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Przydatność dwóch ras bydła mlecznego (polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej) w ekologicznym systemie produkcji na podstawie analizy jakości mleka i dobrostanu krów

Suitability of two breeds of dairy cattle (Polish Holstein-Friesian and Brown Swiss) in an organic production system based on analysis of milk quality and cows welfare

Praca doktorska
Doctoral thesis

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Oświadczenie promotora pracy

Oświadczam, że niniejsza praca została przygotowana pod moim kierunkiem i stwierdzam, że spełnia ona warunki do przedstawienia jej w postępowaniu o nadanie stopnia doktora.

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Data 23.01.2024 Podpis autora pracy Grzegorz Grodkowski

Streszczenie

Aktualnie w Unii Europejskiej obserwuje się szybki rozwój rolnictwa ekologicznego. Związane jest to z presją konsumentów, którzy oczekują produktów wysokiej jakości wytworzonych przy wykorzystaniu procesów nie stanowiących zagrożenia dla środowiska i zapewniających wysoki dobrostan zwierząt. Zwierzęta wykorzystywane w produkcji ekologicznej, z uwagi na jej specyfikę, narażone są na ciągle zmieniającą się bazę paszową oraz warunki atmosferyczne. Biorąc to pod uwagę, dobór odpowiedniej rasy jest kluczowy dla zapewnienia wysokich norm dobrostanowych przy zachowaniu zasad rolnictwa ekologicznego.

Celem niniejszej dysertacji doktorskiej było przeprowadzenie analizy behawioru krów rasy polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej za pomocą czujników ruchu 3D w celu skwantyfikowania istotnych różnic w zachowaniu, mających kluczowe znaczenie dla oceny zdolności adaptacyjnych do zrównoważonego i ekologicznego systemu produkcji.

Badania zostały zrealizowane w certyfikowanym gospodarstwie biodynamicznym Juchowo Farm zlokalizowanym w województwie zachodniopomorskim, utrzymującym bydło mleczne rasy brunatnej szwajcarskiej (BS; około 110 szt.) i polskiej holsztyńsko-fryzyjskiej (PHF; około 230 szt.). W sierpniu 2016 r. ze stada podstawowego, losowo wybrano 118 krów (64 rasy PHF oraz 54 rasy BS). Zwierzęta zostały wyposażone w czujniki ruchu 3D firmy CowManager Sensor (Agis Automatisering, BV, Harmelen, the Netherlands). Dane z systemu CowManager zawierały skumulowaną liczbę minut spędzonych przez daną krowę w danej godzinie na jednej z czterech rozpoznawanych przez czujnik czynności (przeżuwanie, pobieranie paszy, odpoczynek i aktywność fizyczna). Do bazy danych dołączono również informacje pochodzące z oceny użytkowości mlecznej prowadzonej przez PFHBiPM.

Analiza statystyczna prowadzona była w kierunku zbadania różnic behawioralnych pomiędzy obiema badanymi rasami w trzech różnych systemach żywienia, w tym pastwiskowym i zimowym. W drugim etapie zbadano możliwość wykorzystania danych behawioralnych do detekcji sztuk zdrowych oraz chorych na *mastitis*. W tym celu wykorzystano metodę regresji logistycznej oraz metodę uczenia maszynowego.

Analiza statystyczna wykazała, że krowy rasy BS produkowały więcej mleka o wyższej zawartości tłuszczu i białka w porównaniu do krów rasy PHF ($p<0{,}001$). Wykazano, że krowy rasy BS niezależnie od miejsca przebywania i rodzaju zadawanej paszy więcej czasu spędzały na pobieraniu paszy oraz mniej przeżuwały w porównaniu do rasy PHF ($p<0{,}001$). Odnotowano, że czas poświęcany na aktywność pobierania paszy w okresie żywienia zimowego oraz żywienia świeżą zielonką zadaną na stół paszowy wydłużał się w miarę postępu laktacji. W czasie żywienia pastwiskowego nie wykazano różnic między grupami laktacyjnymi.

Kluczowymi zmiennymi w procesie klasyfikacji *mastitis* przy wykorzystaniu modeli neuronowych i regresji logistycznej okazały się zmienne jakościowe, w tym grupa żywieniowa, środowisko w którym przebywały krowy, oraz zmienne ilościowe związane z czasem spędzonym przez krowy na pobieraniu paszy i aktywności fizycznej. Dokładność uzyskanych modeli wynosiła 0,7960, czułość 0,7368, specyficzność 0,7995, dla walidacji odpowiednio 0,7617, czułość 0,7608, specyficzność 0,7618.

Badania wykazały, że zarówno bydło rasy polskiej holsztyńsko-fryzyjskiej, jak i brunatnej szwajcarskiej, wykazuje zdolność adaptacyjną do ekologicznego systemu produkcji mleka. Obydwie rasy mogą być wykorzystywane w ekologicznych gospodarstwach mlecznych, co potwierdza możliwość wdrożenia zrównoważonego podejścia do hodowli i produkcji mleka.

Słowa kluczowe: ekologia, behawior, bydło brunatne szwajcarskie, bydło polskie holsztyńsko-fryzyjskie, *mastitis*, rolnictwo precyzyjne

Summary

Currently, there is a rapid development of organic farming in the European Union. This is related to pressure from consumers, who expect high-quality products produced using processes that do not pose a threat to the environment and ensure high animal welfare. Animals used in organic production, due to its nature, are exposed to a constantly changing feed base and weather conditions. Taking this into account, the selection of a suitable breed is crucial to ensure high welfare norms while maintaining the principles of organic farming.

The purpose of this dissertation was to analyze the behavior of Polish Holstein-Friesian and Brown Swiss cows using 3D motion sensors in order to quantify significant behavioral differences crucial for assessing adaptability to a sustainable and organic production system.

The research was carried out at the certified biodynamic farm Juchowo Farm located in the West Pomeranian Voivodeship, keeping Brown Swiss (BS; approximately 110 head) and Polish Holstein-Friesian (PHF; approximately 230 head) dairy cattle. In August 2016, 118 cows (64 of the HF breed and 54 of the BS breed) were randomly selected from the core herd. The animals were fitted with 3D motion sensors from CowManager Sensor (Agis Automatisering, BV, Harmelen, the Netherlands). Data from the CowManager system included the cumulative number of minutes spent by a given cow in a given hour on one of the four sensor-recognized activities (rumination, feed intake, rest and physical activity). Information from PFHBiPM dairy performance evaluation was also included in the database.

Sadistic analysis was conducted to investigate behavioral differences between the two breeds studied under three different feeding regimes including pasture and winter feeding. In the second stage, the possibility of using behavioral data to detect healthy and *mastitis*-affected animals was investigated. For this purpose, the logistic regression method and the machine learning method were used.

Statistical analysis showed that BS breed cows produced more milk with higher fat and protein content compared to PHF breed ($p<0.001$). It was shown that BS breed cows regardless of location and type of feed inflicted spent more time on feed intake and chewed less compared to PHF breed ($p<0.001$). It was shown that the time spent on feed intake activity during winter feeding and feeding fresh forage inflicted on the feed table increased as lactation progressed. No differences were shown between lactation groups during pasture feeding.

The key variables in the process of classifying *mastitis* using neural models and logistic regression proved to be qualitative variables including the feeding group, the environment in which the cows were housed, and quantitative variables related to the time spent by the cows on feed intake and physical activity. The accuracy of the obtained models was 0.7960, sensitivity 0.7368, specificity 0.7995, for validation 0.7617, sensitivity 0.7608, specificity 0.7618, respectively.

The study showed that both Polish Holstein-Friesian and Brown Swiss cattle breeds are adaptable to an organic milk production system. Both breeds can be used on organic dairy farms, confirming the possibility of implementing a sustainable approach to breeding and milk production.

