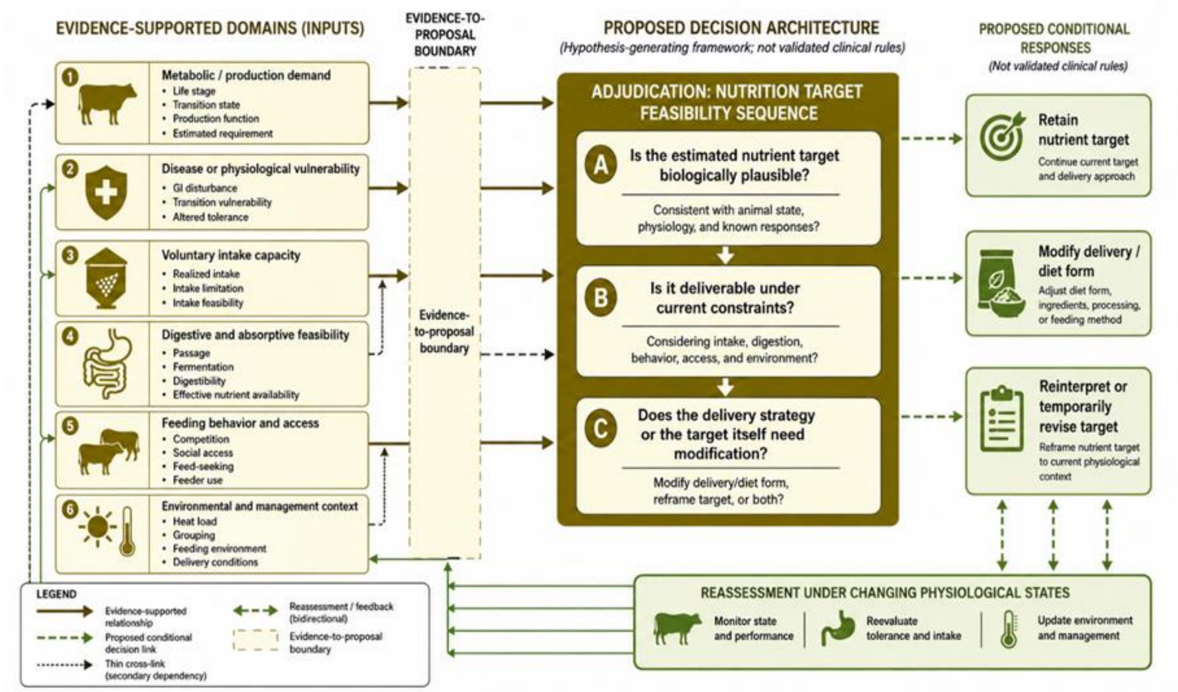

Figure 1. When a nutrient target becomes feasible: adjudicating demand against intake, digestion, behavior, and environment

Table 3 reduces the proposed model to its decisive two-axis test: whether the estimated target remains biologically plausible and whether the animal can actually obtain and utilize it.

Table 3. Nutrient-target decisions created by crossing biological plausibility with delivery feasibility

Estimated nutrient target	Delivery is feasible	Delivery is constrained
Biologically plausible for the current phenotype	Retain the target and select a diet that can deliver it under current intake, digestion, behavior, and environment	Keep the target provisional but modify access, feed form, intake support, or another delivery condition before increasing the target

Estimated nutrient target	Delivery is feasible	Delivery is constrained
Requires reinterpretation because disease, vulnerability, or environment changed	Temporarily revise the target or feeding objective even if delivery capacity appears adequate	Reinterpret the target and address the delivery bottleneck; increasing nutrient density alone cannot resolve both problems

Diet selection as a conditional response

Once the animal state and major constraints are characterized, diet selection becomes a conditional response rather than the initiating act. Factorial broiler evidence shows that grain type and fat source can interact in their effects on nutrient utilization and gut properties [23]. This means ingredient effects cannot always be inferred independently, and a diet that appears appropriate from individual nutrient labels may behave differently as a combined matrix.

Field implementation also reveals trade-offs. A precision-feeding decision-support system for lactating sows was operationalized under farm conditions, while nutrient-supply, excretion, and production outcomes were not uniformly aligned [24]. Precision therefore needs an explicit objective because competing goals may lead to different choices.

