Towards 'humane' shrimp slaughter: A review of current knowledge gaps and methodological challenges for *Penaeus vannamei*

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Abstract

Penaeus vannamei has become the most widely farmed aquatic species worldwide, yet the methods used for its stunning and slaughter remain poorly documented and largely unvalidated scientifically. Growing regulatory attention to decapod sentience calls for a critical assessment of current slaughter practices and of the indicators available to evaluate them. This review is based on a systematic search of the scientific literature covering the last three decades, focused on sentience, pain, stress indicators, stunning and slaughter methods in shrimp *P. vannamei* and other decapod crustaceans. The body of literature identified in this review is composed predominantly of review papers, reports, and non-peer-reviewed documents, with only a limited number of primary experimental studies. These primary studies, together with the available reports, highlight a substantial lack of validated information on indicators of pain, consciousness, and insensibility in *Penaeide*. This gap is further acknowledged within the review papers identified. Consequently, the four available experimental primary articles on stunning and slaughter methods of *P. vannamei* remain difficult to interpret in welfare terms. Establishing whether current slaughter methods of *P. vannamei* are humane would require sequentially validating shrimp sentience, identifying reliable pain markers, translating them

into field-applicable indicators, and then evaluating slaughter methods against these criteria. A chain of evidence that remains largely incomplete for shrimps.

Keywords

Shrimp, slaughter, decapod crustaceans, stunning, chilling, ice slurry, welfare

Highlights

- Few peer-reviewed primary studies exist on shrimp pain at slaughter;
- Existing primary articles use heterogeneous methods, limiting comparability across results;
- Current evidence cannot confirm whether stunning or slaughter methods are humane;
- Shrimp sentience and pain indicators remain scientifically unresolved.

1. Introduction

In a few decades, *Penaeus vannamei* has become the world's most widely produced aquaculture species by volume (FAO, 2025). In 2024, *P. vannamei* accounted for 53% of global crustacean production and 86% of shrimp production. Global production rose from 155,515 tonnes in 2000 to 7,656,263 tonnes in 2024 (FAO, 2025), a 49-fold increase over 24 years. In absolute numbers of individuals, Waldhorn and Autric (2022) estimate that around 440 billion *P. vannamei* are harvested each year, and that 230 billion individuals are present simultaneously on farms, making it the most numerous farmed animal species worldwide.

Alongside this industrial boom, the debate over the ethical status of decapod crustaceans has shifted profoundly. Evaluating whether current stunning and slaughter practices in shrimp are compatible with acceptable welfare standards first requires a clear understanding of key concepts such as sentience, nociception, pain, and consciousness. Throughout this review, we will use the term '**sentience'** as it is employed in animal welfare science: the capacity of an organism to have subjective experiences of positive or negative valence, including subjective experiences that are pleasant or unpleasant, such as experiences of pain, suffering, pleasure or emotion (e.g. frustration, anxiety, fear, happiness, joy) (Birch, 2017). This concept must be distinguished from several related terms. '**Nociception'** refers to the detection and neural processing of potentially harmful stimuli, without necessarily involving a subjective experience (Raja et al., 2020). '**Pain'** refers to a conscious aversive experience that typically arises from nociception, whilst '**suffering'** describes a prolonged or intense negative emotional state (Raja et al., 2020). Central to both pain and suffering is '**consciousness'**, understood here in its phenomenal sense as the capacity for subjective experience (Block, 1995; Browning & Birch, 2022). Therefore, consciousness constitutes a necessary condition for nociception to give rise to pain or suffering in a morally relevant sense. This distinction is particularly relevant given that a substantial proportion of the available literature concerns nociceptive processes without permitting firm conclusions regarding the presence of consciously experienced pain.

Several governments have revised their regulatory frameworks in light of the available scientific evidence. In the United Kingdom, the Animal Welfare (Sentience) Act 2022 recognised decapod crustaceans and cephalopod molluscs as sentient beings for the first time, based on an independent report commissioned by the Department for Environment, Food and Rural Affairs (DEFRA), which concluded that these animals are "likely to be sentient" (Birch et al., 2021). From a scientific perspective, Birch et al. (2021) structured the debate by

proposing an analytical framework comprising eight neuro-behavioural criteria, the joint meeting of which would constitute strong evidence of sentience. When applied to decapods, this framework concludes that there are high levels of confidence for crabs (*Brachyura*) and substantial levels for some lobsters and crayfish (*Astacidea*) but explicitly identifies *Penaeid* shrimps as a group for which the evidence remains insufficient (Birch et al., 2021; Crump et al., 2022).

In practice, despite increasing regulatory pressure, the industrial slaughter of *P. vannamei* remains largely unregulated and relies on methods whose scientific validity has yet to be established. Immersion in an ice slurry bath (thermal shock) is still the most commonly used technique, while electrical stunning is attracting growing interest, particularly in recent industrial and organisational initiatives. However, available data on its effectiveness in shrimps remain limited, particularly for *P. vannamei*. The precautionary principle proposed by Birch (2017) holds that preventive action is justified whenever there is a credible indicator of sentience, even in the absence of certainty. Yet, in the context of industrial shrimp slaughter, this principle is rarely applied explicitly or documented in practice.

This review is conducted in this context of scientific gaps and emerging regulatory pressure. It aims to summarise the current state of knowledge regarding (i) the effectiveness and limitations of the stunning and slaughter methods currently used for *P. vannamei*, (ii) the evidence supporting sentience and pain perception in *P. vannamei* and related decapod crustaceans, and (iii) the behavioural, physiological, and neurological indicators currently available to assess pain, stress, consciousness, or insensibility in these animals. The literature search, covering the last 30 years, identified a limited body of evidence dominated by secondary sources, with very few empirical studies specifically investigating *P. vannamei*. Consequently, available data for other decapod crustaceans were incorporated into the discussion to compensate for this lack of shrimp-specific evidence.

2. Literature review

This section describes the bibliographic research method and provides an initial overview of the available literature.

2.1. Methodology

Publications were identified using Google Scholar, covering the period from 1990 to August 2026. Keywords were defined to cover three main areas: (i) slaughter and stunning methods, (i) sentience and consciousness in shrimp and other decapods, and (iii) assessment of pain, stress, and well-being. The search queries used included:

(i) ["shrimp" OR "prawn" OR "crustacean" OR "decapod crustacean"] AND ["slaughter" OR "harvesting" OR "killing method" OR "stunning" OR "electrical stunning" OR "electrostunning" OR "ice" OR "ice slurry"]

(ii) ["shrimp" OR "prawn" OR "crustacean" OR "decapod crustacean"] AND ["sentience" OR "consciousness" OR "insensibility" OR "pain perception" OR "pain" OR "welfare"]

(iii) ["shrimp" OR "prawn" OR "crustacean" OR "decapod crustacean"] AND ["behavioural indicators" OR "physiological indicators" OR "EEG" OR "neural activity" OR "electrophysiology" OR "evoked response" OR "stress biomarkers"]

References were included when they concerned shrimp or other decapod crustaceans and provided data or analyses related to sentience, pain perception, welfare indicators, neurological, physiological, or behavioural responses to harmful stimuli, or slaughter and stunning methods. Studies dealing exclusively with zootechnical, nutritional, or pathological aspects unrelated to welfare or slaughter were excluded, as were studies on welfare during production whose results could not be extrapolated to slaughter or stunning.

2.2. Identified corpus

We identified 58 references meeting the inclusion criteria, distributed as follows: 23 primary articles (20 of which were peer-reviewed), 20 reviews, 6 reports (3 primary studies and 3 reviews), 6 commentaries, 1 meta-analysis, 1 poster, and 1 protocol. More than half of the corpus consists of secondary literature or documents not subject to peer review.

