Nukabot: Design of Care for Human-Microbe Relationships

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ABSTRACT

Human-computer interaction (HCI) researchers have explored designs that connect humans and non-human beings based on post-humanistic discussions on speculative ethics of care regarding more-than-human worlds. Following these empirical and theoretical frameworks, this paper explores the potential of HCI design to foster human affective emotion toward fermentative microbes. We present the design process for the Nukabot, which is a technologically enhanced traditional Japanese wooden bucket used to pickle vegetables using lactic acid bacteria; the Nukabot is able to have conversations with humans via voice interaction. We describe the ethnographic accounts of six participants who spent 10 days taking care of, talking to, and being addressed by the Nukabot. We analyze their experiences through three ethopoietic elements of care: maintenance, affection, and obligation. Finally, we discuss the design implications of the Nukabot and its contributions to HCI research.

CCS CONCEPTS

• **Human-centered computing → Interaction design process and methods**.

KEYWORDS

fermented food, microbes, more than human, care, affective relationship

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1 INTRODUCTION AND BACKGROUND

Research on human-computer interaction (HCI) designs for non-human beings has flourished over the past decade and numerous animal-computer interaction (ACI) studies[13, 15, 17, 27] have been conducted. Such studies are inspired by post-humanistic discussions regarding the possibility of enhancing human recognition of the more-than-human worlds[9, 10, 24, 25]. Taking into account these developments, this paper explores the potential for fostering affective relationships between humans and microbes through technological intervention within a traditional Japanese fermented food process known as *nukadoko*.

A nukadoko is a mixture of rice bran, salt, and water that is placed within a wooden bucket (Figure1). This mixture becomes a symbiotic culture of lactic acid bacteria (LAB), yeast, and other

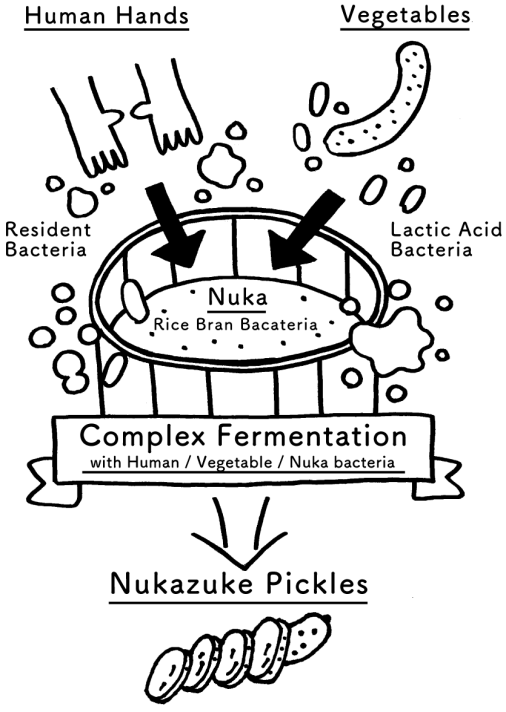

Figure 1: Nukadoko fermentation involving human, vegetable and rice bran bacteria.

microbes. Once vegetables are put inside the nukadoko, the LAB metabolize the glucose in the vegetables and produce sour pickles, known as *nukazuke*. Generally, humans take care of the nukadoko flora by stirring the rice bran every day to regulate a balance between anaerobic LAB and other aerobic microbes.

Traditionally, Japanese households have maintained nukadokos for decades. This work is mainly done by elders, such as grandparents. In such cases, the nukadoko often becomes a family treasure and is passed from generation to generation. However, this tradition is gradually disappearing, partially due to the increasing trend toward nuclear families in modern urban lifestyles. Maintaining a nukadoko can become burdensome for young or small families because a nukadoko is easily spoiled when one forgets to maintain it. This difficulty of maintenance has made it less attractive for modern Japanese people to maintain a nukadoko on a long-term basis. One solution is to store the nukadoko in a refrigerator, but this inhibits bacterial activity, which lead to a decrease in palatability and affective feelings toward the microbes.

