Smart Agricultural Technology 9 (2024) 100549

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Predicting future adoption of early-stage innovations for smart farming: A case study investigating critical factors influencing use of smart feeder technology for potential delivery of methane inhibitors in pasture-grazed dairy systems

Benjamin Marmont [a,b], Callum Eastwood [a,*], Elena Minnee [a], Zack Dorner [c], Mark Neal [a], David Silva-Villacorta [a]

[a] DairyNZ, Private Bag 3221, Hamilton 3240, New Zealand
[b] The University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
[c] Lincoln University, Ellesmere Junction Road, Lincoln 7647, New Zealand

ARTICLE INFO

Keywords:
Smart-feeder
Innovation
Adoption modelling
Dairy farming
Uncertainty

ABSTRACT

Globally, livestock farmers are challenged with reducing greenhouse gas emissions to mitigate climate change. A potential option for pasture-based dairy farmers involves including methane-inhibiting compounds in the diet. A novel approach to deliver these compounds with the required frequency and precision is via smart-feeders, an existing smart farming technology used to feed supplements automatically to animals in-paddock. For this innovation to be successful, however, it must integrate with farm systems and provide farmers with a positive value proposition. The aim of this study was to examine the farm system and technology factors influencing potential uptake of in-paddock smart technologies for delivering methane inhibitors in pasture-grazed systems. We utilized an adoption prediction tool (ADOPT) to model the adoption outcomes of smart-feeders as methane inhibitor delivery mechanisms on dairy farms, with input from industry experts and farmers via focus groups. The results indicated low adoption of smart-feeders in a pasture-based system context. This was further explored with a sensitivity analysis of seven critical ADOPT factors which were identified as influential through the farmer focus groups. We modelled the impact of the seven critical ADOPT factors for two smart-feeder concepts to evaluate their relative adoption potential. The adoption modelling showed that while factors such as technology cost and function were important, adoption would also be highly influenced by future regulation settings, innovation uncertainty, and the alignment with farmer values and worldviews about their farm system. This research highlighted that in-paddock delivery technology, and processes for its use on-farm, represents an early-stage innovation and therefore is vital that farmers and other stakeholders are involved in further development to ensure adoption factors are addressed.

Introduction

Internationally, ruminant livestock production systems face challenges to reduce their environmental footprint, including methane emissions [1,2,3]. Research on ruminant methane reduction has focused on animal breeding [4], farm systems change [5,2], infrastructure and technology [6], and dietary strategies that reduce enteric methane production [7]. Ruminant methane inhibitors, such as *Asparagopsis taxiformis* (Asparagopsis) and *3-Nitrooxypropanol* (3-NOP), have shown significant potential for the reduction of enteric methane [7]. Integrating such inhibitors into farm systems is relatively easy when feed is delivered to animals such as in beef feedlots and housed Total Mixed Ration systems. However, in pasture-based livestock systems, extensive grazing practices and lower supplementary feed input reduces opportunities within the farm system to incorporate inhibitors into the feed source [8]. Successful dietary strategies that reduce enteric methane production will therefore require both technological and farm systems innovations that make economic sense at both the farm and policy or regulatory scale.

Use of rumen methane inhibitors in pasture-based systems requires

---

* Corresponding author.
E-mail address: callum.eastwood@dairynz.co.nz (C. Eastwood).

https://doi.org/10.1016/j.atech.2024.100549
Received 13 December 2023; Received in revised form 29 July 2024; Accepted 26 August 2024

an approach able to deliver small doses of the inhibitor throughout the day to individual animals [7]. The high frequency of small doses is required due to the short active period of the inhibitors [7]. A potential approach is the use of smart farming technology to deliver inhibitors to animals in the paddock. These in-paddock smart-feeders (IPSF), currently used by farmers and researchers to deliver concentrate supplement feeds (from here termed supplements), utilize Radio-Frequency Identification technology to identify individual animals and deliver pre-set amounts of feed [9]. Additionally, the machines can be moved between locations on the farm and are powered via solar panels, batteries and remote connection to the Internet via the cellular phone network. IPSF technology is not widely used on pasture-based farms and is not currently used commercially to deliver inhibitor products contained within supplement feeds. Although there are potential methane mitigation benefits from feeding inhibitors at an individual animal level in pasture-based livestock systems, there is limited information about the important on-farm adoption drivers of smart technology delivery systems.

Farmer adoption of smart farming technologies such as IPSF is influenced by a wide range of factors such as relative advantage, ease of learning, ease of use, integration with existing technologies, uncertainty over technology performance, and perceptions of consumers and society [10–12]. When considering the on-farm use of methane inhibitors, farmers will also need to consider potential impacts on animal productivity, the cost of mitigation, impact on food safety, and potential ability for value added branding related to low carbon emission status [8]. Added to this is a focus on low cost, minimizing capital expenses and labor, and systems that fit in pasture-based farm systems. Sector-wide adoption of IPSF as an inhibitor delivery method will need the right socio-economic conditions, innovation at the regulatory level to avoid delays in approvals, and potential incentives to accelerate adoption [8,13,14]. Achieving a systems-level understanding of the adoption factors from an end-user perspective is vital to ensure effective design of the IPSF technology, as well as institutional and policy requirements for the wider agricultural innovation system [15,16].

This study was conducted to understand the on-farm viability of IPSF, and to determine any technological and socio-economic improvements that would influence adoption outcomes of such smart farming technology. The aim of this study was to examine the farm system and technology factors influencing potential uptake of in-paddock smart technologies for delivering methane inhibitors in pasture-grazed systems. A mixed-method approach was used, using focus groups and modelling of predicted IPSF adoption for inhibitor delivery, based on a case study of pasture-based dairy farmers in New Zealand (NZ). In the following sections we provide background into the context of the case study, the farm systems environment within which smart technology development needs to fit, and then the methods used for the assessment of IPSF technology adoption factors.

Background to case study

The NZ dairy sector and methane mitigation

The NZ dairy sector was used as a case study in this paper to explore the potential adoption of IPSFs. Dairy farming is a significant export earner and employer in NZ, with the sector accounting for USD$16bn of the national economy and USD$31bn in exports in 2020 [17]. The total GDP of NZ in the same year was USD$211bn [18]. In addition, the sector employs approximately 27,500 people on farm and an additional 13,000 people in dairy processing [19], with dairy accounting for up to one third of all jobs in some regions. NZ dairy farm systems are primarily pasture-based with annual spring calving. In 2021, the average herd size was 444 animals and the national herd consisted of 4.9 million dairy cows [20]. Cows are usually milked twice a day, and the cows spend all year outside. The feed base of virtually all NZ dairy farms in grazed pasture and growing and utilizing pasture is a highly important feature of profitable dairy farm systems in NZ. DairyNZ uses a five-stage classification system to categorize farms based on the proportion of imported feed. In this classification, System 1 uses no imported feed, System 2 utilizes 4–14 % imported feed or winters non-lactating cows off-farm, System 3 utilizes 10–20 % imported feed or uses supplementary feeds to extend lactation, System 4 utilizes 20–30 % imported feed or uses supplementary feeds to extend the season, and System 5 utilizes 25–40 % imported feed or imported feed is used all year [21]. The proportions of the farm system types are: low input (System 1 and 2) 24 % of NZ dairy farms, medium input (System 3) 44 %, and high input (System 4 and 5) 32 % [22]. Dairy farmers in NZ generally have a focus on a low cost of production, demonstrated by the lowest total feed cost per kilogram of milksolids (fat + protein) and the second lowest labor cost per kilogram of milksolids relative to other major dairy producers such as Australia, United States, Argentina, Uruguay, South Africa, Ireland and the United Kingdom [23]. New Zealand dairy farmers are the most labor efficient, with the highest number of cows per FTE (Full Time Equivalent) relative to other major dairy producers [23]. Use of new technologies, such as IPSF's and inhibitor-supplement mixes, need to be considered with this efficiency and low cost of production in mind.

There is significant pressure on the dairy sector to reduce its environmental footprint [24]. In 2019, methane accounted for 42 % of NZ's total emissions; of these emissions, 80 % were from ruminants [25]. Under the Paris Agreement, the NZ Government committed to reducing national methane emissions to net zero by 2050. This resulted in the introduction of the Climate Change Response Act [26] which specified that amongst other emission reductions, biogenic methane must reduce by 10 % relative to 2017 emissions by 2030 and up to 48 % relative to 2017 emissions by 2050. In response to this policy, there is an increased focus on research to reduce methane emissions in ruminants, particularly in dairy cattle. This research primarily involves development of methane vaccines, farm system optimization, early-life rumen modification, and rumen methane inhibiting compounds (from here termed 'inhibitors') [27,28].