Algorithmic personalization remains similarly conditional. Individualized supplemental feeding in dairy cows has been prospectively explored using an adaptive algorithm, but responses varied with treatment and time, and the system remained a prototype requiring refinement [25]. The proposed model therefore treats diet selection as the endpoint of prior adjudication and the beginning of another testable cycle. A selected diet is not declared optimal merely because it is individualized; it is acceptable only insofar as it remains compatible with the measured state, feasible constraints, and stated decision objective.

Reassessment under changing physiological states

Precision feeding becomes static if reassessment occurs only when a ration is reformulated. In transition dairy cows, estimated prepartum dry matter intake is associated with subsequent metabolic and production differences, making current intake state potentially informative for later interpretation [26]. That association does not make intake a diagnostic test, but it shows why a feeding decision should remain open when the animal's trajectory changes.

Trajectory itself can carry information that a single measurement misses. The magnitude of prepartum intake change has been modeled alongside rumination, activity, metabolic indicators, health, and subsequent production [27]. A decline, however, may reflect either physiological adaptation or emerging dysfunction; the model therefore avoids predetermined universal trigger values. Reassessment should ask whether the change is unexpected for that animal and state, whether other domains move concurrently, and whether the previous nutrient target remains feasible.

Large repeated-record datasets also show between-animal differences in dry matter intake consistency [28]. Variability around an individual baseline may therefore be more informative than one absolute threshold. Reassessment is thus a recursive comparison between current and prior state, including the possibility that no change is warranted when the trajectory remains compatible with normal adaptation.

Applications to precision feeding

The proposed architecture can organize several existing precision-feeding applications without claiming that it validates them. Mathematical diet optimization can represent the conditional selection stage, individual breeder feeding can operationalize animal-specific allocation, and farm decision-support systems can update diets using changing production information [24]. Adaptive supplementation illustrates a further step in which measured response can be fed back into subsequent allocation [25].

Its practical contribution is to separate technologies by decision function. Sensors or routine production records can help characterize phenotype; requirement equations estimate demand; feeder systems control delivery; and repeated measurements enable reassessment. Combining those technologies does not automatically create a valid phenotype-to-nutrient system unless the inference linking measurement to action is itself tested.

In data-poor settings, behavioral observation, body state, production data, or group-level proxies may still inform decisions, but uncertainty should widen rather than disappear. Farms lacking individual delivery technology may use phenotype information to improve grouping instead of individual rationing. The model therefore permits precision at different resolutions, constrained by measurement quality, delivery capability, and validation evidence.

Research and validation priorities

Validation should proceed from measurement to prediction, then from prediction to decision utility. Models using point-in-time farm data can estimate dry matter intake in mid-lactation Holstein cows, but residual prediction error remains relevant when the estimate is intended to drive feeding decisions [29]. Milk mid-infrared spectra combined with routinely available predictors provide another route to intake estimation using artificial neural networks [30], yet calibration and population shift remain important boundaries.

Dynamic-state inference is also technically feasible in precision systems. An artificial neural network has predicted oviposition events in individually precision-fed broiler breeders using event-level data [31]. That result supports the possibility of inferring time-varying biological states, but it cannot validate nutritional-state inference in another species or task.

External validation is therefore central. Updated dairy dry matter intake equations show that predictive performance depends on model specification and evaluation population [32]. The proposed model should be tested prospectively against simpler alternatives across species, management systems, and changing physiological conditions. Endpoints should include reliability, calibration, decision agreement, target attainment, trade-offs, and whether model-assisted decisions outperform conventional strategies. Failure should prompt refinement or rejection of model components.

A further validation question is whether the architecture improves the ordering of decisions rather than merely their descriptive detail. Comparative studies should therefore test not only predictive error, but also whether state characterization changes ration choice appropriately, avoids unnecessary reformulation, detects infeasible nutrient targets, and remains stable when measurements are incomplete or noisy.

Conclusion

Precision feeding is most defensible when the animal, rather than the diet, defines the starting state. The proposed phenotype-to-nutrient model separates metabolic demand from intake capacity, formulated supply from digestive availability, and intrinsic need from behavioral and environmental constraints. It further treats diet selection as conditional and reassessment as recursive because physiological state, access, and tolerance can change after an apparently appropriate ration is chosen.

The architecture is not a validated algorithm, a species-independent prescription, or evidence that individualized feeding is always superior. Its contribution is to expose where decisions can fail when calculated requirements are assumed to be deliverable. Its usefulness will depend on reliable phenotype measurement, species- and setting-specific calibration, prospective comparison with simpler rules, and evidence that acting on outputs improves decisions rather than merely producing more detailed predictions.

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