Keywords: ecology, behavior, Brown Swiss, Polish Holstein-Friesian, *mastitis*, precision farming

Spis treści

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1 Wstęp

1.1 Charakterystyka rolnictwa ekologicznego

Rolnictwo ekologiczne, będące systemem produkcji żywności opartej na zrównoważonym gospodarowaniu zasobami naturalnymi, nie jest nowym paradygmatem, a jego początki sięgają XIX wieku, szczególnie w krajach niemiecko- i anglojęzycznych (Fromartz, 2007; Vogt, 2007). Nurt rolnictwa ekologicznego dążył do bardziej zrównoważonego i przyjaznego środowisku sposobu produkcji żywności. Jednym z jego głównych pionierów był Justus von Liebig (1807-1873), który zaproponował zamknięty system, oparty na recyklingu naturalnych zasobów, w tym węgla, azotu atmosferycznego oraz składników mineralnych. Na początku, koncepcja rolnictwa ekologicznego nie zdobyła znaczącej popularności, ale wraz z narastającymi obawami dotyczącymi jakości i bezpieczeństwa żywności, zaczęła zdobywać uznanie. Przełom nastąpił w latach 70. XX wieku, kiedy to wzrosło zainteresowanie tą formą uprawy roślin i hodowli zwierząt.

Obecnie zarówno w Europie, jak i na skalę globalną, rolnictwo ekologiczne przechodzi dynamiczny rozwój. W 2019 r. zarejestrowano łącznie 72,3 mln ha gruntów ekologicznych, co stanowiło 1,5% ogólnej powierzchni upraw. W Europie odsetek takich ziem w stosunku do ogólnej powierzchni upraw wynosił 3,3%. W ciągu ostatniej dekady obszar upraw ekologicznych na świecie zwiększył się o 102,4%, a w Europie o 64,8%. Podobna tendencja wykazana została w sektorze ekologicznej produkcji zwierzęcej. Należy podkreślić, że najszybciej rozwija się sektor drobiarski, ponieważ łączne pogłowie brojlerów i kur niosek w latach 2010-2019 zwiększyło się o 110%. Wśród hodowców bydła mlecznego i mięsnego również odnotowano wyraźny wzrost zainteresowania produkcją ekologiczną. Pogłowie bydła w analogicznym okresie zwiększyło się o 81% (FiBL, 2021). Tak szybki rozwój rolnictwa ekologicznego nie mógłby mieć miejsca bez opracowania przez państwa członkowskie Unii Europejskiej (UE) ukierunkowanej strategii rozwoju. Wśród programów realizowanych przez UE należy wymienić program Wspólnej Polityki Rolnej (Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2021/2115), w ramach którego zarówno rolnicy ekologiczni, jak i rolnicy będący w okresie konwersji mogą liczyć na dopłaty do produkcji. Innym projektem jasno określającym przyszły kierunek rozwoju rolnictwa UE jest Europejski Zielony Ład, który zakłada zwiększenie areału upraw w systemie ekologicznym do 25% powierzchni użytków rolnych w poszczególnych krajach i całej UE do 2030 r. (Komisja Europejska, 2020).

Tak duża akceptacja i wsparcie dla rolnictwa ekologicznego wynika z coraz bardziej ugruntowanej świadomości konsumentów o wpływie tradycyjnych metod produkcji na środowisko, zdrowie publiczne i dobrostan zwierząt. Badania wykazują, że rosnąca świadomość ekologiczna w społeczeństwie konsumenckim przyczynia się do wzrostu popytu na produkty ekologiczne oraz zrównoważoną produkcję żywności (Bartels i Onwezen, 2014; Wee i wsp., 2014). Z drugiej strony, rolnicy także dostrzegają pozytywne skutki wynikające z transformacji swoich gospodarstw z konwencjonalnej produkcji na rolnictwo ekologiczne. Decyzja taka może być podyktowana kwestiami finansowymi, gdyż produkty ekologiczne są zwykle droższe w porównaniu z produktami konwencjonalnymi, a sama produkcja wiąże się z wieloma dodatkowymi dopłatami. Inną grupą decydujących się na przejście na rolnictwo ekologiczne są rolnicy, którzy przedkładają kwestie światopoglądowe nad finansowe. Podporządkowują oni swój styl życia pod wartości jakimi kieruje się rolnictwo ekologiczne. Określani są oni jako „pionierzy ekologii", wyznaczają standardy i są prekursorami wprowadzania nowych, jeszcze bardziej zaostrzonych standardów.

Tak dynamiczny rozwój rolnictwa ekologicznego nie mógłby mieć miejsca bez szeregu norm prawnych oraz systemu kontroli i certyfikacji. Na terenie Unii Europejskiej istnieje ujednolicone prawo zawierające wszystkie najważniejsze założenia rolnictwa ekologicznego. Jest ono cyklicznie nowelizowane, a ostatnia zmiana rozporządzenia weszła w życie z dniem 1 stycznia 2022 r. Aktualnie obowiązującym aktem prawnym jest Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2018/848 z dnia 30 maja 2018 r. w sprawie produkcji ekologicznej i znakowania produktów ekologicznych (Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2018/848). Dokument precyzyjnie definiuje pojęcie produktu ekologicznego oraz określa cele i zasady produkcji ekologicznej. W ramach Unii Europejskiej, egzekwowanie przestrzegania norm rolnictwa ekologicznego leży w gestii odpowiednich instytucji krajowych. Proces nadzoru nad działalnością podmiotów prowadzących rolnictwo ekologiczne jest realizowany przez specjalistyczne przedsiębiorstwa, znane jako Jednostki Certyfikujące. Zgodnie z przepisami, każdy podmiot zajmujący się produkcją, przygotowaniem, dystrybucją, przechowywaniem, importem lub eksportem produktów oznaczonych jako ekologiczne, jest zobowiązany przynajmniej raz w roku przystąpić do kontroli. W trakcie tego procesu oceniana jest zgodność prowadzenia produkcji z wymogami określonymi w Rozporządzeniu Parlamentu Europejskiego i Rady (UE) 2018/848. Po pozytywnym przebiegu kontroli, podmiot otrzymuje certyfikat, który potwierdza, że produkty zostały wytworzone zgodnie z aktualnie obowiązującymi normami rolnictwa ekologicznego.

1.2 Ekologiczna hodowla bydła

Istotne różnice między ekologiczną hodowlą zwierząt, a hodowlą konwencjonalną obejmują ograniczenia w zakresie stosowania alopatycznych środków leczniczych, wykorzystania preparatów mlekozastępczych w odchowie cieląt, przeprowadzania procedur generujących ból. W kontekście porównania można zaobserwować rozszerzenie dostępnej przestrzeni dla zwierząt w budynkach inwentarskich w przypadku systemów ekologicznych. Ponadto, w tych systemach legowiska powinny być zaścielone odpowiednio grubą warstwą ściółki. Zwierzęta muszą mieć zapewnioną swobodę ruchu, a w sezonie letnim dostęp do pastwiska. Natomiast stosowanie systemu uwięzionego jest w dużym stopniu ograniczone. W rozporządzeniu Parlamentu Europejskiego i Rady (UE) 2018/848 znajdują się zapisy, które nakładają obowiązek zapewnienia zwierzętom wysokich norm dobrostanu, uwzględniających zaspokajanie potrzeb behawioralnych charakterystycznych dla danego gatunku. Ponadto ustawodawca zwraca uwagę na potrzebę wykorzystywania w hodowli ekologicznej ras rzadkich lub lokalnych ras zagrożonych wyginięciem. Wynika to z ogólnych celów rolnictwa ekologicznego, m.in. powiązania produkcji zwierzęcej z ziemią, poprzez wykorzystanie lokalnej bazy paszowej i krótkich łańcuchów dostaw. Przewiduje się również wydłużenie okresu użytkowania zwierząt, zwłaszcza w przypadku wykorzystania w kierunku produkcji mięsnej. Przepisy limitują minimalny wiek uboju. W związku z tym lokalne i wolno rosnące rasy są preferowane w przypadku produkcji ekologicznej, choć nie ma wyraźnego wymogu ich wykorzystywania. Wszystkie te zapisy prawne mają na celu zapewnienie odpowiednich standardów dobrostanu zwierząt oraz minimalizację wpływu produkcji zwierzęcej na środowisko, co stanowi istotny element zrównoważonego rolnictwa ekologicznego.