Methane inhibitors work by interrupting the final stage of methanogenesis - methane production in the rumen [27]. Two inhibitor compounds have been shown to mitigate methane while not altering the meat or milk production and quality of animals that consume them. Asparagopsis *(Asparagopsis Taxiformis)* is a naturally occurring Australasian red seaweed, and Bovaer *(3-Nitrooxypropanol,* i.e.*, 3-NOP)* is synthetic [7]. Research indicates that Asparagopsis can reduce enteric methane emissions by up to 80 % when fed in housed farm systems, and Bovaer has been shown to reduced enteric methane emissions by 20–40 % [27]. However, these inhibitors have short windows of effectiveness (e.g. a few hours), therefore need to be fed to cattle via a frequent and precise dosing to maximize methane mitigation. While this is achievable in Total Mixed Ration systems where intake is readily controlled [29,30], there are challenges for incorporating inhibitors into the diet of grazing cattle, such as in NZ dairy systems, and therefore a novel in-paddock delivery approach will be required. An option is feeding supplements via in-shed feeding systems, as recent data indicates that 52 % of NZ dairy farms have in-shed feeding capability [31]. However, in grazed dairy systems cows are typically milked twice per day, therefore they could only access in-parlor supplement/inhibitor feeding technology every 12 h, which would not lead to effective inhibitor function. A more frequent cadence is required (e.g. every 3–6 h), however the exact cadence depends on the type of inhibitor and farm systems factors [13]. The inhibitors currently in development (mentioned above) are not able to be delivered via reticulated stock water systems, spread on pasture, or incorporated into silage fed in the paddock. This means a novel delivery approach is required so animals can access supplement-inhibitor mixes regularly throughout the day while in the paddock.

One concept is to feed inhibitors in combination with a supplement feed mix, delivered to individual animals using in-paddock smart-feeders (IPSFs). While some IPSFs currently exist, they represent an emergent technology in this context. Little is known about how this technology will operate on commercial farms, for example how they fit within existing grazing systems, what the implications for farmer practice and costs are, and what the required specifications are of the technology itself. Research into the factors that may influence farmer adoption of IPSFs is required, to ensure effective and responsible technology development through co-design with farmers as end-users [32, 33].

Understanding potential adoption of in-paddock smart-feeders

Adoption of agricultural technologies has been widely studied, including early work on the diffusion of innovation [34], psychology-based research and technology assessment processes [35, 36], and integrated approaches examining internal and external influences on technology adoption [11,37,38]. One adoption assessment approach developed over the past decade, the Adoption and Diffusion Outcome Prediction Tool (ADOPT) has been used in contexts where technology adoption is relatively complex and influenced by not only technology performance characteristics but also factors such as relative advantage of the technology and learning of the relative advantage [11]. ADOPT is based on quantifying twenty-two variables spread across four quadrants that broadly relate to either characteristics of the target population or the technology/practice in question. The quadrants are; population-specific influences on the ability to learn about the practice, population relative advantage, learnability of the practice, and relative advantage of the practice. Relative advantage covers factors related to potential adopters (e.g. risk orientation, enterprise scale) and of the practice or technology itself (e.g. investment cost, reversibility, profit benefits). Learning of the relative advantage relates to adopter-specific influences (e.g. advisory support, relevant skills and knowledge) and learnability characteristics of the practice/technology (e.g. trialing ease, observability of practice). ADOPT estimates the rate of adoption (time to peak adoption) and peak level of adoption and illustrates key determinants of adoption by constructing a temporal adoption diffusion curve [11]. The time to peak adoption is mostly influenced by awareness of the technology (technology awareness and observability of the technology) among the target population and the learning of relative advantage of the technology (ability to easily trial the technology and its complexity to implement) [11]. In the next section, we outline the method to capture data on farmer preferences which was then used to model a range of scenarios in ADOPT.

Methods

A two-step approach was used in this study involving a) identification of key adoption factors through qualitative focus groups, and b) modelling of potential adoption outcomes using focus group insights. We first examined the potential adoption of IPSFs in the NZ dairy farming context by conducting a four focus groups with farmers and other non-farming experts in early 2022. In the second phase, we used the ADOPT model to understand the most important adoption drivers and subsequent implications for IPSF technology development and effective delivery of inhibitors.

Identification of key adoption factors - focus group methodology and participant recruitment

Table 1

Summary of focus group participants including background, farm system and farm size (where relevant). Low Input = System 1–3; High Input = System 4 and 5 (see explanation in the text).

Focus Group 1	Focus Group 2	Focus Group 3	Focus Group 4
Purpose: Explore IPSF adoption factors and test ADOPT methodology	Purpose: Explore IPSF adoption factors from the perspective of low-input farm systems (System 1–3)	Purpose: Explore IPSF adoption factors from the perspective of high-input farm systems (System 4–5)	Purpose: Discuss results from focus groups 2 and 3, and identify main themes that farmers identified
Participants: Social Scientist (innovation and technology) Scientist (feed base and methane) Farm Systems Specialist (economics and farm systems) Economist (agricultural economics) Scientist (farm systems and innovation) Scientist (feed base and methane) Herd Manager (farm management) Research Technician (farm research) Scientist (farm systems and technology)	Participants: Low Input Farmer (500 cows, Northland) Low Input Farmer (550 cows, Waikato) Low Input Farmer (450 cows, Waikato) Research Farm Manager (350 cows, Waikato)	Participants: High Input Farmer (300 cows, Waikato) High Input Farmer (650 cows, Canterbury) High Input Farm Manager (15,000+ cows over 10+ farms, South Island)	Participants: Social Scientist (innovation and technology) Scientist (feed base and methane) Scientist (farm systems and innovation) Scientist (farm systems and technology) Scientist (animal physiology and methane)

Four focus groups, each run over a two-hour period, were conducted to capture insights on the potential on-farm use of IPSFs, summarized in Table 1. Farmers from a range of farm systems were recruited for the research due to the impact that imported supplements associated with inhibitor delivery through IPSFs might have on their farm operation (i.e., the impact is expected to be greater for System 1–3 farms using no or little supplementary feeds, and less for System 4–5 farms where feeding infrastructure is already in place). Participants were recruited via professional networks and DairyNZ administered dairy-farmer Facebook™ groups. The lead researcher telephoned each potential participant to provide more information and invited interested farmers to attend the focus groups. In total, 19 participants provided insights from a range of perspectives. In other studies, using qualitative methods such as focus groups, the inclusion of 10–20 participants has been identified as sufficient to provide rich data and narratives [39,40]. The focus groups were designed to capture deep insights into the on-farm use of IPSF technology and were not intended to be representative of farmers across the NZ dairy sector. All focus groups were held on MS Teams™ to enable people from different regions to attend and to mitigate the risk associated with the Covid19 pandemic. Data captured during the focus groups included notes made by the researchers, audio recordings for later analysis, and quantitative responses to short surveys within the focus group sessions.

Focus group 1 (28 February 2022) consisted of non-farming experts including dairy industry researchers and professionals, outcomes from this group were used to test and refine methods for groups 2 and 3. Focus group 2 (8 March 2022) was held with farmers running low imported feed input systems (System 1–3 on the DairyNZ scale). Focus group 3 (10 March 2022) was held with farmers running high imported feed input systems (System 4–5 on the DairyNZ scale). In these groups, the project team provided a background into the issue of methane mitigation followed by a facilitated discussion to understand existing knowledge of participants on the topic. Participants were then provided with further information needed to assess the IPSF approach via an overview of methane mitigation techniques with specific mention of the methane inhibitors *Asparagopsis* and *3-NOP,* their requirements and mitigation potential.

The in-paddock feeding concept was explained to participants, including potential IPSF performance characteristics, and how the technology could be used to deliver supplement-inhibitors mixes in a pasture-based system. Participants were then asked to rank a range of pre-set IPSF characteristics that would be most important for its success for inhibitor compound delivery in NZ dairy farm systems (Fig. 1). The aim of this comparative process was to initiate feedback on important IPSF features. The list of characteristics was determined by the author team based on their existing experience with IPSFs. Survey Monkey™ was used for the ranking exercise, with participants provided the link via the MS Teams™ chat function during the focus group. Participants were given five minutes during the focus group to complete the ranking exercise individually. This individual ranking process was used to prevent groupthink - where the initial responses of a group participant influence the thoughts and responses of subsequent respondents [41]. During the ranking, participants could suggest additional characteristics not included in the pre-set list using a text box. After completing the ranking task, the results were discussed as a group with themes captured by the researchers. explored how different technology configurations might affect dairy farm businesses.

Finally, to examine the preferences of IPSF functionality, a comparative analysis process was used [42]. Descriptions of two hypothetical and purposefully divergent IPSFs were determined by a) identifying key characteristics for smart feeders in pasture based dairy systems, and b) outlining a range of parameters for each characteristic (Table 2). The two IPSFs generated were: IPSF 1, a small machine with lower cost and efficacy for inhibitor delivery, and IPSF 2, a larger machine with greater costs and efficacy. Participants were presented with IPSF 1 and 2 to differentiate how different characteristics would influence potential adoption outcomes.