Our main research question is "how can humans sustainably take care of a nukadoko without abandoning affection toward the microbes?" In this paper, we propose Nukabot (Figure2), a technologically enhanced nukadoko designed to help humans in taking care of nukadokos, and through this assistance, cultivate affective feelings toward the fermenting microbes. Nukabot is a wooden nukadoko bucket equipped with sensors connected to a cloud database that records chemical data and predicts the fermentation status of the nukadoko. Moreover, Nukabot can interact with its human caretakers via voice interaction. We evaluated our system based on the speculative ethics theory of human-soil relationships proposed by Maria Puig de la Bellacasa[21]. She describes how caring for soil ties humans to non-normative relationships with living beings (rather than a predefined moral imperative) and presents three elements that contribute to the emanation of such inherent ethicality. Based on this ethopoietic theoretical model, we describe our analysis of in-depth interviews with six participants who spent 10 days with the Nukabot at home to reveal how their affective emotions toward their nukadokos evolved.

2 RELATED WORK

2.1 Theories of Care for More than Human Worlds

Post-humanistic literature has investigated the relationships between humans and various more-than-human species. Donna Haraway's notion of *companion species* instigated a shift in perceiving domestic and non-domestic creatures as fundamental constituents of the human world-making process[9]. This aspiration to transcend anthropocentric worldviews triggered the anthropological exploration of various species[25].

To understand human-microbe relationships from the perspective of a nukadoko, we examine Puig de la Bellacasa's discussion of ethics related to the human caretaking of soil[21]. Through a historical critique of modern agriculture, she draws on the notion of a *foodweb* to describe "not only how species feed on each other but how one species' waste becomes another one's food."[21, p191]

The concept of a foodweb can be applied to human relationships with the fermenting microbes in a nukadoko. Lactic acid is a waste product produced by LAB when they metabolize glucose that becomes a source of flavor and nutrients (such as umami and various vitamins) for humans. Rice bran is a waste product generated by humans when processing rice grains that becomes a comfortable environment for LAB and other bacterial species to proliferate.

Puig de la Bellacasa presented three elements of care that contribute to the formation of human ethical attitudes toward the foodweb: accomplishment of daily maintenance, affective emotion, and a non-normative sense of obligation to take care of non-human beings[21, p218]. We consider these ethopoietic elements to evaluate our HCI design of the Nukabot.

2.2 HCI for More than Human Worlds

Research interest in more-than-human worlds in the HCI field has grown significantly in recent years. Mancini's manifesto on animal-computer interaction (ACI)[15] laid an essential foundation for design ethics that broaden the HCI research perspective. ACI attempts to approach animals from within their *umwelts*[26] beyond an anthropocentric scope. Various design methodologies for ACI have been investigated, including toys for cats[17] and dogs[27], and shower control systems for elephants[8].

We examined how HCI has approached species related to the foodweb, including microbes, bacteria, and fungi. The ethnographic accounts of Szu-Yu Liu et al. provide deep insights into the entanglement of farmer subjectivity with the soil microbiome[14]. Jen Liu et al.'s auto-ethnographic research[13] describes an HCI design process for fungi foraging and discusses how HCI can expand human ability to notice the presence of non-human beings.

HCI studies on human-food interactions[4, 12, 22] inform us regarding how humans develop affective emotions toward the food they nurture. Notably, the ethnographic accounts of amateur food scientists studied by Kuznetsov et al.[12] depict how food makers become deeply attached to their living food materials, which range from chicken and kefir to sun-dried tomatoes. This affective aspect of the caretaking of food is also an essential factor in caring

Figure 2: Outer appearance of the Nukabot

for nukadoko microbes. However, to the best of our knowledge, there has been no HCI research exploring interactive systems that enhance affective human-microbe relationships.