Table 1. Primary empirical studies and technical reports on shrimp. This table compiles primary empirical studies and technical reports on shrimp (Decapoda: *Penaeidae* and related taxa) addressing welfare, nociception, sentience-related responses, and stunning or slaughter methods. Only original experimental studies and technical reports on shrimp were included, excluding reviews, protocols, posters, and studies focused on other decapod species. For each entry, the table provides the reference, study type, peer-review status (PR), species (Latin name), and a summary of aims. Studies involving *P. vannamei* are highlighted in bold. * Articles published in journals identified as potentially predatory (MDPI). **This article underwent peer review by undergraduate students as part of an undergraduate-run journal, rather than the standard peer-review process conducted by field experts.

Reference	Type	PR	Species	Subject
Barr and Elwood, 2024	Article	Yes*	*Palaemon elegans*	Pain-related behavioural responses in shrimp under noxious stimuli.
Barr et al., 2008	Article	Yes	*Palaemon elegans*	Directed grooming and escape responses in stimulated shrimp.
Chakraborty and Kumar, 2026	Article	No	*Macrobrachium rosenbergii*	Study of electrical perception thresholds and the feasibility of reversible electroanaesthesia to reduce stress during handling.
Gibbs, 2026	Article	No	*Alpheus angulosus*	Nociceptive integration and pain-related behaviour in shrimp.
Khan, 2026	**Report**	**No**	***Penaeus vannamei***	**Electrical stunning device for prawns.**
Lauridsen and Alstrup, 2024	Article	Yes*	*Palaemon adspersus, Pacifastacus leniusculus, Homarus gammarus, Carcinus maenas, Cancer pagurus Linnaeus*	Analysis of the time required to reach stunning and death temperatures by boiling according to body size and shape.
Somerville et al., 2026	**Article**	**Yes**	***Penaeus vannamei***	**Behavioural and neurological responses to stunning methods in shrimp.**
Weineck et al., 2018	**Article**	**Yes***	***Callinectes sapidus, Procambarus clarkii, Penaeus vannamei***	**Cardiac and neuromuscular responses to thermal and electrical stunning.**
Wycoff et al., 2018	**Article**	**Yes****	***Callinectes sapidus, Procambarus clarkii, Penaeus vannamei***	**Efficacy of eugenol as a reversible anaesthetic in crustaceans.**

This proportion reflects the still preliminary stage of empirical research on the sentience and welfare of decapod crustaceans at slaughter, highlighting the difficulty of basing practical recommendations on robust data. The taxonomic bias is particularly pronounced: the vast majority of primary articles focus on model species that are widely used in neurobiology and ecotoxicology research and are consequently better documented than *P. vannamei*, such as lobster (*Homarus* spp.), crab (*Cancer* spp., *Carcinus* spp.), or crayfish (*Procambarus* spp.). Of the 23 primary articles and the 3 primary reports, only 11 deal with shrimp species (5 not peer-reviewed). Despite being the most farmed species worldwide, *P. vannamei* appears in only 3 primary articles and 1 report. Of these, only one article and the report are devoted exclusively to the species (one non peer-reviewed) while the remaining two articles are peer-reviewed but

cover multiple species, *P. vannamei* being one of them. Thus, only one peer-reviewed primary article focusses exclusively on this species to date within the scope defined in section 2.1. A gap that existing reviews on decapod crustaceans themselves regularly highlight without being able to fill it, due to a lack of available empirical data. Given these gaps, the discussion was broadened to include data available from other decapod crustaceans. These results are treated as indicative rather than directly applicable to *P. vannamei*, given potential taxonomic distance, ecological differences, and variation in central nervous system organization across decapod taxa.

3. Current evidence on stunning and slaughter of *P. vannamei*

The literature search identified only four primary articles and studies directly relevant to the objectives of this review and involving *P. vannamei*.

3.1. Peer-reviewed evidence from laboratory studies

Three peer-reviewed laboratory studies were identified, two of which did not specifically focus on *P. vannamei*, while one specifically investigated this species.

3.1.1. Laboratory studies not specifically focusing on P. vannamei

Weineck et al. (2018) investigated the physiological effects of two stunning methods, ice slurry bath and electrostunning, in three commercially important crustacean species: blue crab (*Callinectes sapidus*), Louisiana crayfish (*Procambarus clarkii*), and white shrimp (*P. vannamei*). The objective was to evaluate the effect of these two techniques on heart rate, muscle activity, and some hemolymphatic markers. Six individuals per species were tested for each condition (ice slurry bath at 0-4°C for 5 minutes; electrostunning at 120 V for 10 seconds). For shrimp, a second group of eight individuals was also tested. Heart rate was measured continuously. Wycoff et al. (2018) studied the effect of eugenol, the active ingredient in clove oil, as a reversible anaesthetic in the same crustacean species as Weineck et al. (2018). As Wycoff et al. (2018) primarily addresses pain and nociception rather than slaughter efficacy per se, this article is not described in this section.

Weineck et al. (2018) found a rapid drop in heart rate when shrimps were placed in an ice slurry bath. This rapid cardiac decline was not mirrored by an immediate or parallel loss of mobility. Shrimp exhibited tail flip and several contractions within the first minutes of ice slurry bath immersion, suggesting that cardiac and immediate motor response are dissociated. After

this initial period, shrimps were into a more sustained immobile state. However, the shrimp regain their activity and mobility when placed back in warm water after a 4-minute ice slurry bath. No measurements of muscle activity could be taken in this species. For electrostunning, the authors described similar paralysis and cardiac disturbance within one minute for the three species, although heart rate appeared to drop most substantially for shrimp, without formal statistical comparison between species. Notably, the authors specify that while the animals may appear visually dead after the shock, physiological functions persist: the scaphognathite continues to beat for ventilation, and residual but disturbed cardiac activity remains detectable. Following electrostunning, heart rate became arrhythmic immediately after the shock in all three species and did not fully recover its pre-stunning pattern, suggesting possible lasting alteration of cardiac function. Finally, tests on isolated abdomens show that tail movements in response to ice slurry exposure emerge within one minute, demonstrating that this response originates in the abdominal nerve cord, independently of the nervous system in head and thorax. This response disappears once the motor nerves connecting the abdominal nerve cord to the muscles are sectioned, confirming a reflexive origin. The authors conclude that the loss (and recovery) of responsiveness to sensory stimuli, as measured through the cardiac reflex, is faster in shrimp than in crabs, but remain cautious: this does not allow to conclude that there is a loss of consciousness. They emphasise that observing behaviour alone is not a reliable indicator of consciousness and call for recommendations to be based on physiological measurements and behavioural observations, rather than on the latter alone. (Weineck et al., 2018).

Several limitations can be noted for this study. The number of animals tested remains small (six to eight per species). Moreover, commercial slaughter conditions vary considerably and may involve either brief immersion in an ice slurry followed by prolonged storage in solid ice, or extended immersion in an ice slurry itself; the 5-minute duration tested here does not capture this full range of conditions. Furthermore, the temperature range used for the ice slurry bath (0 to 4°C) is quite broad: a shrimp immersed at 0°C is not exposed to the same thermal shock as at 4°C, and this variability is not taken into account in the analysis of the results. The severity of a thermal shock depends not only on the magnitude of the temperature drop, but also on the absolute temperature reached. This is because physiological processes follow a temperature coefficient (Q10) that itself varies with temperature. In lobster, for instance, the Q10 remains close to 3 within the animal's normal physiological range, but rises sharply to around 60 within the 2-4°C range (DeWachter and Wilkens, 2006). Consequently, immersion reaching temperatures close to 0°C may push physiological processes across a threshold beyond

which normal function is compromised, even if the absolute temperature drop is similar to less severe cold exposures. Finally, Weineck et al. (2018) use the absence of reaction to the touching of the eye stalk and the absence of coordinated movements as indicators of unconsciousness, without citing any scientific reference validating these criteria as relevant indicators of consciousness or pain perception in shrimp.