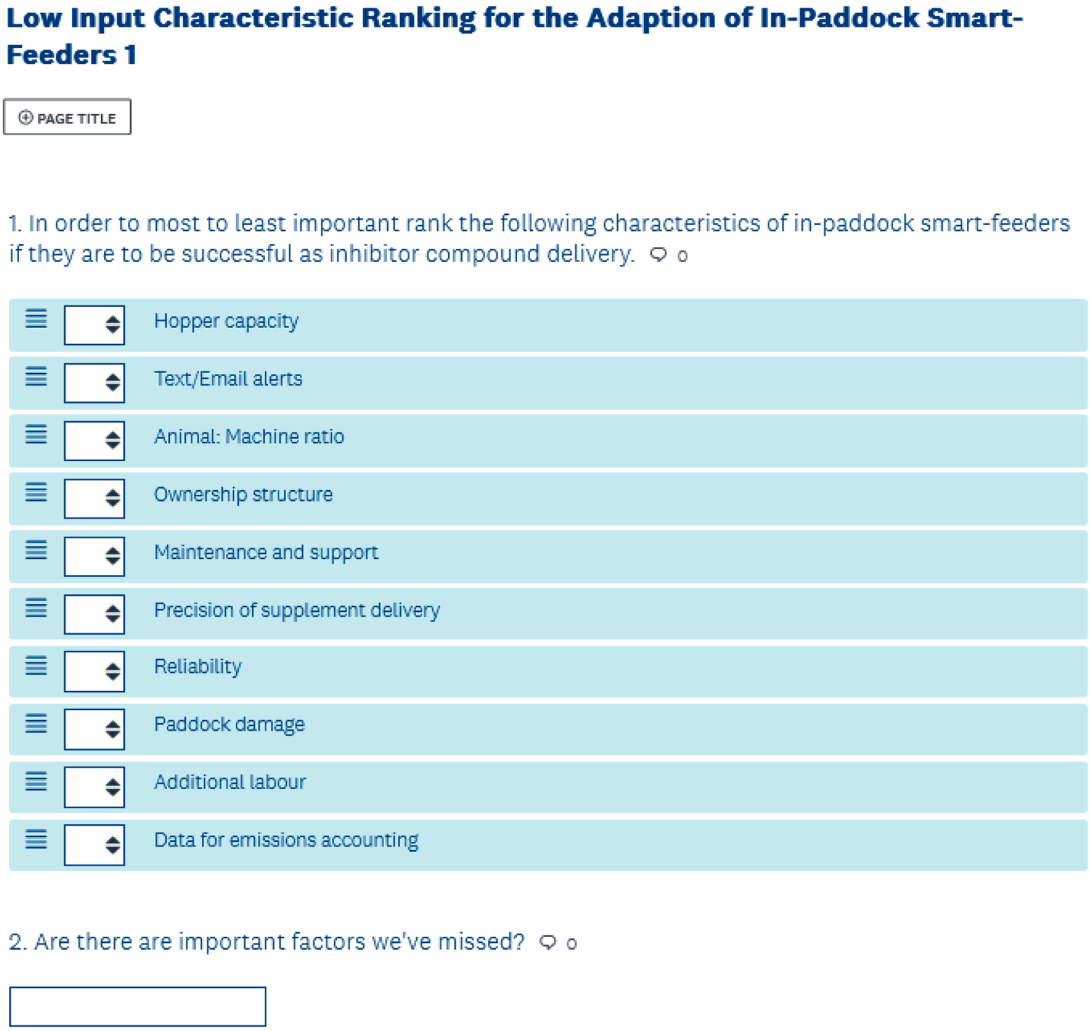
Focus group 4 (16 August 2022) was a reflexive session with farm systems experts to reassess themes from the farmer focus groups. This reflexive session involved reviewing the results of the farmer focus groups and grouping farmer insights into high level themes for use in the adoption modelling.

Modelling of potential adoption outcomes using the adopt model

The adoption modelling analysis was conducted using the ADOPT tool described earlier. The online, subscription-based, version of ADOPT (see: https://adopt.csiro.au) was used to model three scenarios representing potential adoption trajectories for IPSF in NZ dairy farm systems. The aim of this analysis was to determine the factors with the greatest influence on the adoption trajectories for two hypothetical designs – IPSF 1 and 2 (Table 2). The process used for the adoption modelling is outlined below.

Refine adopt factors for IPSF context

The original questions connected to each of the 22 factors were designed to be applicable to a range of uses [11]. For the purposes of this study, the lead researchers (authors 1 and 2) reviewed the questions and adapted those where the language needed to be more context specific, taking caution not to change the overall meaning of each question. For



Low Input Characteristic Ranking for the Adaption of In-Paddock Smart-Feeders 1

1. In order to most to least important rank the following characteristics of in-paddock smart-feeders if they are to be successful as inhibitor compound delivery. 0

- Hopper capacity
- Text/Email alerts
- Animal: Machine ratio
- Ownership structure
- Maintenance and support
- Precision of supplement delivery
- Reliability
- Paddock damage
- Additional labour
- Data for emissions accounting

2. Are there are important factors we've missed? 0

Fig. 1. Ranking exercise used in focus groups 2 and 3 where participants were each provided a weblink to re-rank the features from most to least important.

Table 2
Two In-Paddock Smart-Feeder (IPSF) scenarios presented to focus group participants for feedback.

Characteristic	Definition	IPSF 1	IPSF 2
Hopper capacity	The approximate refill frequency for supplement feed supply based on a smaller or larger hopper size	Five days between refills	Ten days between refills
Alerts via SMS or email	The type of information provided remotely to farmer regarding the machine status and performance, e.g. when the machine is empty or malfunctioning	When empty and malfunctioning	Text when mal-functioning only
Animal: Machine ratio	The number of animals an individual machine can optimally feed, linked to hopper capacity and feed delivery mechanism	75 cows per machine	125 cows per machine
Ownership structure	The business model for machine use, e.g. short-term lease/ subscription or outright purchase	Yearly rental contracts (~NZD $1500/ month)	Purchase for ~NZD$50,000
Maintenance and support	The business model for maintenance and support of the IPSF machine	Local technician for support and readily available parts	Remote support, potential lag time for parts
Precision of supplement delivery (feed + inhibitor)	How accurate the machine delivers pre-set allocation at an individual cow level	Most cows get allocation (some poaching)	All cows get allocation (no poaching)
Impacts on pasture/crop cover	The amount of damage animals may cause to forage plants around the area where the machine is temporarily positioned. This will relate to aspects such as the time the machine is left in one position, the number of cows and visitation rates, the soil type and weather.	Smaller machine with minimal pasture damage as machine moved more often	Bigger machine with moderate pasture damage
Additional labor	The time required to maintain, refill, and move the machines per farm	Twelve hours per week, per machine	Five hours per week, per machine

example, for factor 11 (Table 3) the original question 'What proportion of the target population participates in farmer-based groups that discuss farming?' was adapted to 'What proportion of New Zealand dairy farmers participate in farmer-based groups that discuss farming?' The revised questions were tested with participants in focus group 1. A full list of original and revised questions is provided in Table S1 in the Supplementary Material.

Determine adopt factors that have the most associated uncertainty under different IPSF contexts

Many of the factors relate to the target population for the innovation, rather than specifics around the innovation itself, and therefore a generic answer could be applied for the assessment of IPSF 1 and 2. Using feedback from participants in focus group 1, out of the 22 ADOPT factors we identified 15 low uncertainty factors and 7 factors with high uncertainty in respect to the potential features of IPSF technology (Table 3). High or Low uncertainty was determined by the ability of focus group 1 participants to reach a consensus on answers for each factor in relation to potential adoption of IPSF technology.

Table 3
The four quadrants of the ADOPT model, and relevant factors for each quadrant [11] (underlined text denotes factors with high uncertainty that were used in the sensitivity analysis).

Relative advantage for the population	Learnability characteristics of the practice	Learnability of the population	Relative advantage of the innovation
1 Profit orientation 2 Environmental orientation 3 Risk orientation 4 Enterprise scale 5 Management horizon 6 Short-term constraints	7 Trialable 8 Innovation complexity 9 Observability	10 Advisory support 11 Group involvement 12 Relevant existing skills and knowledge 13 Innovation awareness	14 Upfront cost of the innovation 15 Reversibility of the innovation 16 Profit benefit in years that it is used 17 Future profit benefit 18 Time until future profit benefits are likely to be realized 19 Environmental costs and benefits 20 Time to environmental benefit 21 Risk exposure 22 Ease and convenience

Create rubric to guide selection of adopt factor weightings for low, medium, high scenarios

While keeping the answers to the 15 low uncertainty factors constant across the scenarios, the project team developed a range of answers for the 7 high uncertainty factors to represent low, medium, and high performing IPSF technology (Table 4). These answers were based on feedback from participants in focus groups 1–3 on the two IPSF scenarios (Table 2). For the factor *Trialing ease*, IPSF 1 was considered easier for farmers to trial as it could be leased on a short-term basis, while IPSF 2 required outright purchase up front. These differences also led to IPSF 2 being rated as very large or large in terms of *Upfront costs of the innovation*, compared to IPSF 1 being rated as Moderate, Minor or None depending on the technology performance scenario.

The *Practice complexity* factor relates to how easily the impacts of using the technology can be evaluated. The same settings were used for both IPSF technologies as the direct impact on methane reduction could not easily be observed by farmers, but both technology scenarios would enable performance evaluation through automatically collected data. For example, data collected via electronic identification and on-machine sensors can be uploaded to cloud-based systems for farmers to assess cow intake, visitations and therefore predicted methane mitigation.

In terms of *Profit benefit in years used* and *Profit benefit in future*, investment costs and lifetime of the technology associated with each IPSF will have a major impact on profit, as will the cost of inhibitors and need for additional costly supplement to help deliver the inhibitor to animals. Both machines were assumed to have the same profit impact in the Low and Medium scenarios, with IPSF 1 having a larger profit advantage in the High-performance scenario primarily due to lower initial investment and depreciation costs.