W kontekście ekologicznej produkcji mleka istotnym zagadnieniem jest precyzyjny dobór ras oraz właściwy kierunek selekcji, dążący do doskonalenia określonych cech hodowlanych. W świetle badań naukowych powszechnie akceptowanym poglądem jest, że lokalne rasy krów wykazują lepsze przystosowanie do specyficznych lokalnych warunków środowiskowych, co implikuje ich większą odporność w porównaniu z rasą holsztyńsko-fryzyjską (Van Diepen i wsp., 2007). Lokalne rasy krów efektywnie wykorzystują paszę o niższej jakości, wykazują odporność na pasożyty i stres cieplny, jak również rzadziej zapadają na choroby wymion. Te charakterystyczne cechy sprawiają, że doskonale wpisują się w założenia produkcji ekologicznej oraz odgrywają istotną rolę w zachowaniu bioróżnorodności (Ahlman, 2010). Jednak hodowcy ekologiczni w przeciwieństwie do gospodarstw konwencjonalnych, z uwagi na specyfikę produkcji, mają bardziej zróżnicowane cele hodowlane. Niektórzy specjalizują się w produkcji mleka w celu jego sprzedaży do mleczarni, natomiast inni przetwarzają mleko we własnym zakresie. Dla gospodarstw ekologicznych z własnym przetwórstwem bardzo ważna jest jakość mleka, na którą wpływa zawartość tłuszczu, białka, kazeiny i komórek somatycznych. Lepsza jakość cytologiczna, mikrobiologiczna oraz technologiczna mleka przekłada się na możliwość wytwarzania produktów wyższej jakości, takich jak ser, jogurt czy śmietana. Kolejnym aspektem jest ekologiczne gospodarstwo wielofunkcyjne, gdzie równie istotna jest zarówno produkcja mleka, jak i mięsa. W takich przypadkach hodowcy skupiają się na wartości opasowej cieląt oraz na jakości mięsa. Warto podkreślić, że sprzedaż lub przetwarzanie mięsa na terenie gospodarstwa stanowi integralną część tego rodzaju produkcji (Van Diepen i wsp., 2007; Nauta i wsp., 2009).

Porównując bazę paszową dostępną w systemie ekologicznym i konwencjonalnym można dojść do wniosku, że w systemach ekologicznych koncentracja energii w paszy jest znacznie niższa niż w systemach konwencjonalnych (Ertl i wsp., 2014; Orjales i wsp., 2019). Wynika to głównie z faktu ograniczonego stosowania kiszonki z kukurydzy i wykorzystywaniu w żywieniu zimowym siana, co jest zgodne z ogólnymi założeniami rolnictwa ekologicznego. Brak lub niewielki udział pasz energetycznych w dawce paszowej jest również wynikiem ich wysokich cen oraz ograniczonej dostępności tych komponentów posiadających certyfikat rolnictwa ekologicznego. Aby produkcja ekologicznego mleka była opłacalna, większość pasz musi być wytwarzana w gospodarstwie (Faux i wsp., 2022). Natomiast uprawa energetycznych roślin paszowych np. kukurydzy w warunkach ekologicznych z uwagi na wiele ograniczeń jest niezwykle trudna (Larsen i wsp., 2014).

Chów i hodowla wysokowydajnych krów w warunkach ekologicznych wiąże się z wieloma wyzwaniami, z których kluczowym aspektem jest zapewnienie wysokoenergetycznej paszy w pierwszej fazie laktacji. W związku z tym istnieje wysokie ryzyko wystąpienia ujemnego bilansu energetycznego, co z kolei prowadzi do obniżenia poziomu indeksów reprodukcyjnych (Tamminga, 2006; Chagas i wsp., 2007). Dodatkowo w gospodarstwach ekologicznych krowy są również bardziej narażone na ketozę (Abuelo i wsp., 2014).

Biorąc pod uwagę przedstawione wyżej kwestie, wybór ras najlepiej przystosowanych do produkcji ekologicznej jest przedmiotem wielu dyskusji (Bieber i wsp., 2019; Rodríguez-Bermúdez i wsp., 2019). W wyniku tych rozważań wielu hodowców decyduje się na wybór rasy holsztyńsko-fryzyjskiej (Krieger i wsp., 2017; Ivemeyer i wsp., 2018). Ta rasa cieszy się szczególną popularnością wśród gospodarstw o intensywnym charakterze, nastawionych na uzyskiwanie dochodów ze sprzedaży mleka. Natomiast właściciele gospodarstw o mniejszych nakładach oraz, hodowcy którzy decydują się na przetwórstwo mleka we własnym zakresie, wykazują preferencję wobec ras lokalnych (Nauta i wsp., 2009).

1.3 Behawior pastwiskowy krów

Jednym z kluczowych założeń rolnictwa ekologicznego dotyczących bydła jest zapewnienie zwierzętom dostępu do pastwisk. Dla bydła mlecznego pastwiska stanowią środowisko, w którym zachodzą typowe i naturalne zachowania charakterystyczne dla tego gatunku, co ma duże znaczenie dla ich dobrostanu. Zwierzęta wykazują na pastwiskach behawior stadny, obejmujący interakcje oraz hierarchię, zachowania towarzyszące zbliżeniu się i oddalaniu od innych osobników, jak również kładzenie się w różnych pozycjach oraz pobieranie zielonki pastwiskowej w sposób selektywny. Dostęp do pastwisk wpływa również pozytywnie na ich zdrowie i podnosi poziom dobrostanu (Burow i wsp., 2013). Wykazano, że bydło przebywające na pastwisku manifestuje niższą zapadalność na zapalenia wymienia (Fregonesi i Leaver, 2001; Haskell i wsp., 2006) oraz występowanie kulawizn (Olmos i wsp., 2009). Wypas pastwiskowy, mimo wielu zalet, niesie również ze sobą szereg wyzwań, w tym konieczność odpowiedniej organizacji pracy w oborze, m.in. codzienne przepędzanie bydła z obory na pastwisko. Dlatego też, zwierzętom należy zapewnić odpowiednią infrastrukturę związaną z dostarczeniem wody na pastwisko, przygotowaniem przepędów, czy przygotowaniem zadaszeń chroniących przed światłem słonecznym. Należy też regularnie kontrolować tempo odrastania oraz skład botaniczny runi pastwiskowej.