3.1.2. Laboratory study specifically focusing on P. vannamei

Somerville et al. (2026) compared the effect of in-water electrostunning and ice slurry baths, alone or in combination, in *P. vannamei.* The objective was to determine whether prior electrostunning made ice slurry baths more effective, and whether electrostunning alone could be sufficient to induce a loss of sensitivity.

In this study, the animals were divided into three experimental groups: 15 individuals exposed to the ice slurry bath alone at different temperatures (-2.5 °C, 0 °C, and 2.5-5 °C; n = 5, 5 and 5 respectively), 10 individuals electro-stunned and then placed in the ice slurry bath at 0 °C (selected from 24 animals observed behaviourally across four stunning parameters), and 6 individuals electro-stunned, then left in the stunning tank. The effectiveness of the treatments was assessed by observing behaviour (coordination of leg movements and presence/absence of tail movements) and by electrophysiological recording of spontaneous brain activity, summarised as total frequency spectral power (Ptot) and expressed as a percentage of the pre-treatment baseline value. A loss of sensitivity was considered confirmed when Ptot fell below 10% of this baseline value. The article does not specify some methodological elements, as the precise conditions under which the ice slurry bath was maintained (temperature stability over time, stirring, and the animal's position in the bath). Overall, the behavioural and electrophysiological analyses were not strictly identical across all experimental conditions, which limits direct comparison between groups. Furthermore, the use of eugenol to anaesthetise animals for electrode insertion, despite a recovery period of at least 10 minutes followed by approximately 10 further minutes of baseline recording, could influence the baseline physiological state and neurological responses. Eugenol is known to act pharmacologically by blocking action potential generation (for review see Chung and Oh, 2013) and potentiating GABA receptors responses (Aoshima and Hamamoto, 1999). Neural effects of eugenol can persist up to 30 minutes in fish after removal it (Lehotzky et al., 2023). In crustaceans specifically, recovery of neuronal activity following eugenol exposure typically occurs within 5 to 10 minutes (Dayaram et al., 2017), placing the 20-minute recovery window

used in the study of Sommerville et al. Is closed to the lower threshold of expected neurological recovery. These methodological gaps and bias should be kept in mind when reading the summary of results that follows, as they could influence its interpretation.

The results of Somerville et al. (2026) reveal a significant disconnection between behavioural immobility and neurological insensibility in the three conditions tested:

- In animals electrostunned (2V/cm, 5s) and then left without an ice slurry bath, tail flips occurred at the moment of the electrical shock, and behavioural immobility sets in immediately after the shock. This immobility persisted for several minutes: the first minor uncoordinated movement appeared after 3 minutes and 41 seconds, at which point the electrophysiological analysis was stopped; in a parallel behavioural trial, all animals stunned at 2.5 V/cm for 5 s had recovered within the 3-minute observation period, indicating that the effect of electrostunning alone is reversible within a few minutes. In this electrophysiological trial, brain activity increased significantly over the first 20 seconds following the stun (5-20 s post-stun), although the authors decline to read this as an epileptiform insult and state that they cannot ascertain whether the high-amplitude activity observed would qualify as such. Critically, brain activity recorded during the remainder of the period of behavioural immobility did not differ significantly from baseline levels, indicating that the animals remained neurologically active despite showing no outward signs of it.
- When electro-stunned animals are subsequently placed in an ice slurry bath at 0 °C, the proportion of animals exhibiting tail movement upon immersion dropped with stunning intensity, from 100–86% at 2-2.5 V/cm for 5 s, to 50-29% at 2.5-3 V/cm for 20 s. In both groups, brain activity decreases significantly compared to baseline levels after the ice slurry bath, but this decrease is more pronounced and longer-lasting for the more intense stunning parameters. The loss of sensitivity indicator (10% Ptot threshold) was reached consistently only in animals stunned at higher voltage and longer duration (2.5-3 V/cm for 20 s). By contrast, only half of the animals stunned at lower parameters consistently reached this indicator, despite a significant overall reduction in brain activities in both subgroups.
- In animals placed directly in an ice slurry bath, without prior electrostunning, all animals exhibited tail flip behaviour regardless of the bath temperature applied. However, a complete behavioural analysis was not performed in this condition. The duration and intensity of this behavioral phase was only indirectly inferred from the level of brain

activities, restricting direct behavioral comparison between the different conditions. Brain activity could not be precisely measured during tail-flipping due to movement artefacts and the authors indicated that the duration of this initial agitation phase is shorter in animals that received prior electrostunning than in those placed directly in the ice slurry bath, and also shorter for the coldest ice baths than for baths at 2.5-5 °C. During ice bath immersion, brain activity decreases significantly compared to baseline levels, with the rapidity of this decrease being highly temperature-dependent: as early as 2 minutes for baths at -2.5 °C and 0 °C, compared to 6 minutes for baths at 2.5-5 °C. Notably, the 10% threshold of Ptot is reached even at the warmest temperature tested but reached more rapidly for the coolest temperature (in 4 minutes at -2.5 °C, in 9 minutes at 0 °C and in 28 minutes for 4 of the 5 animals exposed at 2.5-5 °C).

The authors conclude that visual indicators such as immobility are insufficient to confirm a complete loss of sensitivity since the level of brain activity returned to baseline within 20 seconds and thereafter did not differ from it in immobile animals after electrical stunning. They propose that the absence of a tail-flip reaction during a subsequent ice slurry bath could serve as a practical commercial indicator of neural insensibility, although this recommendation currently lacks independent validation and scientific justification beyond their preliminary findings. They therefore recommend systematically following electrical stunning with an ice slurry bath, favouring temperatures close to or below 0°C for the latter, particularly in the absence of prior electrical stunning. However before to consider this recommendation, understanding the neuronal origin of tail flip is essential. The tail flip behaviour can be considered as a reflex response triggered by the lateral giant fibers stimulation (for review Krasne and Edwards, 2002; Herberholz, 2022)) in the shrimp nerve cord or alternatively as a more elaborate escape behaviour coordinated by high nervous centre. The tail-flip observed upon ice slurry bath immersion following electrical stunning is interpreted by the authors as evidence of a still-functional sensory pathway, which they take to imply processing by higher neuronal centres and, consequently, incomplete neural insensibility. This interpretation is questionable, even if animals are still conscious after electrical shock, immersion in ice slurry bath can elicit reflexive tail-flip without brain processes. Cold sensitive neurons are localized along the ventral nerve cord rather than confined to the brain (Tani and Kuramoto, 1998), the tail-flip response to cold exposure could equally reflect a reflex response rather than necessarily demonstrating sustained sensory processing reaching the brain. Moreover, the previous article