The *Risk exposure* ADOPT factor relates to how the technology would affect net exposure to risk for the farm business. A slightly greater reduction in risk was attributed to use of the IPSF 1 compared to IPSF 2, due to IPSF 1 being manufactured locally in NZ and therefore locally maintained which may be beneficial in the event of breakdown. Also adding to the risk associated with both technologies is the future supply

Table 4

Rubric to guide answers in the ADOPT model to seven ‘high uncertainty’ factors for low, medium, and high IPSF technology performance for two IPSF scenarios.

	ADOPT Factor	Technology Performance		
		Low	Medium	High
IPSF 1	7. Trialing Ease	Moderate	Easy	Very easy
	8. Practice Complexity	Difficult to evaluate	Moderately difficult to evaluate	Slightly difficult to evaluate
	14. Upfront Costs	Moderate	Minor	None
	16. Profit benefit in years used	Moderate disadvantage	Small disadvantage	Moderate advantage
	17. Profit benefit in future	Moderate disadvantage	No advantage or disadvantage	Moderate advantage
	21. Risk exposure	Small increase	No increase	Moderate reduction
	22. Ease and Convenience	Moderate decrease	Small decrease	No change
IPSF 2	7 Trialing Ease	Cannot trial	Difficult	Moderately difficult
	8 Practice Complexity	Difficult to evaluate	Moderately difficult to evaluate	Slightly difficult to evaluate
	14 Upfront Costs	Very large	Large	Large
	16 Profit benefit in years used	Moderate disadvantage	Small disadvantage	Small advantage
	17 Profit benefit in future	Moderate disadvantage	No advantage or disadvantage	Small advantage
	21 Risk exposure	Moderate increase	Small increase	No increase
	22 Ease and Convenience	Large decrease	Moderate decrease	Small decrease

of inhibitor and supplement, which could add overall risk to the farm business.

Ease and Convenience would be influenced by aspects such as size of machine, for example IPSF 1 would be smaller therefore easier to move around the farm. Size of the hopper would impact the interval between refilling of supplement, and IPSF 2′s bigger hopper would be more convenient. Overall, IPSF 2 was rated as slightly less convenient to operate on-farm than IPSF 1.

Conduct sensitivity analysis of potential adoption trajectories for two IPSF for low, medium, high scenarios

Using the rubric in Table 4 and the online version of ADOPT, we ran six scenarios (IPSF 1 – low, medium, high; IPSF 2 – low, medium, high). For each scenario, results related to the *Predicted Adoption Rate as percentage of the population* and *Years to peak adoption* were captured (Figs. 2 and 3).

Identify major leverage factors for design and adoption of IPSFs

The ADOPT tool was used to explore the individual impact of adoption factors on the adoption rate and peak adoption level. We used the results from the medium performance scenario for IPSF 1 and 2 as a base case (from 3.2.4), then tested the impact of improved outcomes in the 7 high uncertainty adoption factors from Table 3.

Assess potential adoption of different IPSF technology designs

To provide insights on the key design features for IPSF technology, three improved designs were proposed, and then the potential adoption outcomes modelled using ADOPT. The project team used the most important leverage factors to create the three IPSF designs. For each design, seven factors were improved by one step (e.g. step up from ‘Small disadvantage’ to ‘No profit advantage or disadvantage’ for Profit benefit in years used (q16)) (see Table S2 and S3 in the supplementary material). The three improved designs were (Table 6): Future product 1 – Better profit advantage (q16), lowered business risk (q21), improved

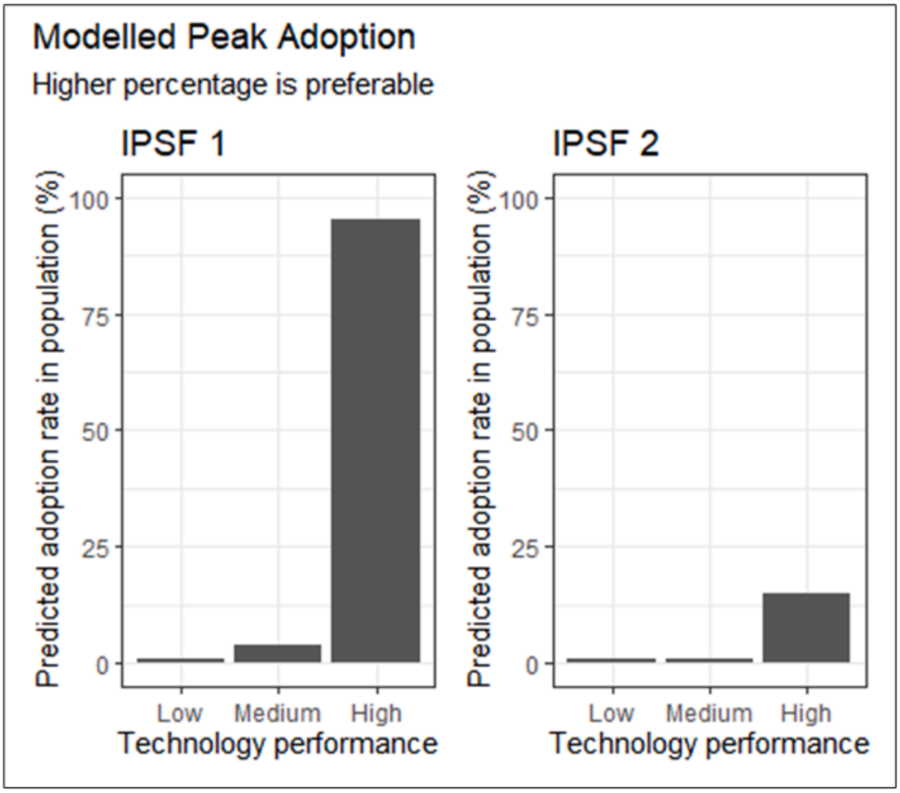


Fig. 2. Predicted adoption rate of two in-paddock smart-feeder technologies based on a ‘low’, ‘medium’, or ‘high’ performance scenario.

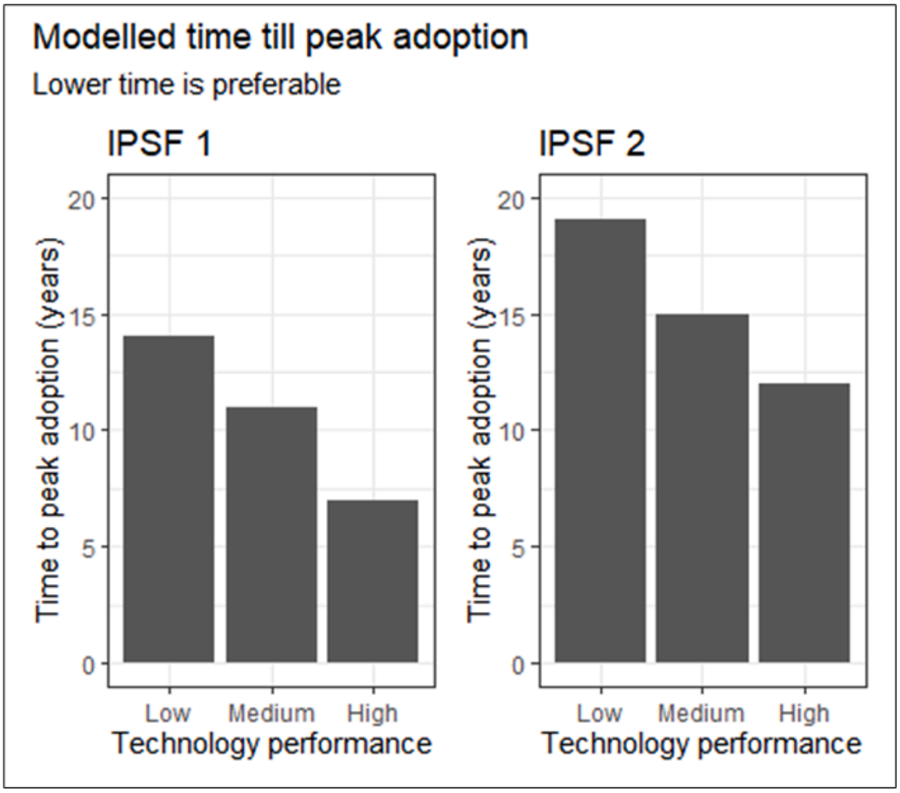


Fig. 3. Predicted time to peak adoption of two in-paddock smart-feeder technologies based on a ‘low’, ‘medium’, or ‘high’ performance scenario.

ease (q22); Future product 2 – Easier to evaluate impact (q8), lowered upfront cost (q14), better profit advantage (q16); Future product 3 – lowered upfront cost (q14), better profit advantage (q16), improved ease (q22).

Results

Key characteristics of in-paddock smart-feeders in pasture-based dairy systems

Participants in Focus Groups 1–3 were asked to rank a range of pre-set IPSF characteristics that would be most important for its success for inhibitor compound delivery in NZ dairy farm systems; results are presented in Table 5. The most highly rated characteristics for successful adoption of IPSF for inhibitor compound delivery were minimal additional labor, hopper capacity, and data collection for emissions accounting. Of medium importance were characteristics such as reliability, precision of supplement delivery, text or email alerts, animal-to-machine ratio, and minimal paddock damage. The least important characteristics were ownership structure or maintenance and support systems.