Krowy z dostępem do pastwiska istotnie zmieniają swoje zachowanie. W oborze wolnostanowiskowej rytm dobowy krów jest stabilny, łączny czas trwania czynności poświęcanych na zaspokojenie podstawowych potrzeb behawioralnych w ciągu doby waha się od 20 do 21,5 h /24 h, w tym: 5–5,5 h to pobieranie paszy, 12–14 h – odpoczynek (leżenie), 10 h – przeżuwanie, 30 min – picie wody, 1,5 h – czas spędzony w alejach przepędowych i przeznaczony na inne zachowania socjalne (Deming i wsp., 2013). Warunki panujące w oborze są zwykle regularne oraz cykliczne. Krowy otrzymują codziennie podobną pod względem składu paszę, zadawaną o tych samych porach dnia. Niewielkie zmiany w strukturze dawki Total Mixed Ration (TMR) mogą powodować nieznaczne wydłużenie lub skrócenie czasu pobierania paszy, co z reguły jest niezauważalne w ogólnym zachowaniu się krów. Sytuacja zmienia się w momencie wyjścia krów na pastwisko. Zielonka pastwiskowa jest trudniejsza do pobrania, a jej skład zmienia się w ciągu roku. Ponadto, krowy wystawione są na zmienne warunki atmosferyczne. Pomimo utrudnionego pobierania zielonki pastwiskowej i zmiennych warunków środowiskowych krowy chętnie przebywają na pastwisku. Wiele prac odnoszących się do behawioru i dobrostanu zwraca uwagę na silną motywację krów do przebywania na pastwisku, w sytuacji gdy mają możliwość wyboru pomiędzy pastwiskiem a oborą. Dokonanie takiego wyboru nie jest jednoznaczne i podlega wpływowi wielu czynników, w tym warunków atmosferycznych, fazy wegetacji roślin, pory dnia oraz wydajności mlecznej zwierząt (Legrand i wsp., 2009; Charlton i wsp., 2011a, 2011b;). Na zmianę zachowania krów przebywających na pastwisku wpływa również większa możliwość interakcji społecznych oraz inny sposób pobierania paszy. Zielonka pastwiskowa jest trudniej dostępna dla zwierząt, dlatego czynności związane z jej pobraniem zajmują zwykle więcej czasu, niż w przypadku łatwo dostępnej paszy TMR (Gomez i Cook, 2010; Pérez-Prieto i Delagarde, 2012). Przebywanie krów na pastwisku przez większą część doby może również powodować zmiany w samym cyklu okołodobowym. Bydło to zwierzęta wykazujące wzmożoną aktywność w okolicach wschodów i zachodów słońca (Rook i Huckle, 1997). Na pastwisku naturalny rytm dobowy nie jest niczym zakłócony, w przeciwieństwie do warunków oborowych, w których zapalone światła i obecność obsługi wpływa na zachowanie się zwierząt.

Biorąc pod uwagę specyfikę produkcji ekologicznej, w tym konieczność zapewnienia naturalnych zachowań krów, dobór rasy musi uwzględniać zdolność adaptacji tych zwierząt do zmiennych warunków środowiskowych.

1.4 Rolnictwo precyzyjne

W rolnictwie ekologicznym kładzie się również duży nacisk na wykorzystanie nowoczesnych rozwiązań w zakresie chowu i hodowli bydła – np. urządzenia pozwalające na ocenę ilości oraz jakości produkowanego mleka, czujniki umożliwiające monitorowanie mikroklimatu w oborze, a także sensory umożliwiające analizę zachowania krów i ich identyfikację. W ten sposób, w ramach podejścia ekologicznego, otwiera się możliwość wprowadzenia pewnych rozwiązań charakterystycznych dla rolnictwa precyzyjnego.

Dostępna jest szeroka gama urządzeń monitorujących parametry fizjologiczne i behawior krów. Pierwsza grupa to czujniki montowane na kończynach, które rejestrują ogólną aktywność fizyczną krowy, liczbę wykonanych kroków oraz w niektórych przypadkach czas spędzony w pozycji leżącej i stojącej (np. AfiTag, CowAlert, CowScout S Leg, Crysta-Heat, IceTag3D, RumiWatch). Kolejna kategoria obejmuje czujniki montowane na głowie i szyi zwierzęcia. Te urządzenia także umożliwiają monitorowanie aktywności fizycznej krowy, liczbę kroków oraz czas spędzony na leżeniu i staniu. Ponadto, czujniki te mogą śledzić charakterystyczne ruchy tych obszarów ciała podczas pobierania paszy i przeżuwania. Dzięki odpowiedniemu algorytmowi, możliwe jest także oszacowanie czasu, jaki krowa poświęca na te konkretnie aktywności. Urządzenia oferujące te funkcje to np. Alpro, CowManager SensOor, HeatBox, HR-Tag, Hi-Tag, Heatime, HeatPhone, MooMonitor, CowScout S Neck, e-stado. Ostatnią kategorią są urządzenia montowane na ogonie, w pochwie oraz na grzbiecie krowy, służące do wykrywania rui lub akcji porodowej.

W ciągu ostatniej dekady, w sektorze rolnictwa precyzyjnego, wprowadzono innowacyjne rozwiązania oparte na różnych technologiach. Powszechnie wykorzystywane są rozwiązania bazujące na technologii Radio-Frequency Identification (RFID) oraz systemy wykorzystujące akcelerometry. W ostatnich latach pojawiła się również całkowicie bezinwazyjna metoda detekcji chorób, oparta na analizie obrazu z kamer. To osiągnięcie stało się możliwe dzięki postępowi w dziedzinie sztucznej inteligencji i sieci neuronowych. Obecnie, dostępność komercyjnych rozwiązań opartych na analizie obrazu jest jeszcze ograniczona, jednakże w literaturze pojawiają się przykłady koncepcyjnych rozwiązań. Przykładem takiego podejścia jest praca Bezen i wsp. (2020), którzy wykorzystali obraz z kamer umieszczonych nad stołem paszowym do oceny ilości pozostałej paszy w kolejnych godzinach po jej podaniu. Oprócz tego, podejmowane są próby automatycznej detekcji kulawizn na podstawie obrazu z kamer (Van Hertem i wsp., 2014) oraz identyfikacji poszczególnych osobników wyłącznie na podstawie obrazu z kamer (Okura i wsp., 2019).

Wprowadzanie nowoczesnych rozwiązań w rolnictwie ekologicznym napotyka na pewne ograniczenia. Systemy wspomniane powyżej często wymagają stałego dostępu do sieci lokalnej lub Internetu. Aby przeciwdziałać temu utrudnieniu, można rozważyć instalację routerów na pastwiskach lub wykorzystanie czujników zdolnych do przechowywania pomiarów i przekazywania ich do sieci w momencie ponownego uzyskania połączenia, na przykład podczas doju. Należy podkreślić, że niektóre jednostki chorobowe mogą wpływać na zmianę behawioru krów, a zastosowanie akcelerometru umieszczonego na ciele zwierzęcia umożliwia ich detekcję. Taka technologia umożliwiała wykrywanie potencjalnie chorych zwierząt. Coraz częściej pojawiają się badania, które wskazują na potencjał wykorzystania monitoringu zachowania krów do wczesnego wykrywania *mastitis*, chorób metabolicznych oraz stresu cieplnego (Xudong i wsp., 2020; Silva i wsp., 2021). Zarówno w stadach konwencjonalnych, jak i ekologicznych, zapalenie wymienia (*mastitis*) stanowi jedno z najpowszechniejszych schorzeń u bydła. Mleko o obniżonej jakości cytologicznej oraz mikrobiologicznej negatywnie wpływa na proces przetwórczy, ze względu na zwiększoną aktywność enzymatyczną, co prowadzi do zmniejszenia wydajności masła i sera oraz niesie ryzyko powstawania fermentacji gazowej w przypadku serów długo dojrzewających. Zgodnie z doniesieniami Halasa i wsp. (2007), zapalenie wymienia prowadzi do znacznych strat ekonomicznych - średni koszt leczenia jednej krowy kształtuje się na poziomie 27-43 euro. U krów ze zdiagnozowanym *mastitis* wykazywana jest mniejsza aktywność ruchowa oraz obniżone pobranie suchej masy (Sepúlveda-Varas i wsp., 2016).

Możliwość realizacji wielu pomiarów bez konieczności ingerencji w naturalny behawior krów stanowi istotny atut w kontekście rolnictwa ekologicznego. Również zdolność do wczesnego wykrywania zwierząt w stadzie będących w początkowej fazie schorzenia jest aspektem o dużym znaczeniu. Takie podejście umożliwia szybką inicjację terapii, jeszcze przed wystąpieniem klinicznych objawów schorzenia, co z kolei eliminuje konieczność nałożenia rozciągniętego okresu karencji po przeprowadzeniu leczenia farmakologicznego, zwłaszcza w odniesieniu do antybiotykoterapii.