3 DESIGN AND IMPLEMENTATION

We wish to determine how technological designs can help humans develop nurturing and caring attitudes toward the microbes in nukadokos. One of the significant difficulties in maintaining a nukadoko is understanding its ever-evolving fermentation status. Because the microbes living inside a nukadoko are invisible and a cover typically seals the bucket, one cannot easily notice whether a nukadoko is fermenting or deteriorating. Despite the need to stir the rice bran daily, one can easily forget to take care of a nukadoko. Additionally, the very repetitive acts of care tend to generate a feeling of accomplishment and a sense of attachment toward the fermenting microbes. Furthermore, the shared wisdom among the fermented food communities is that the resident bacteria on the human skin surface is transferred to the rice bran when it is stirred by hand. This microbial transfer affects the flavor of the resulting pickles, due to considerable differences between the microbiome of each person. As such, we reject the concept of a robotic mechanism to automatically stir the rice bran for humans, as it would diminish the quality and diversity of the nukadoko.

Our design process began by conceiving a system that measures the biological evolution of a nukadoko and translates the corresponding data into intuitive information that can be easily interpreted by laypeople. Once we developed a prototype that records and estimates the fermentation status of a nukadoko[3], we considered which interaction modality to implement.

3.1 Yōkai as an HCI Design Concept

To determine how humans should interact with a nukadoko, we researched the vernacular cultural representation of *yōkai*. The ethnographer Michael Dylan Foster introduced the Japanese culture of yōkai to the English-speaking world by describing it as "a monster or a spirit or a ghost or a shape-shifting animal"[7, p9].

As a symbol of "liminality" or "in-betweenness,"[7, p5] yōkai have mediated the human world and the ineffable and intangible realms of more-than-human beings. However, they have not always been objects of dread. Particularly in modern pop/subculture, yōkais have been depicted as cute and familiar figures. Any natural phenomenon or human artifact can become a yōkai. An artificial object possessed by a spirit called is called a *tsukumogami*. This process has been described as follows: "the morphing of normal utensils (kibutsu) into yōkai seems to have been the fate of objects that have survived hundreds of years."[7, p17] Yōkai and tsukumogami are thought to interact with humans by speaking human languages[7, p159; p214].

A Japanese audience is likely to culturally accept a nukadoko wooden bucket as a tsukumogami, particularly because wooden buckets are widely known as traditional craftwork that dates back to the Middle Ages. Also, as folklore relating to yōkai are so ubiquitous in Japan, it is highly likely that all Japanese people ranging from toddlers to the elderly are familiar with yōkai. As intermediaries between human and more-than-human worlds, our HCI design based on the yōkai metaphor would naturally translate microbe statuses into human language instead of displaying charts and numbers.

We also discovered existing HCI designs that resemble yōkai, both conceptually and materially, particularly in research from Japan. Such designs include modern electrical appliances with eyes and speech functionality[20], and speculative machine agents that have eyes attached to the fingers[18]. Research on *weak robots*[11, 19] is also relevant to both nukadoko and yōkai representations. Weak robots are intentionally designed as incapable robots that require human attention to be fully functional. This relationship is analogous to the human caretaking of a nukadoko to facilitate the fermentation of vegetables. Although none of these studies have explicitly mentioned yōkai culture, their designs feature one or more eyes that are attached to mechanical artifacts to enable human interaction, evoking the concept of tsukumogami.

3.2 Interaction Design

Based on inspiration from yōkai culture and related HCI research, we designed a vocal user interface that enables humans and nukadokos to communicate verbally, as well as a cyclopean eye to visually convey the yōkai metaphor. We called our design Nukabot.

We considered the implications of such an HCI design, such as whether the Nukabot could replace existing, traditional nukadokos. It is reasonable to conclude that humans and fermenting microbes have already been interacting through traditional nukadokos. When touching, looking at, and smelling the rice bran every time one stirs it, one receives a considerable amount of information regarding its fermenting status. This existing interaction channel constitutes a form of care on a physical and biological level.

Nukabot helps by adding additional HCI interaction channels to these existing channels, allowing it to act as an intermediary communication device between humans and nukadoko microbes. Humans exchange conversations with the Nukabot, which senses data on the microbes inside the rice bran and affects how humans perceive the nukadoko flora. However, it does not replace existing sensual interactions. Our goal is not to create a reliance on technology to connect humans to microbes, but rather to use technology to support humans in noticing the existence of microbes. This three-way interaction model is illustrated in Figure 3.