of Weineck et al. (2018) demonstrated that isolated abdomens exhibited tail movements in response to ice slurry exposure. These findings do not provide clear evidence to support a link between the absence of a tail-flip and a loss of neural sensibility. Several other methodological limitations warrant caution when interpreting these results. Sample sizes were small, and the 2.5-5 °C category covered a broader temperature range than the other groups, complicating comparisons. Critical maintenance details, such as water stirring and the animal's position in the ice slurry bath, are not specified. Animal position and orientation are fundamental factors in electrical stunning, because they directly influence the intensity of stimulation received. In electrofishing research, an animal positioned closer to the electrode plate may experience a stronger stimulation (Beaumont et al., 2006). In shrimp, the stimulus intensity experienced is also stronger when the body axis is perpendicular rather than parallel to the electrodes (Wathne, 1967), and vary also with total body length (Klima, 1968). The authors (Somerville et al., 2026) states that animals were aligned head to tail before the stun, which addresses the orientation component but leaves the distance to the electrode plates and the variation with body length unaccounted for. These factors introduce a source of variability in the consistency of electrical stunning protocols that is rarely considered for in standard experimental designs. Furthermore, no evidence yet establishes that a reduction in brain activity below the 10% threshold actually corresponds to a loss of consciousness or pain perception in this species. Moreover, no experimental condition combined multiple electrical stunning intensities in the absence of cold immersion, leaving open whether different stunning intensities produce divergent neuronal insensibility. Finally, movement artefacts prevented the analysis of brain activity during the first two minutes of immersion, making early comparisons difficult. Nevertheless, the observed disconnect between immobility and neural activity after stunning is a valuable new result that calls into question the use of purely behavioural criteria to judge stunning effectiveness.

3.2. Insights from grey literature: institutional reports

Khan's report (2025), published by Ace Aquatec, the manufacturer of the tested stunning device (Humane Stunner Universal, A-HSU), evaluated the effectiveness of this electrostunning system in an aqueous environment for *P. vannamei* at an industrial site in Thailand. The objective was to verify whether the device achieved a predefined threshold of less than 5% coordinated movement immediately after stunning, to compare two device settings ("Normal" and "High"), to assess behavioural recovery time, and to verify the absence of any impact on the commercial quality of the product.

The shrimp were transported by trucks that had carried the animals for several hours (the exact duration and transport conditions were not specified). After stunning, the animals were placed in different post-stun environments (air, ambient water, crushed ice) and observed for 15 minutes to detect signs of coordinated or uncoordinated movement. A scan sampling method was used, with the animal's behaviour recorded at the end of each 30-second interval, yielding 31 behavioural records per prawn over the 15-minute observation period. The size, weight, and developmental stage of the animals, as well as the exact voltage of the two settings tested, are not reported. Furthermore, a subgroup of shrimp deemed "not very lively" upon arrival was assessed separately (n = 30) and excluded from the primary efficacy analyses. Finally, low recovery numbers prohibited statistical analysis for behaviour data.

Khan (2025) did not observe coordinated movement of the appendages (pleopods, pereiopods) during the 20 seconds following stunning. No tail flip was observed in this same interval after stunning, whereas 100% of the shrimp in the control group, placed directly in the ice slurry bath without prior stunning, exhibited this behaviour within 20 seconds. No difference was reported between the "Normal" and "High" settings for coordinated movements. Over 15 minutes of observation, behavioural recovery remained very limited among stunned animals: no resumption of coordinated movement in those subsequently kept in the ice slurry bath, only one individual out of 24 showing a tail flip at 15 minutes among those kept in ambient water, and a low proportion of coordinated movements in animals kept in air (7% to 12.5% depending on the trial) appearing between 4 and 15 minutes.

The authors conclude that the A-HSU device achieves its target of less than 5% coordinated movements after stunning, that there is no difference in effectiveness between the two tested settings, and that the absence of coordinated movement or tail flips in the minutes following stunning may indicate a loss of consciousness. Consequently, they argue this method is preferable to ice slurry bath alone, which result in almost systematic tail flipping. They nevertheless recommend combining electrical stunning with a second slaughter method within four minutes of stunning as a precaution.

This report was produced and published by the manufacturer of the tested device, which constitutes a potential conflict of interest that must be considered when interpreting the results. Several additional methodological limitations exist. The duration and conditions of upstream transport, which strongly influence the shrimp's physiological state, are not documented. The behavioural criteria used to distinguish between “conscious” and “unconscious” movements are

only described qualitatively; no scientific basis or independent validation is provided to justify this classification. This limitation is particularly critical here, as the report's entire conclusion rests on this distinction. The case of the “tail twitch” illustrates this inconsistency: the authors specify that this behaviour cannot be definitively classified as conscious or unconscious and is likely an artefact of the electrical stunning, yet this caveat does not preclude its interpretation as a possible sign of consciousness in later sections. Furthermore, no statistical analysis is presented for behavioural comparisons between groups, despite significantly different sample sizes (ranging from 24 to 96 individuals).

More broadly, the interpretation of the behavioural results is questionable. The absence of coordinated movement is interpreted as a sign of unconsciousness, but the converse (the presence of movements may imply consciousness) is not discussed. Similarly, the absence of tail flips after electrical stunning is interpreted as a reduction in pain. However, as suggested by the study of Somerville et al. (2026), electrical stunning can mechanically block an animal's ability to produce escape reflexes without necessarily implying a loss of neural activity. The inability to react could even constitute an additional source of distress if the animal remains conscious. Finally, while the comparison between “Normal” and “High” settings is relatively robust because both were tested with an ice slurry bath, other comparisons remain fragile as groups differ across multiple parameters (e.g. mechanical resistance in the environment), preventing the specific effect of electrical stunning from being isolated.

3.3. Stunning and slaughter of *P. vannamei*: a body of evidence too limited to draw conclusions

The documents examined in this section constitute the entirety of the primary empirical studies, articles and reports identified on the effects of ice slurry baths and electrostunning in *P. vannamei* according to the inclusion criteria defined for this review (excluding posters and non-primary publications). It should be noted, however, that this corpus is heterogeneous in terms of scientific validity (article or industry report). This corpus remains extremely small, both in terms of the number of studies and the sample sizes involved in each. None of these studies, individually or collectively, allows for conclusions regarding the state of consciousness or pain perception in this species at the time of stunning and slaughter. The behavioural indicators used lack independent scientific validation, the available electrophysiological indicators are still under development and interpretation, and no study can definitively determine whether the

immobility observed after a given treatment reflects a genuine loss of sensitivity or simply a mechanical inability to move.

In addition, these article, report and studies were conducted on isolated animals or in very small groups, under controlled experimental conditions. These settings are far from real-world slaughter conditions, where several hundred individuals are treated simultaneously, which can alter the speed and homogeneity of the effects. The precise implementation parameters (temperature and composition of the ice slurry bath, voltage and duration of the electrostunning, aqueous or air-based) vary considerably from one study to another and are often poorly documented, which limits both the comparability between studies and their transposition to commercial practices. Finally, the size, weight, and physiological state of animals tested are rarely representative of the variability encountered within commercial batches.

These studies are nonetheless valuable, as they highlight several concrete questions that warrant further investigation. The voluntary or reflexive nature of the tail flip, for example, remains to be clarified. This behaviour could be both a sign of consciousness and a motor response that can be mechanically blocked by the treatments, without one necessarily excluding the other. Similarly, the relevance of immobility as a definitive sign of unconsciousness is directly challenged. Variations in metabolic biomarkers observed under different stunning treatments offer a path for developing more robust physiological indicators than behavioural observations alone. Although Weineck et al. (2018) did not find any significant differences in serotonin and octopamine in shrimp specifically, these neuromodulators remain relevant candidates given their established role in stress and emotional responses in crustaceans (Fossat et al, 2014). As another biomarker, L-lactate, identified as the most robust physiological predictor of stress in decapod haemolymph by meta-analytic evidence (Conneely et al., 2024) is another promising candidate for developing more robust indicators.