Main themes from discussion on smart-feeder features

When presented with the two IPSF scenarios, participants in focus groups 1–3 provided insights into major potential implications of using IPSFs in pasture-based dairy systems. The project team (authors 1, 2, and 3 of the current paper) grouped these implications into themes through the reflexive analysis session in focus group 4. The themes were: impacts on existing farm systems and practices, impact on farm economics, adaptation of the delivery approach and the need to utilize existing infrastructure. These themes are further described below.

Table 5
Average rankings of focus group participant for a range of pre-set IPSF characteristics where ‘1′ is most important, and ‘10′ is least important, for IPSF success for inhibitor compound delivery in NZ dairy farm systems (note: two features were adapted after feedback from focus group 1: using ‘Hopper capacity’ instead of ‘Refill frequency’ and ‘Text/email alerts’ instead of ‘Ability to check machine performance via phone’. Four features were also added at this stage: ‘Reliability’, ‘Precision of supplement delivery’, ‘Data for emissions accounting’ and ‘Additional labor’.).

Rank	Focus Group 1 (non-farming experts)	Focus Group 2 (farmers in low input farm systems)	Focus Group 3 (farmers in high input farm systems)
1	Animal to machine ratio	Additional labor	Data for emissions accounting
2	Refill frequency	Animal to machine ratio	Hopper capacity
3	Ability to check machine performance via phone	Hopper capacity	Text/email alerts
4	Paddock damage	Data for emissions accounting	Additional labor
5	Maintenance and support	Precision of supplement delivery	Maintenance and support
6	Ownership structure	Paddock damage	Reliability
7	Country of machine manufacture	Reliability	Precision of supplement delivery
8		Ownership structure	Ownership structure
9		Text/email alerts	Paddock damage
10		Maintenance and support	Animal to machine ratio

Farm system impacts

An implication identified by participants was the potential transition away from NZ’s pasture-based dairy system. New Zealand is among a few pasture-based dairy-producing countries [43]. Widespread use of IPSF technology to deliver methane inhibitors would increase average supplement feed use on NZ dairy farms and therefore higher

Table 6
Potential adoption rate and time to peak adoption for three improved designs of IPSF 1 and IPSF 2 (Numbers in brackets refer to results where 2 step ups were applied, however, * denotes no second step up was possible in the ADOPT tool).

ADOPT settings changed in three alterative designs.	Peak adoption level in population (%)		Time to peak adoption (years)	
	IPSF 1	IPSF 2	IPSF 1	IPSF 2
Future design 1: Better profit advantage (q16), lowered business risk (q21), improved ease (q22)	26 (79)	4 (30)	11 (10)	15 (14)
Future design 2: Easier to evaluate impact (q8), lowered upfront cost (q14), better profit advantage (q16)	9 (19*)	2 (4)	10 (8*)	13 (11)
Future design 3: lowered upfront cost (q14), better profit advantage (q16), improved ease (q22)	18 (51*)	3 (14)	11 (11*)	14 (13)

supplementary input farm systems and potential reduced ability for NZ dairy producers to market their product as predominantly pasture based.

A cause of concern to farmers was paddock damage stemming from high traffic in the area around the smart-feeder [44]. Concerns related to paddock damage may relate to soil type and the subsequent ability of pasture to recover after damage. Participants suggested that methods to ensure the IPSF could be moved regularly, without additional labor, such as making the IPSF self-propelled or pulled via a winch system, may lessen the impact on pastures. Participants ranged in their concern around the potential for pasture damage, and it may be a topic where more research or information is required for farmers to enable better risk assessment. Pitman [45] found that farmers tend to overestimate the costs of paddock damage due to the damaged areas being readily observable and front-of-mind.

Impact on farm economics

Participants were concerned with the costs of adopting the IPSF technology. Economic viability is essential for farms, as with any business, and participants were clear that cost neutrality of any methane mitigation approach was a requirement of adoption. Due to the novelty of using IPSF for methane inhibitor delivery and uncertainty of future carbon cost policies, it was difficult to provide information on financial costs and benefits of the innovation. However, it was discussed how adopting IPSF might affect working expenses due to introducing new costs in terms of smart-feeder ownership/rental, inhibitors, additional labor, and additional supplement costs. However, participants of focus group 3 (high input farmers) indicated that they were less worried about the cost of supplement as it was already a sunk cost in their farm system. These farmers could use the IPSFs to deliver supplements rather than their existing delivery method. Therefore, we expect IPSFs to be more economical in higher input systems. An additional cost factor is the animal:machine ratio and therefore the number of IPSFs that larger farms would require, and have to regularly shift between paddocks, this aspect was noted as an important factor by those in the focus groups running larger dairy farms.

Major barriers to IPSF adoption identified through the focus groups were financial and time-related costs to the farm system. Uncertainty surrounding the financial benefits of the approach were also highlighted. As inhibitor technology develops, the financial costs and benefits will become clearer and participants were clear that the approach's profitability was most important if it is to become widespread, regardless of its environmental benefit. Focus group participants estimated that it would take six hours a week per machine to refill the hopper and move the IPSF with the cows to new paddocks, which would be difficult for them and their teams to fit into an already busy workday. It was difficult to provide participants with accurate costs and benefits given the early stage of technological development. As inhibitor and IPSF technology and future pricing of greenhouse gas emissions are better understood the financial performance will become clearer. Subsequent research provided more clarity around potential profitability, in terms of breakeven methane price, and found a wide range of potential financial outcomes for farmers depending on factors such as supplement cost and inhibitor efficacy [13].

Adaptation of the delivery approach and utilization of existing infrastructure

Participants explained that choosing how they would deploy the smart-feeders and having the flexibility to adapt to their different farm environments was vital. This flexibility was further explored to include different parts of the year, such as winter grazing. The ability to efficiently deliver other supplements/minerals as needed was identified as a potential benefit. In addition, participants, particularly those in the high-input group (Focus group 3), expressed a desire to utilize existing infrastructure already on their farms to deliver methane inhibitors, such as in-shed feeding, trailer-based feed troughs or stock water reticulation systems. However, experts highlighted that current inhibitors were not able to be effectively delivered through the water supply, and feed troughs may not provide the precise individual dosing required. Also, because in-shed feeding is limited to when cows are milked, this would mean only two opportunities to feed an inhibitor mix per day, possibly less depending on a farm's milking interval [46]. For one type of inhibitor, it has been shown that this frequency in a pasture-based system has negligible mitigation potential [47]. Additionally, with the seasonal profile of NZ dairy farming, there would be no opportunity to deliver the inhibitor through an in-shed system outside of the 250- to 300-day milking season.

Potential adoption rates for a range of adopt scenarios for in-paddock smart-feeders

The adoption modelling indicated that under the low and medium performance scenarios, neither IPSF technology would be widely adopted, and that adoption would be slow. Under the 'medium' performance scenario, the ADOPT model indicated a low adoption rate for both technologies (Fig. 2), with slightly higher potential adoption for IPSF1. In terms of time to peak adoption (Fig. 3) in the medium scenario, the ADOPT model predicted 11 and 15 years for IPSF1 and IPSF2, respectively. Under the high-performance scenario, which represented a highly optimistic outlook, the IPSF 1 technology design might be widely adopted (91 % of the population), whereas IPSF 2 might only be adopted by 15 % of farmers. However, this is a highly optimistic scenario due to the assumptions of no upfront costs and no impact on the ease and convenience of farming.

To assess the impact of different IPSF technology features on potential future adoption, a sensitivity analysis was conducted using the ADOPT factors previously identified as being most uncertain in this technology context. Settings in ADOPT were increased one and two 'step ups' for each individual factor, therefore increasing the positivity of adoption. The low potential peak

IPSF adoption in the sensitivity analysis (Table S3 in supplementary material) may reflect the interaction between technological characteristics and with population characteristics, and which factors were identified in the ADOPT sensitivity analysis as having the biggest influence on changes in peak adoption and time to peak. Technology adoption can be driven by these technology and population characteristics but can also be influenced by activities and settings in the wider innovation system, such as regulation and corporate policies [10,12]. IPSF 1 showed a small increase in potential adoption rate compared to the base case of 4 % adoption, for example, there was an increase of 10 %-points adoption (to 14 % of the population) with two step-ups in factors of increased profit benefit or lowered business risk. In comparison, there was little change in the predicted adoption rate for IPSF 2, even under the two step up scenarios. For both IPSF technologies, there was little change in time to peak adoption under the one or two step up settings.

The three 'improved design' scenarios highlighted that with some better outcomes across several adoption factors, there was a greater likelihood for farmer adoption. Future design 1 showed the most potential for improved adoption, with 26 % and 79 % adoption for IPSF 1 with one or two step ups, respectively, in the three factors. IPSF 2 still showed limited adoption potential, with 30 % adoption across the dairy farmer population for Future design 1 with two step ups.

Discussion

This study highlights the opportunities and challenges associated with on-farm adoption of a smart farming in-paddock feeding approach for delivery of rumen methane inhibitors in pasture-based dairy systems. We used a mixed method approach of capturing farmer-centered feedback and applying the insights to guide modelling of adoption trajectories. This enabled identification of the potential sector-wide adoption of IPSF technology and design improvements to enhance adoption rate (% of population) and time to peak adoption for this smart farming approach.