2 Hipotezy badawcze, cel i zakres pracy

2.1 Hipotezy

1. Behawior krów mlecznych różni się w zależności od rasy (rasa polska holsztyńsko-fryzyjska vs. brunatna szwajcarska), co ma istotny wpływ na zdolności adaptacyjne zwierząt do warunków środowiskowych.
2. Analiza behawioru krów może być wykorzystana jako element systemu wczesnego diagnozowania *mastitis.*
3. Rasy mleczne bydła, w tym polska holsztyńsko-fryzyjska i brunatna szwajcarska, mogą być utrzymywane w ekologicznym systemie produkcji, co implikuje ich zdolność adaptacji do zrównoważonego i ekologicznego systemu.

2.2 Cel i zakres prac

Celem niniejszej dysertacji doktorskiej było przeprowadzenie analizy behawioru krów rasy polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej za pomocą czujników ruchu 3D w celu skwantyfikowania istotnych różnic w zachowaniu, mających kluczowe znaczenie dla oceny zdolności adaptacyjnych do zrównoważonego i ekologicznego systemu produkcji.

Zakres prac:

1. Zastosowanie podejścia ilościowego w analizie alokacji czasowej w celu skwantyfikowania różnic w zachowaniu między krowami rasy polskiej holsztyńsko-fryzyjskiej oraz brunatnej szwajcarskiej oraz ocena, w jaki sposób alokacja wpływa na zdolności adaptacyjne do zróżnicowanych warunków środowiskowych.
2. Zbadanie i zidentyfikowanie potencjalnych różnic w zachowaniu krów mlecznych, które mogą służyć jako wskaźniki wczesnej diagnostyki *mastitis*.
   → Zidentyfikowanie i skwantyfikowanie zmian w zachowaniu krów mlecznych, które mogą wystąpić w początkowym stadium *mastitis*.
   → Wskazanie specyficznych zachowań charakterystycznych dla krów chorych na *mastitis*.
   → Stworzenie systemu monitoringu, który umożliwi hodowcom szybką i nieinwazyjną diagnozę *mastitis* na podstawie behawioru krów.
3. Zbadanie i porównanie zdolności adaptacyjnych rasy polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej do zrównoważonego i ekologicznego systemu produkcji.
   → Zdefiniowanie perspektyw i ograniczeń ekologicznej produkcji mleka.

3 Metody badawcze

3.1 Finansowanie

Badania zrealizowane w ramach dysertacji doktorskiej zostały sfinansowane ze środków Narodowego Centrum Badań i Rozwoju w ramach programu FP7 ERA-net, nr umowy: CoreOrganicPlus/2-ORG-COWS/125/IGHZ/2015 pt.: „Profilaktyka zdrowotna w stadach rodzimego bydła dwustronnie użytkowego przystosowanego do ekologicznego systemu produkcji opartego na wykorzystaniu użytków zielonych oraz innowacyjnym podejściu do realizowanej strategii hodowlanej i zapisu ocenianych cech”.

3.2 Miejsce prowadzenia badań

Badania zostały zrealizowane w certyfikowanym gospodarstwie biodynamicznym Juchowo Farm zlokalizowanym w województwie zachodniopomorskim (Rycina 1 oraz 2). W gospodarstwie utrzymywane jest bydło mleczne rasy brunatnej szwajcarskiej (BS; około 110 szt.) i polskiej holsztyńsko-fryzyjskiej (PHF; około 230 szt.) w systemie wolnostanowiskowym boksowym (dla krów będących w laktacji) oraz wolnostanowiskowym na głębokiej ściółce (dla krów zasuszonych). Średnia wydajność stada w czasie trwania badań wyniosła około 6560 kg mleka za laktację standardową, o zawartości tłuszczu 4,31% i białka 3,20%. Krowy były dojone 2-krotnie w ciągu dnia w hali udojowej typu rybia ość 2x16 firmy Happel (Mühlweg, Niemcy). Hala udojowa wyposażona była w wbudowane i certyfikowane przez ICAR urządzenia do pomiaru ilości wydojonego mleka, zainstalowane w kolektorach zbiorczych dla każdego stanowiska. Natomiast dane dotyczące zawartości tłuszczu oraz białka pochodziły z comiesięcznych badań prowadzonych w ramach oceny użytkowości mlecznej stada wykonywanych przez Polską Federację Hodowców Bydła i Producentów Mleka (PFHBiPM).

Rycina 1. Lokalizacja fermy w Juchowie. Źródło: www.google.com/maps

Rycina 2. Zabudowania farmy wraz z przyległymi pastwiskami. Źródło: www.google.com/maps

W sezonie zimowym krowom zadawano siano *ad libitum* wraz z dodatkiem paszy treściwej i suplementów witaminowo-mineralnych. W sezonie letnim (pastwiskowym), o ile tylko było to możliwe, zwierzęta korzystały z pastwiska. Natomiast czas przebywania na pastwisku uzależniony był od warunków atmosferycznych (temperatury i opadów). W przypadku korzystnych warunków atmosferycznych zwierzęta spędzały na pastwisku około 20 h w ciągu doby, schodząc do obory jedynie na czas doju, po którym otrzymywały dodatek paszy treściwej w ilości uzależnionej od fazy laktacji (od 6-8 kg na początku laktacji, 3-4 kg w środkowej fazie laktacji, 1 kg w końcowej fazie laktacji). Pasza treściwa podzielona była na dwie porcje i zadawana była po doju wieczornym i porannym. W przypadku niekorzystnych warunków atmosferycznych zwierzęta żywione były ściętą zielonką dostarczoną na stół paszowy w oborze.

3.3 Układ doświadczenia

Doświadczenie rozpoczęło się w sierpniu 2016 r. Ze stada podstawowego, losowo wybrano 118 krów (64 rasy PHF oraz 54 rasy BS). Zwierzęta zostały wyposażone w czujniki ruchu 3D firmy CowManager Sensor (Agis Automatisering BV, Harmelen, Holandia). Czujniki zainstalowano według zaleceń producenta na lewej małżowinie usznej (Rycina 3). System monitorował aktywność krów, wykorzystując pomiar przyspieszenia mierzonego przez akcelerometr (3D). Następnie, dane przekazywane były do rutera i dalej na serwery dostawcy systemu, gdzie algorytm klasyfikował dane do poszczególnych aktywności (pobieranie paszy, przeżuwanie, odpoczynek, aktywność fizyczna niska, aktywność fizyczna wysoka). W czasie, gdy zwierzęta przebywały na pastwisku, poza zasięgiem rutera, dane były zapisywane w pamięci urządzenia, a ich przesyłanie do sieci Internet następowało podczas doju na hali udojowej, gdzie znajdował się ruter.

Rycina 3. System CowManager zainstalowany w małżowinie usznej krowy (oznaczony czerwoną strzałką). Źródło: zdjęcie własne.

W fazie inicjalnej eksperymentu system CowManager był rozwiązaniem nowym, dlatego też w dostępnej literaturze nie było prac dotyczących walidacji urządzenia. W związku z powyższym, przed rozpoczęciem akwizycji danych, system poddany został kalibracji celem zbadania jego dokładności i dostosowania jego czułości do specyfiki stada. Przeprowadzono walidację urządzenia, która polegała na wykonaniu wizualnych obserwacji zachowania wybranej krowy w interwałach minutowych przez okres jednej godziny i porównywania go z danymi pochodzącymi z systemu CowManager. Po przeprowadzeniu 56 godzin obserwacji, obejmujących różne osobniki (zarówno krowy rasy polskiej holsztyńsko-fryzyjskiej, jak i brunatnej szwajcarskiej), uzyskano następujące współczynniki determinacji zgodności zapisów w ankietach i odczytów z systemu: pobieranie paszy R^2=0,86, przeżuwanie R^2=0,97, odpoczynek R^2=0,94 (Grodkowski i wsp., 2017). Przyjęto, że system w sposób dostatecznie dokładny klasyfikuje poszczególne typy zachowań krów.

Wysokość runi pastwiskowej w sezonie letnim mierzona była raz w tygodniu za pomocą urządzenia Jenquip EC10 Plate Meter (Jenquip, Feilding, New Zealand). Pomiary wykonywano metodą kopertową, co 10 m. Na każdym pastwisku każdorazowo robiono minimum 30 pomiarów, z których obliczano średnią wysokość runi na pastwisku.