Another important finding emerges from all these researches: neither electrical stunning nor ice slurry baths appear to be true slaughter methods. Electrical stunning alone produces reversible behavioral effects at the intensities and durations tested, with animals recovering mobility within minutes, and does not reduce nervous activity of brain, used as a putative marker of unconsciousness in shrimp. The ice slurry immersion produces both a drop in brain nervous activity and behavioral immobility. These effects may be reversible for shorter exposures, whereas prolonged immersion at temperatures at or below 0°C produced a sustained reduction in brain activity maintained for at least 30 minutes. High-intensity electrical stunning

(3 V/cm for 20 s) was associated with animal death within two hours, suggesting that at such parameters, lethality may result from tissue damage rather than from humane slaughter. The death of animals kept in ice slurry bath alone may results from other mechanisms, such as asphyxiation, progressive crushing due to overcrowding, or osmotic shock, rather than from the cold itself. This aspect is not directly investigated by any of the studies examined here, but it deserves consideration in assessing animal welfare throughout the entire slaughter process, not just its initial phase.

The welfare benefit of electrical stunning over cold shock alone remains ambiguous. The time required to reach the brain activity insensibility threshold is very close to animals exposed to electrical stunning followed by ice bath immersion, or to ice bath immersion alone at sufficiently low temperatures**.** Furthermore, given that electrical stunning alone does not reduce brain activity, animals may remain neurologically sensible during this procedure and potentially experienced aversive stimulation from the electrical shock. The consecutive ice bath immersion may be therefore a new aversive stimulus. The authors do not compare these times or consider these successive aversive stimuli, which would be necessary to correctly evaluate whether electrical stunning offers a benefit over a well-calibrated cold shock used alone. These findings, while not allowing for definitive conclusions, usefully guide future research priorities for *P. vannamei*.

Beyond the limited evidence available for *P. vannamei*, the literature on stunning and slaughter methods in other decapod crustaceans also remains comparatively scarce.

3.4. Comparative evidence from other decapod crustaceans

The literature concerning the welfare of other decapod crustaceans at slaughter found with the criteria described in the second section of this review comprises a corpus of 12 documents: 9 primary research articles and 3 industrial or project reports (Table 2). As the search terms targeted decapod crustaceans generally rather than individual species, this body of work was not the result of species-specific searches, but happened to cover a diverse range of species, including the red swamp crayfish (*Procambarus clarkii*), European and American lobsters (*Homarus gammarus* and *Homarus americanus*), Norway lobsters (*Nephrops norvegicus*), edible brown crabs (*Cancer pagurus*), shore crabs (*Carcinus maenas*), giant freshwater prawns (*Macrobrachium rosenbergii*), and smaller shrimp and crayfish (Table 2).

Table 2. Studies and technical reports on crustacean decapods stunning and slaughter (except *P. vannamei*). For each entry, the table provides the reference, study type, peer-review status (PR), species (Latin name), and a summary of aims.

Reference	Type	PR	Species	Subject
Adams et al. (2019)	Article	Yes	*Procambarus clarkii*	Assessment of the impact of different heating rates and boiling on neural circuits, heart rate, and behaviour.
Albalat et al. (2022a)	Article	Yes	*Nephrops norvegicus*	Comparison of the effectiveness of electrical stunning versus chilling on neural activity and commercial quality.
Chakraborty and Kumar (2026)	Article	No	*Macrobrachium rosenbergii*	Study of electrical perception thresholds and the feasibility of reversible electroanaesthesia to reduce stress during handling.
Fregin and Bickmeyer (2016)	Article	Yes	*Homarus americanus, Homarus gammarus, Astacus astacus, Astacus leptodactylus*	Electrophysiological investigation of different anaesthesia methods (electrical, thermal, chemical) on central nervous system activity.
Kells et al. (2023)	Article	Yes	*Jasus edwardsii, Paranephrops zealandicus*	Evaluation of the effectiveness of Crustastun™ on New Zealand species using recordings of overall neural activity.
Lauridsen and Alstrup (2024)	Article	Yes	*Palaemon adspersus, Pacifastacus leniusculus, Homarus gammarus, Carcinus maenas, Cancer pagurus*	Analysis of the time required to reach stunning and death temperatures by boiling according to body size and shape.
Lorenzo et al. (2025)	Article	No	*Homarus americanus*	Evaluating the impact of electrical stunning on the welfare and meat quality of the American lobster.
Neil (2012)	Report	No	*Cancer pagurus, Homarus gammarus*	Project report demonstrating the immediate inactivation of central and peripheral nervous systems by electrical stunning.
Neil et al. (2022)	Article	Yes	*Cancer pagurus*	Study of the impact of electrical stunning on neural activity and the metabolic stress response through L-lactate measurement.
Neil et al. (2024)	Article	Yes	*Carcinus maenas, Homarus gammarus*	Research into the most reliable indicators of insensibility and demonstration of the unreliability of heart rate as a proxy for consciousness.
Roth and Grimsbø (2013)	Report	No	*Cancer pagurus*	Development and industrial validation of dry electrical stunning protocols on conveyor systems for processing facilities.

Yue (2008)	Report	No	*Homarus gammarus, Cancer pagurus, Palaemon spp.*	Review of current knowledge on crustacean sentience and critique of traditional slaughter methods in favour of more humane techniques.

The results of these studies are only partially comparable due to significant variations in experimental design and the specific physiological indicators measured. While several studies employ electrophysiological recordings of the central nervous system to define insensibility, the specific parameters for electrical stunning, such as voltage, current type, and duration, vary considerably and fundamentally alters the efficacy and lethality of the treatment. Furthermore, stimulation intensity received by the animal may vary depending on its size and shape. For instance, the time required to reach lethal temperatures in the neural ganglia of small species like prawns is seconds, whereas it takes several minutes in a large lobster or crab (Lauridsen and Alstrup, 2024). A critical finding across the more recent primary research is that behavioural indicators, such as immobility or the lack of an eye-withdrawal reflex, are frequently unreliable and do not necessarily correlate with true neurological insensibility (Neil et al., 2022). Notably, cardiac activity has been invalidated as a proxy for sensibility because the neurogenic heart of many decapods can continue to beat for over an hour after the central and peripheral nervous systems have been successfully silenced by an electric shock (Neil et al., 2024).

Recent research further distinguishes electrical stunning as a potentially reversible anaesthetic method rather than a terminal dispatch method, with the duration of the electrical shock significantly influencing the time window for recovery (Lorenzo et al., 2025). In lobsters (*H. americanus*), a 10-second stun cycle resulted in a righting response time, a reliable indicator for the recovery, that was ten times longer (~4.5 hours) than a 5-second cycle (~31 minutes) (Lorenzo et al., 2025). Additionally, electrical stunning may induce a secondary physiological stress response characterised by elevated L-lactate and glucose levels, although increased L-lactate may also partly reflect vigorous muscle contractions induced by the electric current rather than stress per se (Lorenzo et al., 2025).

Validation of slaughter methods is highly species-specific and depends on whether the goal is reversible anaesthesia or irreversible death. Electrical stunning is widely validated as the most humane and rapid method for large cold-water decapods like lobsters and brown crabs, as it can induce a state equivalent to anaesthesia in less than one second and effectively silence neural activity if parameters such as voltage, current intensity, and duration are optimised (Albalat et al., 2022; Kells et al., 2023; Lorenzo et al., 2025; Neil, 2012; Neil et al., 2022). Consequently,

while electrical stunning provides a sufficient 'stun-to-kill' window, it must be followed by a secondary slaughter method while the animal remains insensible (Neil et al., 2024; Lorenzo et al., 2025).