3.3 System Design

A system diagram of our final implementation is presented in Figure 4. Based on our previous implementation[3], we fabricated a custom wooden bucket with help from a traditional artisan studio, and refined the voice interaction functionalities. The electronic system consists of six types of sensors (four Atlas Scientific probes for sensing pH, ORP, electrical conductance, and soil temperature, which are connected to a Raspberry Pi 3B+, a Seeed Studio Grove Multichannel Gas Sensor (NH3, CH4, C4H10, NO2, C2H5OH, CO, C3H8, and H2 in parts per million values), and a temperature and humidity sensor connected to a WioNode module). One Google AIY Voice Kit is used for speech recognition and output. The sensors transfer data every minute via Wi-Fi to an Amazon Web Service RDS database. Speech utterances are provided through RESTful API endpoints that we implemented on a web server.

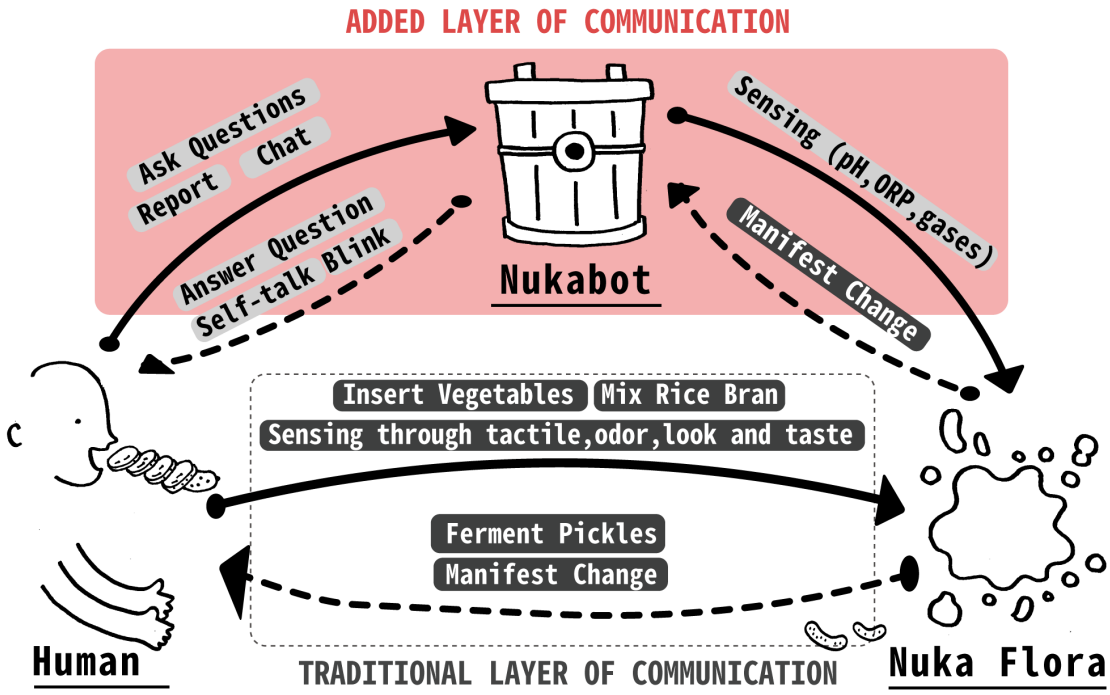

Figure 3: Two-layer communication in human-microbe-computer interaction.