Akwizycję danych zakończono w październiku 2017 r. Dane z systemu CowManager zawierały skumulowaną liczbę minut spędzonych przez daną krowę w danej godzinie na jednej z czterech rozpoznawanych przez czujnik czynności (przeżuwanie, pobieranie paszy, odpoczynek i aktywność fizyczna). W ten sposób zebrano ponad 960 tys. rekordów. Do tak utworzonej bazy danych dołączono informację o zdiagnozowanych chorobach, występowaniu rui oraz informacje pochodzące z próbnych dojów prowadzonych przez PFHBiPM.

3.4 Analiza statystyczna

Publikacja 2

Grodkowski, G., Gołębiewski, M., Slósarz, J., Sakowski, T., & Puppel, K. (2023). Comparison between the Behavior of Low-Yield Holstein-Friesian and Brown Swiss Cows under Barn and Pasture Feeding Conditions. **Animals**, 13(10),1697 **(100 pkt., IF 3,231)**.

Dane z systemu CowManager zawierały skumulowaną liczbę minut spędzonych przez daną krowę w danej godzinie, na jednej z czterech rozpoznawanych przez czujnik czynności (przeżuwanie, pobieranie paszy, odpoczynek i aktywność fizyczna). W ten sposób zebrano ponad 960 tys rekordów. Do tak utworzonej bazy danych dołączono informację o zdiagnozowanych chorobach, występowaniu rui oraz informacje pochodzące z próbnych dojów prowadzonych przez PFHBiPM. Ostateczna analiza obejmowała 181 dni żywienia zimowego, 108 dni żywienia pastwiskowego i 64 dni żywienia zielonką w oborze. Z analizy wyłączono 24 dni żywienia zielonką w oborze podczas dni deszczowych oraz 75 dni żywienia przejściowego. W celu przeprowadzenia analizy zachowania się krów w różnych fazach laktacji i systemach żywienia, dane godzinowe zostały zsumowane dla uzyskania całkowitej ilości czasu spędzonego na wykonywaniu danej czynności przez pojedyncze zwierzę w ciągu dnia (min/dzień). Natomiast dane godzinowe (min/h) zostały wykorzystane do analizy wpływu czasu doju na zachowanie krów.

Analiza statystyczna została przeprowadzona przy użyciu oprogramowania IBM SPSS 23. Do obliczeń wykorzystano ogólny model liniowy z wieloma zmiennymi.

$$y_{ijkl} = \mu + A_i + B_j + C_k + (A_i \times B_j) + (A_i \times C_k) + (B_j \times C_k) + (A_i \times B_j \times C_k) + e_{ijkl}$$

Gdzie: y_{ijkl} jest zmienną zależną, A_i jest efektem rasy (gdzie i=1 lub 2, w którym 1=PHF, 2=BS), B_j jest efektem żywienia (gdzie j=1-3, w którym 1=żywienie zimowe, 2=sezon pastwiskowy, 3=świeża zielonka pastwiskowa w oborze), C_k jest efektem fazy laktacji (gdzie k=1-3, w którym 1=początkowa faza laktacji, 2=środkowa faza laktacji, 3=końcowa faza laktacji), $(A_i \times B_j)$ to stały efekt interakcji między rasą a żywieniem, $(A_i \times C_k)$ to stały efekt interakcji między rasą a fazą laktacji, $(A_i \times B_j \times C_k)$ to stały efekt interakcji między rasą, żywieniem i fazą laktacji, a e_{ijkl} to błąd losowy.

Korelacja Spearmana została wykorzystana do oceny związku między ilością suchej masy w dawce pokarmowej a czasem spędzonym na pobraniu. Do porównania wielu zmiennych zastosowano test LSD Fishera.

Publikacja 4

Grodkowski, G., Szwaczkowski, T., Koszela, K., Mueller, W., Tomaszyk, K., Baars, T., & Sakowski, T. (2022). Early detection of mastitis in cows using the system based on 3D motions detectors. **Scientific Reports**, 1–11 **(140 pkt., IF 4,997)**.

Dane pochodzące z czujników CowManager połączono z danymi pochodzącymi z raportów weterynaryjnych dotyczącymi zdiagnozowanych zachorowań na *mastitis*. W trakcie trwania doświadczenia odnotowano 51 takich przypadków. Łącznie uwzględniono 3785 rekordów w celu zbudowania modeli predykcyjnych występowania *mastitis*.

W modelach predykcyjnych uwzględniono wpływ następujących czynników:

- stan osobnika – wartość średnia, odchylenie standardowe;
  - → spoczynek,
  - → pobranie paszy,
  - → przeżuwanie,
  - → aktywność,
  - → aktywność wysoka – zachowania rujowe i przepęd bydła (kryterium stanowiła wartość przyśpieszeń i czas ich trwania),
  - → aktywność całkowita – wyliczeniowa,
- rasę;
- grupę żywieniową;
- lokalizacje;
- pierwszą laktację;
- grupę zdrowotną;
- datę obserwacji;
- identyfikator osobnika.

Dane poddano procesowi migracji do relacyjnych struktur osadzonych na poziomie SQL Server 2017. Grupowanie przeprowadzono bazując na kolumnie identyfikator krowy i dacie. Ta dodatkowa relacja, z wykorzystaniem operacji złączenia, znacząco przyspieszała realizację zapytań, które służyły do tworzenia zbiorów wykorzystywanych w procesie budowy modeli. Proces generowania zbiorów oparty był o założenia badawcze. Dotyczyły one między innymi określenia okresu występowania *mastitis*. W systemie odnotowano tylko dzień zdiagnozowania choroby. Natomiast przy tworzeniu zbiorów przyjęto zasadę, iż okres trzydniowy przed i dwudniowy po rozpoznaniu choroby należy uznać za stan chorobowy. Rozpoznane okresy w formie unikatowych dat stanowiły jedno z istotnych kryteriów selekcji, przy tworzeniu zbiorów danych, dotyczących zarówno zwierząt chorych, jak i zdrowych. Kolejne ograniczenia przy generowaniu tych zbiorów obejmowały:

- uwzględnienie tylko danych z dni, gdy indeks temperatury i wilgotności (THI) był mniejszy od 72. Zgodnie z badaniami Armstrong (1994) oraz pracy przeglądowej Polsky i Keyserlingk (2017) za próg komfortu dla krów uznaje się THI poniżej 72;

- do zbioru danych zwierząt zdrowych zaliczono tylko osobniki, które w całym okresie badawczym nie wykazywały żadnego stanu chorobowego – krowy cierpiące na inne, towarzyszące choroby wykazują istotne zmiany w swoim zachowaniu w porównaniu do krów zdrowych już na wiele dni przed diagnozą (González i wsp., 2008; King i wsp., 2018), w związku z tym usunięto je ze zbioru.

Sieci neuronowe (ANN) oraz modele regresji logistycznej z perspektywy wykrywania *mastitis*, zrealizowano na podstawie siedmiu zbiorów danych (tabela 1). Pierwsze dwa zbiory zawierały dane dotyczące wszystkich zwierząt danej rasy, niezależnie od miejsca ich przebywania. Natomiast kolejne cztery dysjunktywne zbiory danych zawierały informacje o pojedynczych zwierzętach z dwóch różnych ras w dwóch różnych lokalizacjach (pastwisko i obora). W drugim przypadku, w procesie tworzenia zbioru związanego z lokalizacją zwaną pastwiskiem, przyjęto regułę przypisywania tylko tych zwierząt, które przebywają w tej lokalizacji przez kilka godzin dziennie lub przez 24 godziny. Ostatni analizowany zbiór zawierał dane łączone, gdzie rasa i lokalizacja zostały dodane do modeli jako czynniki. Zmienne ilościowe i jakościowe przyjęte do tworzenia modeli zostały zasygnalizowane wcześniej. W przypadku zmiennych jakościowych, takich jak grupa laktacyjna i lokalizacja, uwzględniono trzy poziomy, ale pierwsza grupa była zmienną dychotomiczną.