For tropical species like the giant freshwater prawn, electroanaesthesia has been demonstrated to be effective for reversible sedation during transport, with all animals regaining normal posture and coordinated movement within 1 to 8 minutes following cessation of the electric field, though precise thresholds for humane slaughter remain less documented (Chakraborty and Kumar, 2026). Conversely, thermal chilling in ice water has been largely invalidated as a humane slaughter method for temperate and cold-water species, as it induces a state of torpor or paralysis without systematically suppressing neural activity, potentially leaving the animal conscious during subsequent processing (Albalat et al., 2022; Kells et al., 2023). In contrast, chilling appears more effective for warm-water species, though it may require long immersion times (several minutes; Weineck et al., 2018).

Direct boiling is generally rejected, considered inhumane for large decapods because the time to reach brain death is too long, often exceeding several minutes (Lauridsen and Alstrup, 2024; Yue, 2008). However, Lauridsen and Alstrup (2024) article suggests that direct boiling might be an ethically acceptable alternative for very small specimens, as the near-instantaneous heat transfer produces incapacitation times comparable to those achieved by electrical stunning (9-24 seconds). Other methods, such as CO2 gassing and gradual heating, are consistently rejected due to the intense physiological stress and extreme avoidance behaviours they provoke (Adams et al., 2019; Yue, 2008). Finally, while chemical agents like eugenol and lidocaine are effective at inducing insensibility for research purposes, their validation for commercial slaughter is hindered by regulatory concerns regarding chemical residues in food products (Adams et al., 2019; Kells et al., 2023; Yue, 2008).

Overall, while electrical stunning is emerging as the gold standard, the literature emphasises that definitive validation requires standardised neurological protocols for crustacean decapods, such as visual evoked responses or frequency analysis of brain activity, to move beyond subjective behavioural assessments (Kells et al., 2023; Neil et al., 2024). Crucially, monitoring cardiac activity has been explicitly invalidated as a proxy for sensibility; in both crabs and lobsters, the neurogenic heart can continue to beat for over an hour after the central and peripheral nervous systems have been successfully silenced by an electric shock (Neil et al., 2024).

In light of these gaps, for *P. vannamei* and decapod crustaceans more broadly, the following section offers a broader overview of the knowledge on the sentience of shrimp and decapods in general, and on the indicators of pain, stress and well-being available in the literature. The following section aims to identify scientific avenues for better interpreting the empirical data discussed here, and to determine what remains to be established to form solid recommendations on the slaughter process of *P. vannamei*.

4. Outstanding questions regarding shrimp sentience

The evaluation of sentience in *P. vannamei* must be situated within a broader scientific debate regarding the capacity of decapod crustaceans to experience subjective states. To rigorously assess this, recent literature has adopted the framework developed by Birch and al. (2021), which establishes 8 criteria for sentience: (1) possession of nociceptors; (2) integrative brain regions; (3) neural pathways connecting them; (4) modulation of responses by anaesthetics or analgesics; (5) motivational trade-offs; (6) flexible self-protective behaviours; (7) associative learning, and (8) behaviour showing the animal values analgesia when injured. Within this framework, the level of confidence in sentience varies significantly across taxa due to the uneven distribution of scientific attention (Crump et al., 2022). For *Penaeid* shrimps such as *P. vannamei*, there is high confidence in the possession of nociceptors (criterion 1) and medium confidence regarding the modulation of responses by local anaesthetics (criterion 4), yet confidence levels remain low for most other criteria primarily because these species have been studied very little compared to crabs or lobsters (Birch et al., 2021; Crump et al., 2022). Consequently, while crabs (*Brachyura*) are considered to show strong evidence of sentience, the evidence for *Penaeids* is currently classified as 'sentience unknown' (Birch et al., 2021; Crump et al., 2022).

The neurobiological organisation of *P. vannamei* and related decapods presents specific challenges for the identification of consciousness. Unlike the more centralised nervous system of crab, in which thoracic and abdominal ganglia are partially merged into a compact ganglionic mass, shrimps have a more distributed nervous system, with a brain connected to a segmental ventral nerve cord running the length of the thoracic and abdominal body parts. Each body segment contains a paired of thoracic and then abdominal ganglia. (Birch et al., 2021). This segmental structure, combined with the small physical size of *P. vannamei*, complicates the use of electrophysiological recordings tools and the precise targeting of specific brain regions. The absence of a layered cortical structure analogous to the vertebrate neocortex makes it difficult

562 to identify clear neural correlates of consciousness using tools developed for vertebrates.
563 However, this neurological architecture difference does not reflect an absence of conscious
564 capacity, given that subcortical structures and homologous have been recognised as sufficient
565 neural substrates for conscious states even in vertebrates (Low et al, 2012). In invertebrates
566 several neuronal structures have been identified with similar function of subcortical structures
567 in vertebrates. Decapods possess complex neuronal structures such as hemiellipsoid bodies,
568 which are involved in higher sensory integration and are considered evolutionarily convergent
569 with insect mushroom bodies, themselves associated with learning and memory (Wolff et al.,
570 2017). They may also possess structures homologous to the insect central complex, a highly
571 conserved brain region involved in spatial navigation, sensorimotor integration, memory, and
572 notably nociceptive processing in insects (Pfeiffer and Homberg, 2014; Wolff et al., 2017; Chou
573 et al., 2021). The study of these regions in *Penaeids* is still few documented and the absence of
574 clearly identified neural pathways specifically transmitting nociceptive information to higher
575 brain centres remains a significant evidence gap (Birch et al., 2021).

576 A critical area of ambiguity lies in distinguishing between purely reflexive (nociception) and
577 consciously experienced (pain). Nociception refers to the detection and neural processing of
578 potentially harmful stimuli without necessarily involving a subjective experience (Raja et al.,
579 2020). Pain, however, requires consciousness (the capacity for subjective experience) as a
580 necessary condition for nociception to give rise to a morally relevant aversive state (Block,
581 1995; Raja et al., 2020; Browning and Birch, 2022). This distinction is highlighted by the
582 different behavioural outputs observed in shrimp. For instance, studies on the glass prawn
583 (*Palaemon elegans*) demonstrated that applying noxious chemicals to an antenna or eyestalk
584 elicited prolonged, specifically directed grooming and rubbing of the affected site (Barr et al.,
585 2008; Barr and Elwood, 2024). This complex localised behaviour indicates an awareness of the
586 injury's location and suggests central involvement, which is consistent with the experience of
587 pain (Barr et al., 2008; Elwood, 2012). Conversely, the tail flip escape response, common in *P.*
588 *vannamei*, involves giant interneurons and can be executed as a swift, non-sentient nociceptive
589 reflex (Barr et al., 2008); the significance of this reflex, and its proposed use as a behavioural
590 indicator of insensibility, is discussed in detail in Section 3.

591 Ultimately, the question of sentience in *P. vannamei* remains undecided, but this status
592 reflects a lack of evidence rather than evidence of a lack of sentience (Birch et al., 2021). Given
593 that sentience is a ‘private’ experience that cannot be directly observed, the application of the
594 precautionary principle is often advocated: in the presence of severe welfare risks and evidence

of non-reflexive responses to injury, it is reasonable to treat these animals as capable of experiencing pain and suffering (Birch et al., 2021 Crump et al., 2022). Further research into nociceptive integration and motivational trade-offs in *Penaeids* is required to fill these gaps and move beyond the current state of scientific uncertainty (Gibbs, 2026; Crump et al., 2022).