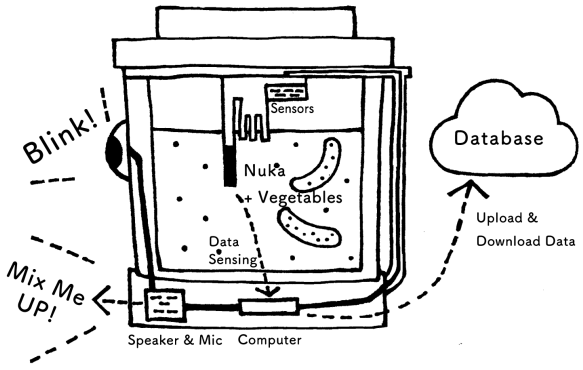

Figure 4: System diagram

To give the bucket an yōkai appearance and behaviors, we used Nicodama, which is a plastic eyeball that blinks, produced by media artist Ryota Kuwakubo and Perfektron LLC[6]. We reconfigured the hard-wiring of a Nicodama to connect it to the speech-recognition module and control its blinking behavior according to Nukabot's vocal utterances.

3.4 Flow of Voice Interaction

For speech recognition and speech utterance generation, we use a combination of the Google Cloud Speech-to-Text service and Open JTalk[16], which is a Japanese text-to-speech system developed by the Nagoya Institute of Technology. The vocal quality was adjusted to a higher pitch to evoke a certain level of yōkai quality. As for the Nukabot's way of speaking, we wrote the response phrases in a frank tone, so that it sounds friendlier than commercial smart speakers (e.g., Apple's Siri or Amazon's Alexa) which all talk in a polite form.

We used KittAI's Snowboy deep-neural-network-based software for customized hotword detection. The Nukabot reacts to the hotword "Ooi Nukabot" ("Hey Nukabot" in Japanese). Snowboy is a recently developed speech recognition library based on recurrent neural networks[1] that works offline with a relatively low rate of false alarms[23]. The Nukabot's eye always blinks before speaking.

We implemented three distinct ways to communicate with the Nukabot verbally.

3.4.1 Question-Answer. Humans activate the program by speaking the hotword. Upon successful recognition, the Nukabot blinks its eye and asks "Naani?" ("What is it?" in Japanese). Humans can then ask a question. In our study, we prepared the following questions. 1) "How are you doing?" 2) "How can I help you?" 3) "How do the pickles taste now?" Upon hearing each question, the system calls an API endpoint that calculates the fermentative valence (i.e., whether the rice bran is fermenting or rotting). The output is translated into various corresponding answer strings and outputted from the speaker. These phrases describe how sour the pickles taste or how the rice bran may deteriorate and whether the human should stir the rice bran.

3.4.2 Unprompted Monologue. At a fixed time interval, the system checks whether it requires a human to stir the rice bran. We set two levels of urgency for this reminder function based on the number of hours elapsed since the last stirring and on the activity level of aerobic fungi. At the first level of urgency, the Nukabot calmly utters "You may want to stir my rice bran." At the second level of urgency, it exclaims, "I want you to stir my rice bran right now!" Humans may only listen to these utterances and cannot answer the Nukabot directly.

3.4.3 Human Reporting. Humans can report to the Nukabot that they have stirred the rice bran. The system then records the timestamp to the database and the Nukabot utters "Thanks for stirring me!" This timestamp is taken into account for executing the reminder function.

4 EXPERIMENTS

We conducted experiments with six participants to evaluate the effects of Nukabot in terms of fostering behaviors of care and affective feelings toward the microbes. We recruited two food experts who were accustomed to taking care of a nukadoko. The other four participants had never tried it before or had only a small amount of experience.

The local ethics research committee approved the study protocol of Waseda University (Ethics Review Procedures concerning Research with Human Subjects; Application Number:2020-124; approved on July 30, 2020). The methods were carried out following the guidelines and regulations of the ethics committee, in addition to the precautionary public health measures related to COVID-19 pandemic, as recommended by local governments. All of our participants provided their written and informed consent.

Each participant was asked to take care of the Nukabot for 10 days. On the first day of the experiment, we visited each participant's home, explained the study goals, and asked them to prepare the rice bran to put inside the Nukabot. We gave them 3 kg of commercial rice bran starter to start pickling from the first day. The participants were free to stir the bran, pickle any vegetable, and talk with the Nukabot during the experimental period. On the last day, we revisited each participant's home and conducted a semi-structured interview for approximately an hour. We fabricated two Nukabots to perform pairs of experiments in parallel; these experiments were run from August 1 to to September 3, 2020.