Tabela 1. Wygenerowane zbiory danych wraz z oznaczeniami.

Oznaczenie	**Opis**
PHF-BS*	krowy obu ras (polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej) w obu lokalizacjach
PHF*	krowy rasy polskiej holsztyńsko-fryzyjskiej przebywające we wszystkich lokalizacjach
BS*	krowy rasy brunatnej szwajcarskiej przebywające we wszystkich lokalizacjach
PHF-CO	krowy rasy polskiej holsztyńsko-fryzyjskiej utrzymywane tylko w oborze
PHF-PA*	krowy rasy polskiej holsztyńsko-fryzyjskiej przebywające zarówno na pastwisku jak i w oborze
BS-CO*	krowy rasy brunatnej szwajcarskiej utrzymywane tylko w oborze
BS-PA*	krowy rasy brunatnej szwajcarskiej przebywające zarówno na pastwisku na jak w oborze

Zbiory oznaczone * - przy budowie modeli regresji logistycznej niektóre zmienne miały postać funkcji kwadratowej

Sieci neuronowe

Tworzenie modeli neuronowych wiąże się z poszukiwaniem typu sieci adekwatnych do postawionych celów. Na tej podstawie możliwe jest przetestowanie różnych typów sieci neuronowych, takich jak: sieć liniowa, probabilistyczna sieć neuronowa (PNN), uogólniona regresyjna sieć neuronowa (GRRN), sieć MLP oraz sieci z radialnymi funkcjami bazowymi (RBF). Struktura zbiorów, które były brane pod uwagę składała się ze zmiennych wejściowych i 1 nominalnej zmiennej wyjściowej. Utworzone zbiory treningowe przeznaczone do wygenerowania modeli neuronowych zostały wykorzystane w oprogramowaniu STATISTICA. Każdy z przygotowanych zbiorów został podzielony na trzy podzbiory (zgodnie ze standardowym podziałem zaimplementowanym w pakiecie statystycznym 2:1:1):

- podzbiór treningowy wykorzystywany do trenowania sieci,
- podzbiór walidacyjny, ułatwiający kontrolę wyników działania algorytmu treningowego w trakcie procesu uczenia,

- podzbiór testowy, który pozwala na przeprowadzenie ewaluacji wygenerowanej sieci neuronowej - podzbiór testowy nie bierze udziału w generowaniu modelu klasyfikacyjnego, którym zajmują się autorzy.

Kolejnym krokiem była walidacja jakości danego modelu neuronowego, w wyniku której uzyskano odpowiednie mierniki ilościowe. Jednak ostateczną weryfikację stanowiły parametry uzyskane na zbiorze testowym. Standardową miarą poprawności klasyfikacji wygenerowanej ANN jest błąd RMS (Root Mean Square). Miara ta definiowana jest jako sumaryczny błąd popełniany przez sieć na zbiorze danych (treningowych, testowych oraz walidacyjnych). Wyliczany jest zgodnie z poniższym wzorem:

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - z_i)^2}{n}}$$

gdzie:

- n – liczba wszystkich przypadków w zbiorze uczącym,
- y_i – i-ta wartość rzeczywista,
- z_i – i-ta wartość wyznaczona z wykorzystaniem ANN.

Małe wartości błędu RMS świadczyć mogą o tym, że sieci neuronowe typu MLP w zagadnieniach klasyfikacyjnych posiadają prawidłową zdolność uogólniania wiedzy.

Regresja logistyczna

Innym alternatywnym podejściem zastosowanym w tej pracy była regresja logistyczna. Zmienna zależna, podobnie jak zmienna wyjściowa w modelach neuronowych, miała charakter dychotomiczny: 1 (krowa chora na *mastitis*) versus 0 (krowa zdrowa). Założono, że obserwujemy n niezależnych par postaci (x_i,y_i), i=1,⋯,n, gdzie x_i^'=(x_0i,x_1i,⋯x_pi) i x_0i=1, oznacza wektor p+1 ustalonych wartości zmiennej dla i-tej jednostki, a y_i=0 lub 1 oznacza, wspomnianą realizację zmiennej losowej Y_i .

$$\mathrm{logit}\, P(Y_i = 1 / \mathrm{x}_i) = \ln \frac{P(Y_i=1/\mathrm{x}_i)}{1-P(Y_i=1/\mathrm{x}_i)} = \mathrm{x}_i'\beta.$$

Lewą stronę równania nazywamy szansą wystąpienia *mastitis*. W tak przekształconym modelu szacowano logarytm szansy i zakładano, że zależy on w sposób liniowy od zmiennych objaśniających. Wektor parametrów β w modelu estymowany był metodą największej wiarygodności zgodnie z metodyką podaną przez Hosmer i wsp. (1997).

Proces doboru optymalnego zestawu zmiennych objaśniających do modelu przeprowadzono za pomocą strategii krokowej wstecznej, rozpoczynając od modelu z wszystkimi mierzonymi zmiennymi, które opisywały zachowanie krów oraz jakościowymi zmiennymi towarzyszącymi. W kolejnych krokach eliminowano nieistotne zmienne. Szczegółowy opis zastosowanej procedury opisany został przez Hosmer i Lemeshow (2000).

Weryfikacja modelu obejmowała ocenę: istotności zmiennych i grup zmiennych, dopasowania modelu do obserwowanych danych oraz jakości predykcji. Istotność zmiennych w modelu badano testem ilorazu wiarygodności (LR) wraz z przyrostową statystyką chi-kwadrat oraz testem Walda. Do oceny dopasowania modelu zastosowano statystykę odchylenia, która porównuje maksymalną wiarygodność oszacowanego modelu z maksymalną wiarygodnością modelu doskonale dopasowanego (Agresti, 1996). Przyjmuje się, że jeżeli wartość ilorazu statystyki odchylenia i liczby stopni swobody jest bliska 1 to model dobrze pasuje do danych (McCullagh i Nelder, 1989). Dokładność dopasowania modelu do danych weryfikowano testem Hosmera i Lemeshowa (1989), który porównuje rozkład liczebności oczekiwanych i obserwowanych w grupach.

Do wyboru najlepszego modelu wykorzystano również Pseudo R^2 Nagelkerka (1991) oparty na funkcji wiarygodności i opisujący poprawę przewidywań analizowanego modelu względem modelu tylko z wyrazem wolnym. Miary Pseudo R^2 są znacznie mniejsze od klasycznego współczynnika determinacji R^2 w modelach regresji, przyjmując zazwyczaj wartości rzędu 0,2 do 0,5 (Hosmer i Lemeshow, 2000). Wartość miary Pseudo R^2, podobnie jak klasyczne R^2 rośnie, jeżeli do modelu dodamy kolejne zmienne, dlatego weryfikacji stopnia dopasowania modelu dokonano też przy wykorzystaniu Bayesian Information Criteria (Schwarz, 1978).

Kolejnym etapem weryfikacji modelu była ocena modelu pod kątem jakości predykcji. Przy pomocy oszacowanego modelu przewidywano prawdopodobieństwo sukcesu, jeżeli to prawdopodobieństwo było większe od ustalonej wartości π_0, zwanej punktem odcięcia to przyjmowano, że wystąpiło *mastitis* $(\hat{y} = 1)$, w przeciwnym wypadku zdarzenie nie wystąpiło $(\hat{y} = 0)$. W modelu logistycznym jako punkt odcięcia przyjęto 0,5. Przy niskiej częstości występowania danego zdarzenia, można przyjąć mniejszą wartość π_0, na poziomie częstości obserwowanej (Cramer, 1999).

Na podstawie tak prognozowanych wartości utworzona została macierz klasyfikacji, w której podano liczbę przypadków prawidłowo zaklasyfikowanych (TP – true positive; TN – true negative), oraz błędnie zaklasyfikowanych (FP – false positve; FN – false negative).