Worldwide, ruminant livestock farming sectors are exploring ways to reduce methane emissions [2]. An underlying aim is to achieve reductions without creating unprofitable systems, or creating overly complex systems that require unachievable farm systems change. Participants in our study identified the potential impacts on pasture-based dairy systems from an IPSF-based approach. These included a concern about a systemic shift in the balance between grazed pasture and imported supplementary feeds. Such a shift could have impact for the profitability of pasture-grazed dairy systems [48], and have implications for the infrastructure and skills required to run such farms successfully [49]. Any required change in feed inputs could also conflict with the worldview and values of individual farmers, as highlighted by study participants running 'low input' farm systems. Our study highlighted the importance of these factors in potential adoption of smart farming technologies.

Other adoption factors identified by participants were the direct monetary costs of investment in the IPSF technology, along with ongoing costs associated with the inhibitors, supplementary feeds, labor and management time. Dairy farmers in pasture-based systems (like many farmers) are time-poor [50,51], therefore any change that requires significant additional labor needs to provide clear benefits to be adoptable. Our research highlighted that a successful IPSF design requires limited refilling, limited time to move with the herd (which is often every 12 h in NZ dairy systems), and farm system fit achieving the most methane reduction gains for the least cost in terms of technology hire, labor, and feed/inhibitor input. One approach would be to leverage existing in-shed feeding technology present in many pasture-based dairy farms [52] by developing inhibitor technology that only needed to be administered at milking (i.e. two times per day). An alternative option may be to reduce labor needs by development of autonomous smart-feeders that are able to follow the herd around the farm, however this may present additional barriers for example cost, safety regulations and design specifications, as seen in recent studies [53,54].

The characteristics selected for the two IPSF scenarios (IPSF 1 and 2) were purposely divergent. This enabled participants to highlight key technology features that would impact adoption factors such as profit benefit, trialability, ease of use, and business risk [11,55]. Trialability and limited sunk costs by leasing rather than outright purchase were key factors. As IPSF technology for inhibitor delivery represents an early-stage innovation it was difficult to provide participants with precise information on costs and benefits as methane inhibitors are yet to be available in NZ, in part due to regulatory approvals being required. This uncertainty impacted on the participants' ability to confidently ascribe costs and benefits to the approach. Reducing the uncertainty associated with new methane mitigation technologies and upcoming regulation will be vital for their adoption on-farm. The impact of uncertainty with smart farming technologies has been highlighted in several studies [10,56] and can be a rational decision for farmers to wait until greenhouse gas regulation is in place and technologies are proven in practice [57,58]. Farmer beliefs, values and the perspectives of their influential networks will also be instrumental to adoption of mitigation approaches. Previous studies of farmer environmental change using institutional logics theory highlights the role of building networks, knowledge development, supportive regulations, peer-to-peer support, and evolving farming cultures [59,60]. Given the international urgency for reductions in emissions across all industries, innovation uncertainty could be addressed through actions such as highly visible demonstration farms, lower entry costs for early adopters, flexible lease arrangements, and support or enforcement through government policy or agri-environmental schemes [61].

The adoption barriers identified by participants in our study, and the data from the modelled adoption trajectories, highlight the need for further design improvements for inhibitor delivery technology. As technology and system complexity increases there is greater need for farmers to be involved in the innovation process [62]. To ensure usability and usefulness of inhibitor delivery solutions in a pasture-based farming context a farmer-centered design approach is recommended [63]. In addition, making the innovation easy to observe in practice is important [11], and this can be achieved by use of on-farm research and demonstration [64]. In this study, we focused on the smart technology for in-paddock delivery of inhibitors, but in practice farmers will be asked to adopt a technology package that includes both IPSF and novel inhibitor compounds. This will increase the adoption uncertainty and the need to work with farmers and rural professionals to ensure adoption factors such as practice complexity, business risk, knowledge and awareness, and advisory support are effectively addressed [11,55].

The eventual use of IPSF technology in grazed livestock systems will by highly influenced by forms of inhibitors available, their ideal delivery method, and associated regulations and policy regarding their use. Participants in our study were conscious of these potential factors, for example they highlighted the need for easy or automated recording of feeding data for proof of practice for any emissions accounting regulations. With farmers facing a growing compliance burden [16,65], simple or 'hands-free' recording and reporting will be important [66]. Farmers in our study placed a priority on utilizing existing infrastructure such as in-parlor feeding to deliver inhibitors before investing in IPSF. Therefore, a wider system approach may be needed to ensure successful use of inhibitors, and this calls for proactive policy to address potential market failure in the adoption process [67]. The use of policy packages has long been recognized as an important approach to address complex adoption challenges [67]. Examples of policy packages for smart farming technology adoption include acting to address rural connectivity (enabling real time IPSF data upload), R&D funding for co-design activities, building linkages with agri-environmental schemes and regulations, and fostering skill and knowledge development in advisory networks [68,69].

Limitations and future research

Focus groups of 8–10 participants would be ideal for this kind of study, and 10 farmers had indicated they planned to attend each group and received text message reminders the day before the meeting. Despite the smaller number of farmers and stakeholders in the focus groups, important insights were gained that were sufficient to inform the adoption analysis using the ADOPT model. The focus group methodology is not intended to produce representative insights from the target population (i.e. NZ dairy farmers), rather this method is designed to provide a range of deep insights into an issue, therefore the lower participant numbers were still sufficient to guide the subsequent analysis. Focus group participants also identified additional context-specific adoption considerations not covered by the modelling process, highlighting the benefit of using a farmer-centered qualitative approach. The study highlights the need for more research into effectiveness of potential delivery technologies for rumen inhibitors in pasture-based contexts. Our findings can help guide IPSF design, however further research is required to co-design technology that works within the farm system and therefore will be adopted by farmers. Use of co-design practices that are farmer centered would ensure practical technology development [32] and help technology companies develop suitable business models for future technology and robotics in this area [70]. Farmers also noted the uncertainty surrounding on-farm use of the technology and potential return on investment. Research should focus on these two areas, such as formal trials of the technology to determine integration within the farm system (e.g. cows/machine, labor requirement, impact on animals and pastures), and economic modelling to determine the financial viability and potential IPSF pricing structures required. Price and efficacy of inhibitor-based supplements, and other factors like presence of subsidies and IPSF costs, will impact the predicted adoption rate and time to peak adoption for IPSF technology. At the time of this study, there was limited information available on these aspects for pasture grazed systems therefore further adoption modelling is needed when more clarity exists.

Conclusions

Timely adoption of on-farm innovation for methane mitigation will be critical to the future of grazed livestock systems. However, there are a wide range of factors that can impact the eventual adoption of smart technology to administer inhibitors via feed supplement mixes. We highlight how smart technology adoption is influenced by a range of factors such as uncertainty, regulation, return on investment, impact on farm systems and the on-farm adaptation required. Adopting a co-design innovation process where farmers and other stakeholders are included in research and development will ensure that any solutions or smart technologies are rapidly adoptable. The inclusion of farmers and other experts in our study highlighted major features required from smart-feeder technology, including: 1) ease of use in grazing systems is a priority, 2) design needs to be conscious of extra hours required to fill and move the device, 3) upfront cost needs to be minimized and trialability maximized through leasing and cost needs to offset emissions pricing, 4) automated data capture and proof of practice is important given the regulatory context of methane emissions reduction. Adoption outcome modelling confirmed the importance of these features, illustrating that profit benefit, reduction of business risk, and ease and convenience were important levers for successful adoption and therefore should be a focus for both smart-feeder and inhibitor development.

CRediT authorship contribution statement

Benjamin Marmont: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Callum Eastwood:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Elena Minnee:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Zack Dorner:** Writing – review & editing, Supervision. **Mark Neal:** Writing – review & editing, Supervision, Conceptualization. **David Silva-Villacorta:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements and funding sources

The authors would like to sincerely thank the farmers and industry stakeholders who participated in the two focus groups. This study was funded by the New Zealand Agricultural Greenhouse Gas Research Centre Innovation Fund and New Zealand dairy farmers through DairyNZ Inc. We would also like to thank the two anonymous reviewers who invested their time and expertise in improving this paper.

Ethics statement

All procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the University of Waikato Management School Ethics Committee (application 21/238.). Informed consent was obtained for experimentation with human subjects and the privacy rights of human subjects were observed.

Supplementary materials

Supplementary Material for Marmont et al - Predicting future adoption of early-stage innovations for smart farming: a case study investigating critical factors influencing use of smart feeder technology for potential delivery of methane inhibitors in pasture-grazed dairy systems. Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2024.100549.

References

[1] M. Herrero, B. Henderson, P. Havlík, P.K. Thornton, R.T. Conant, P. Smith, S. Wirsenius, A.N. Hristov, P. Gerber, M. Gill, K. Butterbach-bahl, H. Valin, T. Garnett, E. Stehfest, Greenhouse gas mitigation potentials in the livestock sector, Nat. Clim. Chang. 6 (5) (2016) 452–461, https://doi.org/10.1038/nclimate2925.

[2] D. Mayberry, H. Bartlett, J. Moss, T. Davison, M. Herrero, Pathways to carbon-neutrality for the Australian red meat sector, Agric. Syst. 175 (2019) 13–21, https://doi.org/10.1016/j.agsy.2019.05.009.