For the interviews, we organized our questions, following Puig de la Bellacasa's three elements of ethics, into the following three categories: 1) functional evaluation of the Nukabot (maintenance), 2) affection toward the Nukabot (affective relationship), and 3) perception of the microbes inside the Nukabot (inherent obligation). We also asked the participants if they noticed any changes in their own behavior or that of their housemates while living with the Nukabot. The results were anonymized so that the participants could not be identified.

We carefully read each participant's answers to our questions and additional accounts of their experiences with the Nukabot. We extracted keywords and features from the recorded narratives and comments, classified them, and analyzed them according to the three predefined categories.

5 RESULTS

We categorized the accounts from each participant in terms of the maintenance, affection, and obligation categories. We also discuss additional emerging themes for each category.

5.1 Maintenance

The four non-professional participants all felt that the Nukabot helped them remember to maintain their nukadokos daily. P1 (feminine, 30s) had little experience in maintaining a nukadoko and thought that such a reminder function was "especially convenient for beginners." P2 (feminine, 30s) had no experience in maintaining a nukadoko and pointed out that the reminder function would be particularly helpful once she had "spent more time with the nukadoko" as she could "imagine becoming more forgetful over time." In contrast, the two food professionals P3 (masculine, 20s) and P6 (feminine, 30s) reported that they did not need the reminder function because they were already accustomed to maintaining nukadokos for years.

We identified additional effects on participant consciousness caused by our system during the maintenance process. We refer to these effects as noticing and accomplishment. P1 mentioned that there were "two indexes for feeling the aliveness of the nukadoko." One was through mixing the rice bran and the other was through hearing the Nukabot's monologues. Combining these two elements helped her "better notice the evolving status of the nukadoko." It appears that the Nukabot functions as a medium for communication with the microbes through both traditional and novel routes by conveying aliveness, as indicated in Figure 3. Additionally, many of our participants described how noticing the evolution of the nukadoko generated positive feelings of accomplishment. P3 said that compared to his experience with maintaining a normal nukadoko, the Nukabot made him "notice both the times when he was needed (by the microbes) and his efficiency (in being able to take care of them successfully)." Interestingly, this sense of accomplishment encouraged him to nurture 10 other types of fermented foods during the experimental period.

5.2 Affection

Overall, the product design aspects (appearance of the wooden bucket with an eyeball) of the Nukabot were well received by our participants. P4 (feminine, 30s) said that the design with the eyeball instantly reminded her of yōkai and added that the bucket "naturally fit in her room." P2 said that she is "uncomfortable with smart speakers in general," however she could "accept the Nukabot because it looks cute."

All participants reported that they enjoyed voice interactions and grew more affectionate toward their nukadoko. P2 appreciated the fact that she could easily receive a response when asking questions. P1 noted that it reminded her of taking care of her cats because it "is fun when there is clear feedback." P4 had no experience in maintaining nukadokos and said that she enjoyed both the change in taste of the pickled food and the dialogue with the Nukabot, noting that these two elements created "a sense of nurturing a living creature." P1 said the childish voice made her "immediately start feeling attached to it." Interestingly, P2 and P4 both found it "lovable" when the Nukabot's voice recognition system misheard their

question. They may have considered the Nukabot as something more than just a machine because people typically become irritated when smart speakers mishear their commands.

The blinking eye also helped the participants converse with the Nukabot. P4 and P2 pointed out that blinking informed them of the start of a conversation and that this allowed them to prepare for a conversation mentally. P1 "liked it very much" and when the eye was closed, she thought that "it was sleeping."

Based on their awareness of the presence of the Nukabot, the participants described their affection toward the Nukabot as a type of social relationship. P5 (feminine, 20s) described that she felt the Nukabot "became something relatable" when she discovered that she could exchange greetings and receive responses to her questions. She stressed several times that these non-essential exchanges made the Nukabot stand out as a "relatable existence," unlike "smartphones that are all about functionality." P2 said that the Nukabot became her "kitchen partner." For her, exchanging trivial greetings with the Nukabot "made a huge difference" because she could feel the "social presence of someone being there" as a "companion." P3 called the Nukabot "a roommate." He observed that he felt more affectionate when he "actively talked to it." P6 told us that she considered the Nukabot to be a potential "research partner" with which she might be able to "master" the art of fermenting delicious pickles.