Given this uncertainty and the application of the precautionary principle, identifying reliable indicators of pain and stress becomes essential to translate this conceptual caution into practical welfare assessment. The following section reviews the behavioural and physiological indicators currently used to detect pain and stress in *P. vannamei*, drawing on data from other decapod crustaceans where species-specific evidence is lacking, to evaluate their respective strengths and limitations.

5. Behavioural and physiological indicators of pain and stress: an unresolved issue

A critical challenge in assessing the welfare of *P. vannamei* during stunning and slaughter is the technical and conceptual dissociation of consciously experienced pain from purely reflexive nociception, as demonstrating that a response is reflexive does not, in itself, rule out the coexistence of an affective component. Consequently, determining the internal state of *P. vannamei* requires a multidimensional approach that integrates electrophysiological data, behavioural studies, and physiological biomarkers (Birch et al., 2021).

5.1. Electrophysiological tools

Electrophysiological tools are considered the gold standard in vertebrate welfare for detecting the loss of consciousness, but their direct application to shrimp remains complex due to the segmental organisation of the crustacean central nervous system. A primary methodological challenge is therefore to identify species-specific signatures of brain activity that reliably distinguish conscious from unconscious states in *P. vannamei*, rather than simply transposing vertebrate-derived EEG criteria. One promising alternative involves Visual Evoked Responses (VERs), which assess the brain's ability to process sensory information as a neurological proxy for consciousness. The abolition of VERs is considered an objective indicator of sensibility loss across a range of fish species (e.g. Bowman et al., 2019; Bowman et al., 2020), an approach that Somerville et al. (2026) identify as a necessary complement to their own recordings.

A parallel and complementary challenge concerns the identification of the neural structures and pathways underlying pain processing in this species. Pain, being a conscious experience requiring central integration, the absence of a vertebrate neocortex does not exclude pain in shrimp, but it makes it necessary to identify which specific neural substrates in the decapod brain perform analogous integrative functions (Birch et al., 2021; Crump et al., 2022; Low et al., 2012). Electrophysiological recordings on in vitro or semi-intact brain and nerve cord preparations therefore offer the opportunity to map the neural pathways involved in nociceptive signal transmission. The supplementary use of biomolecular tools to detect markers of neural activation following nociceptive stimulation would also be beneficial in this context. Technical constraints, including the small physical size of *P. vannamei*, the presence of a rigid exoskeleton, the aquatic environment, and the typically invasive nature of electrode implantation, complicate the implementation of all such approaches.

5.2. Metabolic and physiological biomarkers

Metabolic and physiological biomarkers, specifically hemolymph L-lactate and glucose, are classic proxies for stress in decapods, yet they are fraught with confounding factors during stunning. Levels of these markers can rise independently of pain due to mechanical handling, anaerobic respiration during emersion, or the vigorous muscle contractions induced by electrical current or cold shock (Albalat et al., 2022; Conneely and Coates, 2023; Elwood, 2019; Kasiouras et al., 2026). Similarly, while cardiac activity is accessible via less invasive methods, it is highly variable and sensitive to numerous non-noxious stimuli, making it an unreliable indicator of a conscious experience (Adams et al., 2019; McGaw and Ebrahim, 2024; Neil et al., 2024; Weineck et al., 2018). Currently, there are very few species-specific data points for *P. vannamei* regarding these markers in a stunning and slaughter context.

5.3. Behavioural indicators

Behavioural indicators remain the only practically viable tools for assessing welfare in industrial field conditions, where rapid and non-invasive assessment of possible pain or distress is required. This use of behaviour is distinct from its application in experimental paradigms designed to infer sentience in decapods, such as aversive learning tests or modulation of injury responses by anaesthetics (Elwood and Appel, 2009; Barr et al., 2008; Crump et al., 2022). While such studies have been instrumental in advancing the debate on sentience, they are not directly transferable to operational slaughter contexts. In contrast, field applications require validated behavioural indicators that can reliably signal likely painful or non-painful states

during stunning or slaughter. However, such species-specific, operational indicators remain undeveloped for *P. vannamei*, and existing approaches often rely on broad and insufficiently validated distinctions in motor activity. As suggested by Somerville et al. (2026), electrical stunning may induce motor paralysis without necessarily indicating immediate loss of neurological function.

In conclusion, while progress has been made in identifying potential welfare markers, no single indicator is currently validated as a reliable and sufficient marker of insensibility in *P. vannamei*, highlighting the urgent need for cross-validated protocols that move beyond subjective visual observations to ensure humane slaughter practices.

6. Conclusion: welfare implications of current stunning and slaughter methods for *P. vannamei*

The studies examined in section 3 constitute, to date, the only directly available empirical basis for evaluating the effect of the stunning and slaughter methods currently used on *P. vannamei*. Sections 4 and 5, however, have highlighted several conceptual and methodological shortcomings that call for a reinterpretation of these results with increased caution.

6.1. Ice slurry bath

Ice slurry bath remains the most widely used commercial method, partly because of its operational simplicity. Studies discussed in this review reported that shrimp immobilised by chilling recovered activity and mobility once returned to warm water, and Somerville et al. (2026) confirmed that brain activity in animals placed directly in an ice slurry bath declines progressively over the course of immersion, with the rate of decline depending on bath temperature. This suggests that, unlike other stunning contexts discussed in Section 5.1, behavioural immobility during ice slurry immersion is at least broadly accompanied by a corresponding decline in neural activity, although whether this decline reflects a genuine loss of consciousness or of pain perception remains to be established.

This uncertainty is further reinforced by the reversibility of the process. None of the available studies demonstrates that chilling alone constitutes an effective killing method. The recovery of cardiac and neural activity following rewarming suggests that mortality in ice-maintained animals may instead result from secondary mechanisms, such as asphyxia, progressive compression linked to stocking density, or prolonged osmotic stress, rather than from cold

exposure itself. Although this hypothesis was raised in Section 3.3, it has not, to our knowledge, been directly investigated experimentally.

Finally, the potential suffering associated with thermal shock remains largely undocumented for *P. vannamei*. Although cooling is sometimes used experimentally as an anaesthetic approach in aquatic invertebrates, this does not necessarily imply that sudden immersion in ice slurry is devoid of aversive experience. Cold-sensitive neurons may generate nociceptive or stress-related responses during the transition itself, independently of any subsequent loss of consciousness. Consequently, the welfare impact may depend not only on the final temperature reached, but also on the rate of cooling and the abruptness of the thermal transition. Future studies should therefore investigate whether progressively reducing water temperature, rather than imposing an acute thermal shock, could mitigate potential distress while maintaining operational effectiveness. In addition, the risk of osmotic shock linked to uncontrolled salinity changes in melted ice is not discussed in any of the four primary studies, despite representing another potentially important source of pain and stress under commercial conditions (Conte et al., 2021; McKay et al., 2023).

6.2. Electrical stunning

Electrical stunning, presented as a promising alternative by retailers and manufacturers, has variable efficacy, which tempers this optimism. Somerville et al. (2026) documented a significant increase in brain activity over the first 20 seconds following the shock, suggesting an epileptiform-like response. In vertebrate species, such as fish, an epileptiform response, characterised by high-amplitude, high-frequency EEG activity followed by a period of marked electrical depression, is considered a neurological indicator incompatible with consciousness (Lambooij et al., 2010). However, the authors do not formally conclude that the high-amplitude, high-frequency activity recorded in shrimp following electrical stunning constitutes an epileptiform response comparable to that described in vertebrates. Moreover, the relationship between this kind of EEG activity and loss of consciousness is not even universally validated across all vertebrate groups (Small et al., 2023).