[3] S. Mohamad Salleh, C. Kronqvist, E. Detmann, J. Karlsson, R. Danielsson, Is it possible to predict the methane emission intensity of Swedish dairy cows from milk spectra? Smart Agric. Technol. 5 (2023) 100286.

[4] Y. de Haas, R.F. Veerkamp, G. de Jong, M.N. Aldridge, Selective breeding as a mitigation tool for methane emissions from dairy cattle, Animal 15 (2021) 100294, https://doi.org/10.1016/j.animal.2021.100294.

[5] M.M. Della Rosa, E. Sandoval, D. Luo, D. Pacheco, A Jonker, Effect of feeding fresh forage plantain (Plantago lanceolata) or ryegrass-based pasture on methane emissions, total-tract digestibility, and rumen fermentation of nonlactating dairy cows, J. Dairy Sci. 105 (8) (2022) 6628–6638, https://doi.org/10.3168/jds.2021-21757.

[6] J. MacPherson, A. Voglhuber-Slavinsky, M. Olbrisch, P. Schöbel, E. Dönitz, I. Mouratiadou, K. Helming, Future agricultural systems and the role of digitalization for achieving sustainability goals. A review, Agron. Sustainable Develop. 42 (4) (2022) 70, https://doi.org/10.1007/s13593-022-00792-6.

[7] R.D. Kinley, G. Martinez-Fernandez, M.K. Matthews, R. de Nys, M. Magnusson, N. W. Tomkins, Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, J. Clean. Prod. 259 (2020) 120836, https://doi.org/10.1016/j.jclepro.2020.120836.

[8] K.A. Beauchemin, E.M. Ungerfeld, A.L. Abdalla, C. Alvarez, C. Arndt, P. Becquet, C. Benchaar, A. Berndt, R.M. Mauricio, T.A. McAllister, W. Oyhantçabal, S. A. Salami, L. Shalloo, Y. Sun, J. Tricarico, A. Uwizeye, C. De Camillis, M. Bernoux, T. Robinson, E. Kebreab, Invited review: current enteric methane mitigation options, J. Dairy Sci. 105 (12) (2022) 9297–9326, https://doi.org/10.3168/jds.2022-22091.

[9] T.C. Husz, C. Goad, R. Reuter, The effect of competition for an automated supplement feeder on supplement intake behavior of stocker steers, J. Anim. Sci. 97 (2019) 15.

[10] C. Eastwood, A. Renwick, Innovation uncertainty impacts the adoption of smarter farming approaches, Front. Sustainable Food Syst. 4 (2020) 1–14, https://doi.org/10.3389/fsufs.2020.00024.

[11] G. Kuehne, R. Llewellyn, D.J. Pannell, R. Wilkinson, P. Dolling, J. Ouzman, M. Ewing, Predicting farmer uptake of new agricultural practices: a tool for research, extension and policy, Agric. Syst. 156 (2017) 115–125, https://doi.org/10.1016/j.agsy.2017.06.007.

[12] O. Montes de Oca Munguia, D.J. Pannell, R. Llewellyn, Understanding the adoption of innovations in agriculture: a review of selected conceptual models, Agronomy 11 (1) (2021) 139.

[13] B. Marmont, Z. Dorner, D. Silva-Villacorta, C.R. Eastwood, E.M.K. Minnee, M. Neal, Farm-level cost-effectiveness analysis of in-paddock feeding of methane inhibitors in pasture-based dairy, J. NZ Grasslands 85 (2023) 265–273.

[14] J.M. Tricarico, Y. de Haas, A.N. Hristov, E. Kebreab, T. Kurt, F. Mitloehner, D. Pitta, Symposium review: development of a funding program to support research on enteric methane mitigation from ruminants, J. Dairy Sci. 105 (10) (2022) 8535–8542, https://doi.org/10.3168/jds.2021-21397.

[15] C. Charatsari, E. Lioutas, M. De Rosa, Y. Vecchio, Technological innovation and agrifood systems resilience: the potential and perils of three different strategies, Front. Sustainable Food Syst. 6 (2022) 872706, https://doi.org/10.3389/fsufs.2022.872706.

[16] C. Eastwood, J.P. Edwards, J.A. Turner, Review: anticipating alternative trajectories for responsible Agriculture 4.0 innovation in livestock systems, Animal 15 (2021) 100296, https://doi.org/10.1016/j.animal.2021.100296.

[17] Dorigo, E., & Ballingall, J. (2020). Dairy's economic contribution. https://www.dcanz.com/UserFiles/DCANZ/File/Dairy%20economic%20contribution%20slides%20_Sense%20Partners%20August%202020.pdf [Accessed: 21/02/2023].

[18] The World Bank. (2021). GDP (current US$)—New Zealand | Data. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?end=2021&locations=NZ&start=1960&view=chart [Accessed 21/02/2023].

[19] J. Ballingall, D. Pambudi, NZIER Report—Dairy Trade's Economic Contribution to New Zealand, New Zealand Institute of Economic Research, 2017. https://www.think-asia.org/handle/11540/7268 [Accessed: 21/02/2023].

[20] DairyNZ. (2021). New Zealand Dairy Statistics 2020-21. DairyNZ. https://www.dairynz.co.nz/media/5794941/nz-dairy-statistics-2020-21-web.pdf [Accessed: 26/07/2024].

[21] P. Hedley, E. Kolver, C. Glassey, B. Thorrold, A. Bystereldt, J.F. Roche, K. Macdonald, Achieving high performance from a range of farm systems, in: Proceedings of the 4th Dairy3 Conference, 2006, pp. 147–166. https://www.researchgate.net/publication/288194837_Achieving_high_performance_from_a_range_of_farm_systems [Accessed: 21/02/2023].

[22] DairyNZ. (2024). DairyNZ Economic Survey 2022-23. DairyNZ https://www.dairynz.co.nz/resources/resource-list/dairynz-economic-survey-2022-23/ [Accessed: 26/07/2024].

[23] D. Beca, Labour cost and labour efficiency within the australian dairy industry, Austr. Agribus. Perspect. (18) (2021) 24.

[24] A. Romera, A. Bos, M. Neal, C. Eastwood, D. Chapman, W. McWilliam, D. Royds, C. O'Connor, R. Brookes, J. Connolly, P. Hall, P. Clinton, Designing future dairy systems for New Zealand using reflexive interactive design, Agric. Syst. 181 (2020) 102818, https://doi.org/10.1016/j.agsy.2020.102818.

[25] StatsNZ. (2020). New Zealand's greenhouse gas emissions. https://www.stats.govt.nz/indicators/new-zealands-greenhouse-gas-emissions [Accessed 21/02/2023].

[26] Climate Change Response (Zero Carbon) Amendment Act 2019, No 61 (2019).

[27] K.A. Beauchemin, E.M. Ungerfeld, R.J. Eckard, M. Wang, Review: fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation, Animal 14 (S1) (2020) s2–s16, https://doi.org/10.1017/S1751731119003100.

[28] J.L. Black, T.M. Davison, I. Box, Methane emissions from ruminants in Australia: mitigation potential and applicability of mitigation strategies, Animals (4) (2021) 11, https://doi.org/10.3390/ani11040951.

[29] A. Hristov, A. Melgar, Variability in the relationship between enteric methane emission and dry matter intake in dairy cows, in: Proceedings of the 7th International Greenhouse Gas and Animal Agriculture Conference (GGAA2019), 7th International Greenhouse Gas and Animal Agriculture Conference (GGAA2019), 2019. https://www.researchgate.net/publication/335326992_Variability_in_the_relationship_between_enteric_methane_emission_and_dry_matter_intake_in_dairy_cows [Accessed: 21/02/2023].

[30] H.A. Stefenoni, S.E. Räisänen, S.F. Cueva, D.E. Wasson, C.F.A. Lage, A. Melgar, M. E. Fetter, P. Smith, M. Hennessy, B. Vecchiarelli, J. Bender, D. Pitta, C.L. Cantrell, C. Yarish, A.N. Hristov, Effects of the macroalga Asparagopsis taxiformis and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows, J. Dairy Sci. 104 (4) (2021) 4157–4173, https://doi.org/10.3168/jds.2020-19686.

[31] DairyNZ. (2023). Technology and Workplace Practices Survey Report 2023. DairyNZ https://www.dairynz.co.nz/media/55lbd2cw/technology-survey-report-2023-v51.pdf [Accessed: 26/07/2024].

[32] C.R. Eastwood, B. Dela Rue, J.P. Edwards, J. Jago, Responsible robotics design–A systems approach to developing design guides for robotics in pasture-grazed dairy farming, Front. Robot. AI 9 (2022), https://doi.org/10.3389/frobt.2022.914850.

[33] U. Kenny, Á. Regan, Co-designing a smartphone app for and with farmers: empathising with end-users' values and needs, J. Rural Stud. 82 (2021) 148–160, https://doi.org/10.1016/j.jrurstud.2020.12.009.

[34] Rogers, E.M. (1962). Diffusion of innovations (Vol. 31). New York, NY: Free Press of Glencoe.

[35] I. Ajzen, Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior1, J. Appl. Soc. Psychol. 32 (4) (2002) 665–683, https://doi.org/10.1111/j.1559-1816.2002.tb00236.x.

[36] E. Palm, S.O. Hansson, The case for ethical technology assessment (eTA), Technol. Forecast. Soc. Change 73 (5) (2006) 543–558, https://doi.org/10.1016/j.techfore.2005.06.002.