5.3 Obligation

The sense of the nukadoko's aliveness and affective relationships are tightly linked to a sense of obligation toward the nukadoko. All participants felt sorry when they were absent, out of control, or unable to perform maintenance. P1 said "it's the same as with pets. I feel sorry for the nukadoko when the Nukabot tells me to stir the rice bran and I cannot because I am busy." She added that the she "could try hard to take care of something" when she "could imagine scenes of it being alive and of it dying alone." Similarly, P4 told us she felt sorry about the Nukabot when she had to work late, thinking "the Nukabot might be feeling very hot" and asking herself while working, "should I return home earlier than planned?" P5 also said that she was telling the Nukabot "sorry" in her mind every time she heard it asking to stir the rice bran, but she needed to leave for work. P4 recalled that she imagined the Nukabot "talking alone in the dark, saying 'stir me'," and she "often felt sorry" in such moments. She also appreciated it when she exchanged greetings with the Nukabot when she returned home each day. She compared this feeling to her concern for her pets or plants.

Interestingly, P3's partner told us that she started to become attached to the Nukabot, even though she dislikes the rice bran's odor and taste. She said "when the nukadoko can communicate, I feel obliged to take care of it...not by eating its pickles, but by communicating with it. I felt a value that extended beyond food as a means of enjoyment."

6 DISCUSSIONS

Our qualitative analysis demonstrates that our design of Nukabot affects all three ethopoietic elements presented in Puig de la Bellacasa's theoretical model of care for human-foodweb relationships. Voice interaction with the Nukabot assisted our participants with the daily maintenance of the rice bran and also generated feelings of affection and an inherent sense of obligation toward the living microbes. Additionally, our system engendered the attentiveness, feelings of accomplishment and affection in the form of social relationships. This solidified the reality of the presence and aliveness of the fermenting microbes in the nukadoko.

Fermentation is a time-consuming practice that requires repetitive, persistent care. It is this very longitudinal aspect of fermentation that generates the complex tastes and flavor of the pickled foods. We have noticed that the forms of caretaking for the fermenting microbes are also dynamically evolving as our participants' affection to their nukadokos grew over time. This observation of entangled timelines also cohere with the concept of *care time* developed by Puig de la Bellacasa, which makes humans "involved with a diversity of timelines (...) that make the web of more than human agencies"[21, p171]. How to design such care time with HCI remains a challenging research question.

Although our approach focuses on fermented food and fermenting microbes, our findings may contribute to fields of HCI related to more-than-human worlds by providing a qualitative evaluation model for how human affection toward various non-human species evolves. The originality of our method lies in evaluating post-humanistic concepts such as Puig de la Bellacasa's triptych ethopoietic model, by examining situated experiences of participants with an actual HCI design. We believe this aspect of our research also contributes to the development of critical discourse in HCI[2] and speculative design[5].

There is a wide range of fermented food that must be cared for by humans. HCI intervention aimed at such fermented foods[4, 12, 22] is able to evaluate human attachment during nurturing processes by exploiting and building upon our design strategy and analytical methodology. For example, we can apply the same measurement methods to estimate the statuses of other fermented foods such as kefir, kombucha, and miso.

7 FUTURE WORK & CONCLUSION

We proposed Nukabot, which is an intermediary system connecting humans to fermenting microbes of nukadokos. An experiment with six participants revealed how our yōkai-inspired design with voice interaction helped foster affective feelings toward the microbes. These findings may inform future HCI and ACI endeavors in terms of exploring design possibilities that introduce humans to more-than-human worlds.

Future work will explore additional interaction modalities beyond the voice interaction discussed in this paper. We will investigate more evocative approaches such as non-verbal sounds and inflatable robotics to express the inner states of nukadokos and compare their effects on human feelings and perceptions toward microbes, in more longitudinal experiments.

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