The interpretation of post-shock movements also remains contested. The Khan report (2025) interprets the absence of coordinated movements as a sign of loss of consciousness, but this inference is not supported by any independent validation. As highlighted in section 3.2 the tail twitch, in particular, illustrates this ambiguity: described as a probable electrical artefact by the

717 authors themselves, it is nevertheless used later in the same report as a possible indicator of
718 residual consciousness. This internal inconsistency serves as a reminder that the presence or
719 absence of movement can be interpreted in opposing ways depending on the theoretical
720 framework used, in the absence of a standard scientifically validated criterion.

721 The duration of the 'stun-to-kill' window adds a further complication. In other decapods,
722 this window has proven extremely sensitive to application parameters: in the American lobster,
723 a 10-second stimulation cycle resulted in a recovery time ten times longer than a 5-second cycle
724 (Lorenzo et al., 2025). No studies on *P. vannamei* have yet characterised this dose-response
725 relationship for commonly used parameters (aqueous or air environment, temperature, animal
726 size, power, duration), which prevents the definition of a reliable safety window before the
727 application of a second killing method. This issue of the 'stun-to-kill' window relates to a crucial
728 nuance often overlooked in the debate: electrical stunning is not a killing method, but a
729 reversible state that must be followed by an effective slaughter method rapidly. This
730 requirement, already highlighted for other decapods (Neil et al., 2024), now stated explicitly
731 for *P. vannamei* by Somerville et al. (2026), and reiterated as a precautionary recommendation
732 by Khan (2025), practically requires the rapid and reliable implementation of this second step,
733 a condition that remains far from trivial in a commercial context. Where experimental
734 conditions allow for precise control of the time between stunning and slaughter, industrial
735 production lines introduce a different source of variability: although stunned shrimp are
736 typically transferred together and immediately into the same ice slurry bath, the subsequent
737 time spent in that bath before being moved to bulk ice storage can vary considerably, as batches
738 accumulate before transfer. This practical difficulty is compounded by the scientific uncertainty
739 surrounding the very duration of this window. Without precise knowledge of the recovery time
740 according to the parameters used, it becomes impossible to guarantee, on an industrial scale,
741 that stunning actually fulfils its protective role rather than simply delaying the perception of
742 pain during the actual slaughter.

743 6.3. Variability in slaughter conditions and implications for welfare
744 assessment

745 Beyond the limitations inherent to each method, the variability of commercial conditions further
746 complicates the assessment of the animal's state of consciousness or unconsciousness during
747 stunning and slaughter. Biological factors (size, moulting stage, and the overall health status of
748 the individuals) potentially modify sensitivity to treatments, although none of the four primary

749 studies on *P. vannamei* discussed in this review isolated their specific effect. Environmental
750 factors, particularly salinity, water temperature, and animal density during handling, also vary
751 considerably between production sites and their effects are poorly documented in the available
752 studies. This lack of documentation has a direct impact on the reproducibility of the studies and
753 the validity of the indicators. A protocol validated under specific experimental conditions (small
754 sample sizes, isolated animals, fixed parameters) does not guarantee comparable effectiveness
755 under commercial conditions, which are far more heterogeneous.

756 All of these elements together form a chain of conditions that must be met before a stunning
757 or slaughter method can be considered the best to use (Figure 1). It is necessary to (1) establish
758 whether the species in question is capable of feeling pain, then (2) identify reliable markers of
759 pain, before (3) linking these markers to indicators measurable in the field, and (4) verify that
760 these field indicators remain valid and interpretable independently of the slaughter method
761 itself. Finally, it is essential to ensure that (5) these indicators are easily applicable and remain
762 functional on a large scale. Only after this process is it possible to (6) rigorously assess the
763 humaneness and feasibility of a given stunning or slaughter method.

764 This review highlights that several of these steps still largely require scientific validation for
765 *P. vannamei*. Sentience remains unresolved, with a level of confidence deemed insufficient. No
766 marker, whether electrophysiological, metabolic, or behavioural, has been independently
767 validated as a reliable signature of sensitivity loss in this species. The link between these
768 potential markers and indicators actually usable in commercial conditions also remains to be
769 established. In this context, the four studies discussed in this review, however informative, do
770 not provide sufficient evidence to determine whether thermal shock or electrical stunning can
771 genuinely be considered humane methods for *P. vannamei*. This uncertainty, far from justifying
772 inaction, should instead guide future research toward the development and validation of
773 indicators, essential conditions for industrial practices to be evaluated on a scientific basis.

774 From a regulatory standpoint, the lack of robust data specific to *P. vannamei* puts authorities
775 in a delicate position: the increasing recognition of decapod sentience in legislative frameworks
776 (e.g., United Kingdom) creates pressure for stricter culling standards, even though the scientific
777 data needed to define precise and validated thresholds are still lacking for this species. In this
778 context, the implementation of the precautionary principle may be influenced by
779 anthropomorphic interpretation of externally observable behaviours during slaughter,
780 potentially biasing welfare assessments in favour of methods that rapidly induce immobility,

such as electrical stunning. Addressing these uncertainties should now constitute a research priority, with regulatory authorities encouraged to support targeted investigations aimed at developing scientifically robust and operational welfare standards for the industry.

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Declaration of interests

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Figure 1

HOW TO SCIENTIFICALLY VALIDATE A HUMANE SLAUGHTERING?

WHAT DO WE KNOW ABOUT SHRIMP SLAUGHTER?

Has any physiological, neurological or behavioral indicator been identified?

IF YES

Several ongoing work on potential indicators: lactate[1], EEG[2], heartbeat[3,4], reactivity [5], coordinated movements [2,6,7], tail flip [2,4,7], reversibility[2], tail twitch (artefact) [7], righting reflex [2,7]

Does the indicator reflect the shrimp's pain?

IF YES

Insufficient data, electrophysiological tools are the gold standard but application remains complex. Lactate is a classic proxy for stress in decapod but is subjected to confounding factors during stunning. Heartbeat invalidated as a proxy for sensibility[3].

Is the indicator a practical, robust, and reproductible measure that can be applied across different slaughter methods?

IF YES

Insufficient data, in a study, EEG not analyzed in ice slurry between 0 and 2min (+/- ES)[2] because shrimp were moving too much. Tail flip hardly visible in ice slurry.

Does the indicator remain a valid measure of pain regardless of the slaughtering method used?

IF YES

Insufficient data, tail flip can be interpreted as an electrical artefact or as an indicator of residual consciousness[7].

Can the indicator be reliably measured in aquaculture farms (practical, observable, quick)?

IF YES

Insufficient data, EEG or lactate are not feasible in the field. Necessity to find behavioral indicators, like reactivity [5].

References (in lab or field)

1 Somerville et al, 2025 (TCS25)
2 Somerville et al, 2026
3 Neil et al, 2024
4 Weineck et al, 2018
5 Reverchon-Billot et al, 2025
6 Weis et al, 2020
7 Khan, 2025

Does the indicator actually work in practice?

IF YES

Insufficient data, necessity to find behavioral indicators, like reactivity [5].

SELECTION OF THE INDICATOR AND FIELD TESTS

Have the parameters that are likely to vary during slaughter under commercial conditions been identified and characterized?

Some parameters identified: biological factors (size, moulting stage, flow of animals) and environmental (salinity, temperature, animal density)
Several variations sources identified but not defined: voltage, intensity and duration for electrical stunning; temperature and duration for ice slurry bath.