[37] C. Eastwood, M. Ayre, R. Nettle, B. Dela Rue, Making sense in the cloud: farm advisory services in a smart farming future, NJAS 90–91 (2019) 100298, https://doi.org/10.1016/j.njas.2019.04.004.

[38] O. Montes de Oca Munguia, D.J. Pannell, R. Llewellyn, P. Stahlmann-Brown, Adoption pathway analysis: representing the dynamics and diversity of adoption for agricultural practices, Agric. Syst. 191 (2021) 103173, https://doi.org/10.1016/j.agsy.2021.103173.

[39] G. Guest, A. Bunce, L. Johnson, How many interviews are enough?:an experiment with data saturation and variability, Field Methods 18 (1) (2006) 59–82.

[40] K. Vasileiou, J. Barnett, S. Thorpe, T. Young, Characterising and justifying sample size sufficiency in interview-based studies: systematic analysis of qualitative health research over a 15-year period, BMC Med. Res. Methodol. 18 (1) (2018) 148.

[41] Janis, I.L. (1972). Victims of groupthink: A psychological Study of Foreign-Policy Decisions and fiascoes. (pp. viii, 277). Houghton Mifflin.

[42] K. Heitkämper, L. Reissig, E. Bravin, S. Glück, S. Mann, Digital technology adoption for plant protection: assembling the environmental, labour, economic and social pieces of the puzzle, Smart Agric. Technol. 4 (2023) 100148.

[43] Moscovici Joubran, , Alice, Karina M. Pierce, Niamh Garvey, Laurence Shalloo, Tom F. O'Callaghan, Invited review: a 2020 perspective on pasture-based dairy systems and products, J. Dairy Sci. 104 (7) (2021) 7364–7382, https://doi.org/10.3168/jds.2020-19776.

[44] S. Laurenson, T.J. van der Weerden, P.C. Beukes, I. Vogeler, Evaluating the economic and production benefit of removing dairy cows from pastures in response to wet soil conditions, N.Z. J. Agric. Res. 60 (3) (2017) 223–244, https://doi.org/10.1080/00288233.2017.1298630.

[45] Graeme. Pitman, Comparing a covered stand-off pad for on/off grazing during winter with conventional winter block grazing 2017-19 at DTT Stratford demonstration farm, J. NZ Grasslands (2021) 145–152, https://doi.org/10.33584/jnzg.2021.83.3489.

[46] J.P. Edwards, B. Kuhn-Sherlock, B.T. Dela Rue, Short communication: Technologies and milking practices that reduce hours of work and increase flexibility through milking efficiency in pasture-based dairy farm systems, J Dairy Sci 103 (8) (2020) 7172–7179.

[47] S. Muetzel, K. Lowe, P.H. Janssen, D. Pacheco, N. Bird, N. Walker, O. Vidoni, L. Schweikert, L. Clasadonte, M. Kindermann. Towards the application of 3-nitrooxypropanol in pastoral farming systems. Proceedings of the 7th Greenhouse Gas and Animal Agriculture Conference. Iguassu Falls, Brazil. (Abstr.) (2019), p. 81.

[48] M. Neal, J. Roche, Profitable and resilient pasture-based dairy farm businesses in New Zealand, Anim. Prod. Sci. 60 (1) (2019) 169–174, https://doi.org/10.1071/AN18572.

[49] C. Eastwood, T. White, J. Sheridan, M. Manning, K. Mashlan, Skills required by dairy farmers when strategically adapting their farm system, Rural Extension Innov. Syst. J. 13 (2) (2017) 22–31, https://doi.org/10.3316/informit.187049156496532.

[50] B.T. Dela Rue, C.R. Eastwood, J.P. Edwards, S. Cuthbert, B.T.D. Rue, C. R. Eastwood, J.P. Edwards, S. Cuthbert, New Zealand dairy farmers preference investments in automation technology over decision-support technology, Anim. Prod. Sci. 60 (1) (2019) 133–137, https://doi.org/10.1071/AN18566.

[51] M. Santhanam-Martin, R. Nettle, J. Major, J. Fagon, E. Beguin, P. Bridge, D. Pacheco, M. Santhanam-Martin, R. Nettle, J. Major, J. Fagon, E. Beguin, P. Bridge, D. Pacheco, The work assessment method shows potential to improve performance and social sustainability on australian dairy farms, Anim. Prod. Sci. 62 (1) (2021) 90–100, https://doi.org/10.1071/AN20438.

[52] B.T. Dela Rue, C.R. Eastwood, Individualised feeding of concentrate supplement in pasture-based dairy systems: practices and perceptions of New Zealand dairy farmers and their advisors, Anim. Prod. Sci. 57 (7) (2017) 1543–1549.

[53] R. Abbasi, P. Martinez, R. Ahmad, The digitization of agricultural industry – a systematic literature review on agriculture 4.0, Smart Agric. Technol. 2 (2022) 100042.

[54] S.M. Pedersen, S. Fountas, S. Symons, Field robotics – economic, technical and environmental perspectives, Smart Agric. Technol. 5 (2023) 100314.

[55] L. Guerin, T. Guerin, Constraints to the adoption of innovations in agricultural research and environmental management: a review, Aust. J. Exp. Agric. 34 (4) (1994) 549, https://doi.org/10.1071/EA9940549.

[56] D. van der Velden, J. Dessein, L. Klerkx, L. Debruyne, Constructing legitimacy for technologies developed in response to environmental regulation: the case of ammonia emission-reducing technology for the Flemish intensive livestock industry, Agric. Human Values (2022), https://doi.org/10.1007/s10460-022-10377-4.

[57] J. Lowenberg-DeBoer, B. Erickson, Setting the record straight on precision agriculture adoption, Agron. J. 111 (4) (2019) 1552–1569, https://doi.org/10.2134/agronj2018.12.0779.

[58] C.J. Rutten, W. Steeneveld, A.G.J.M. Oude Lansink, H. Hogeveen, Delaying investments in sensor technology: the rationality of dairy farmers' investment decisions illustrated within the framework of real options theory, J. Dairy Sci. 101 (8) (2018) 7650–7660, https://doi.org/10.3168/jds.2017-13358.

[59] J. Ingram, D. Maye, J. Kirwan, N. Curry, K. Kubinakova, Interactions between niche and regime: an analysis of learning and innovation networks for sustainable agriculture across Europe, J. Agric. Educ. Extension 21 (1) (2015) 55–71, https://doi.org/10.1080/1389224X.2014.991114.

[60] J. Knook, J.A. Turner, Reshaping a farming culture through participatory extension: an institutional logics perspective, J. Rural Stud. 78 (2020) 411–425, https://doi.org/10.1016/j.jrurstud.2020.06.037.

[61] J. Knook, V. Eory, M. Brander, D. Moran, The evaluation of a participatory extension programme focused on climate friendly farming, J. Rural Stud. 76 (2020) 40–48, https://doi.org/10.1016/j.jrurstud.2020.03.010.

[62] B. Douthwaite, J.D.H. Keatinge, J.R. Park, Why promising technologies fail: the neglected role of user innovation during adoption, Res. Policy 30 (5) (2001) 819–836, https://doi.org/10.1016/S0048-7333(00)00124-4.

[63] C.R. Eastwood, F.J. Turner, A.J. Romera, Farmer-centred design: an affordances-based framework for identifying processes that facilitate farmers as co-designers in addressing complex agricultural challenges, Agric. Syst. 195 (2022) 103314, https://doi.org/10.1016/j.agsy.2021.103314. -.

[64] L.J. Thompson, K.L. Glewen, R.W. Elmore, J. Rees, S. Pokal, B.D. Hitt, Farmers as researchers: in-depth interviews to discern participant motivation and impact,

Agron. J. 111 (6) (2019) 2670–2680, https://doi.org/10.2134/agronj2018.09.0626.

[65] G. Kaine, V. Wright, Relative advantage and complexity: predicting the rate of adoption of agricultural innovations, Front. Agron. 4 (2022) 967605, https://doi.org/10.3389/fagro.2022.967605.

[66] H. Görge, I. Dittrich, N. Kemper, J. Krieter, Solutions and prospects for digital documentation of treatment data on-farm, Smart Agric. Technol. 5 (2023) 100299.

[67] G. Feder, D.L. Umali, The adoption of agricultural innovations: a review, Technol. Forecast. Soc. Change 43 (3) (1993) 215–239, https://doi.org/10.1016/0040-1625(93)90053-A.

[68] C.R. Eastwood, J. Knook, J.A. Turner, A. Renwick, Policy approaches for enhanced dairy sector innovation – a review of future pathways and policies for effective implementation of digital agriculture, NZ Econ. Papers 2023 (2023) 1–8, https://doi.org/10.1080/00779954.2022.2161935.

[69] M. Kukk, A. Põder, A.-H. Viira, The role of public policies in the digitalisation of the agri-food sector. A systematic review, NJAS 94 (1) (2022) 217–248, https://doi.org/10.1080/27685241.2022.2147870.

[70] G. Gil, D.E. Casagrande, L.P. Cortés, R. Verschae, Why the low adoption of robotics in the farms? Challenges for the establishment of commercial agricultural robots, Smart Agric. Technol. 3 (2023) 100069.