W oparciu o tę macierz wyznaczono miary jakości klasyfikacji powszechnie używane w modelach diagnostycznych, takie jak dokładność (ACC), czułość (SE) i specyficzność (SP).

Czułość: $SE = \frac{TP}{TP+FN}$ Specyficzność: $SP = \frac{TN}{TN+FP}$

Dokładność: $ACC = \frac{TP+TN}{TP+TN+FP+FN} = \frac{TP+TN}{N}$

W oparciu o wartości SE i 1-SP konstruowano dla wszystkich możliwych punktów odcięcia krzywą ROC. Krzywą ROC wykorzystano jako narzędzie do oceny i porównywania między sobą modeli klasyfikacyjnych. Pole pod krzywą ROC, oznaczane jako AUC (area under curve), można traktować jako miarę jakości dyskryminacyjnej danego modelu. Oprócz współczynników regresji w modelu oszacowano też ilorazy szans. Wszystkie obliczenia w odniesieniu do obydwu metod wykonano w programie Statistica wersja 13.3.

4 Omówienie głównych wyników prac

Publikacja 1

Grodkowski, G., Gołębiewski, M., Slósarz, J., Grodkowska, K., Kostusiak, P., Sakowski, T., & Puppel, K. (2023). Organic Milk Production and Dairy Farming Constraints and Prospects under the Laws of the European Union. **Animals**, *3*, 1–20 **(100 pkt., IF 3,231)**.

W czasie trwania badań realizowanych w ramach dysertacji doktorskiej zmianie uległo prawodawstwo dotyczące rolnictwa ekologicznego obowiązujące na terenie Unii Europejskiej. Rozporządzenie Rady (WE) nr 834/2007 z dnia 28 czerwca 2007 r. w sprawie produkcji ekologicznej i znakowania produktów ekologicznych i uchylające rozporządzenie (EWG) nr 2092/91 (Rozporządzenie Rady (WE) nr 834/2007) zostało zastąpione przez Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2018/848 z dnia 30 maja 2018 r. w sprawie produkcji ekologicznej i znakowania produktów ekologicznych i uchylające rozporządzenie Rady (WE) nr 834/2007 (Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2018/848).

Tabela 2. Główne wymogi prawne dla utrzymywania krów mlecznych w systemie ekologicznym na terenie UE (opracowanie własne).

	Ograniczenia i dopuszczenia w rolnictwie ekologicznym	**Akt prawny**
Dobór ras	Preferowane rasy lokalne	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.3.2, d
		Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.3.3
Dobrostan	Konieczność zapewnienia potrzeb behawioralnych zwierząt oraz wysokiego dobrostanu	Rozporządzenie (EU) 2018/848, punkt 44
Stosowanie inseminacji	Dozwolone	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.3.2
Stymulacja owulacji	Dozwolone w indywidualnych przypadkach	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.3.2, b
Programy MOET	Zabronione	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.3.2, c
Klonowanie	Zabronione	Rozporządzenie (EU) 2018/848, punkt 23
Utrzymanie na uwięzi	Dozwolone w indywidualnych przypadkach po uzyskaniu pozwolenia (możliwe w gospodarstwach utrzymujących nie więcej niż 50 sztuk bydła)	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.7.5
Dostęp do pastwisk	Wymagany	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.7.3
		Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.9.1.1, e
Utrzymanie bezściołowe	Zabronione	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.9.1.2, b
Dawka paszowa	Co najmniej 60 % suchej masy dziennej dawki pokarmowej musi stanowić pasza objętościowa, świeża zielonka, susz paszowy lub kiszonka	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.9.1.1, f
Pasze GMO	Zabronione	Rozporządzenie (EU) 2018/848, Artykuł. 11, punkt 1
Dekornizacja	Dozwolona w uzasadnionych przypadkach	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.7.8

Kastracja	Kastracja fizyczna jest dozwolona w celu zachowania jakości produktów i tradycyjnych praktyk produkcyjnych	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.7.10
	Wymagane stosowanie znieczulenia podczas zabiegu kastracji	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.7.9
Preparaty mlekozastępcze	Zabronione	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.4.1, g
	Minimalny okres żywienia mlekiem, najlepiej mlekiem matki, wynosi 90 dni	Rozporządzenie Wykonawcze Komisji (EU) 2020/464 Rozdział II, Sekcja. 1, Artykuł 2, a
Użycie antybiotyków	Profilaktyczne stosowanie antybiotyków jest zabronione	Rozporządzenie (EU) 2018/848, punkt 43
		Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.5.1.3
	Leczenie antybiotykami dozwolone, gdy jest to konieczne w leczeniu jednostek chorobowych	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.5.2.2
	Okres karencji w przypadku stosowania antybiotyku jest dwukrotnie dłuższy niż określono w art. 11 dyrektywy 2001/82/WE	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.5.2.5
	Zabrania się stosowania więcej niż trzech kuracji antybiotykowych u jednego zwierzęcia w ciągu 12 miesięcy	Rozporządzenie (EU) 2018/848, Załącznik II Część II punkt 1.5.2.4.

W związku z powyższym, w publikacji „Organic milk production and dairy farming-constraints and prospects under the laws of the European Union" przeprowadzono syntetyczne podsumowanie norm regulujących rolnictwo ekologiczne w kontekście prawodawstwa Unii Europejskiej (tabela 2), ze szczególnym naciskiem na produkcję mleka i hodowlę bydła. Ponadto skoncentrowano się na analizie kluczowych aspektów produkcji ekologicznej, a także przeprowadzono kompleksowe porównanie rozwiązań systemowych charakteryzujących rolnictwo ekologiczne z kanonami praktyk prezentowanymi przez gospodarstwa konwencjonalne.

Publikacja 2

Grodkowski, G., Gołębiewski, M., Slósarz, J., Sakowski, T., & Puppel, K. (2023). Comparison between the Behavior of Low-Yield Holstein-Friesian and Brown Swiss Cows under Barn and Pasture Feeding Conditions. **Animals**, 13(10),1697 **(100 pkt., IF 3,231)**.

Celem pracy było zbadanie różnic w zachowaniu krów rasy polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej w warunkach produkcji ekologicznej. Analiza alokacji czasu przez krowy na różne aktywności stanowi kluczowy obszar badawczy, podlegający wpływowi wielu zmiennych, w tym m.in. czasu doju, częstotliwości oraz momentu karmienia (King i wsp., 2016), a także stopnia rozdrobnienia dostarczanej paszy (Schwab i wsp., 2002; Beauchemin i Yang, 2005). W badaniach własnych skupiono się na szczegółowej alokacji czasowej krów, analizując dystrybucję czasu w zależności od lokalizacji (pastwisko vs. obora), fazy laktacji oraz przynależności do określonej rasy. Należy podkreślić, że motywacja krów do pobierania paszy z pastwiska jest bardzo silna, a skrócenie czasu dostępu powoduje zwiększenie intensywności pobierania paszy i skrócenie czasu przeznaczonego na inne czynności, takie jak odpoczynek i przeżuwanie (Soca i wsp., 2014). Ponadto, skupiono się na analizie behawioru bez ograniczeń w dostępie do pastwiska - krowy przebywały na pastwisku około 20 h dziennie. Przeprowadzone analizy umożliwiły precyzyjną ocenę alokacji czasu dokonywanej przez krowy w kontekście przebywania na pastwisku oraz w oborze wykazane zostały istotne wzorce zachowań, które wyróżniają te dwa odmienne systemy żywienia.

Tabela 3. Średnie wartości produkcyjne i behawioralne krów rasy polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej w różnych warunkach żywieniowych

		PHF			BS			*p*-value		
	LSM /SEM	**Zima**	**Pastwisko**	**Świeża zielonka zadana w oborze**	**Zima**	**Pastwisko**	**Świeża zielonka zadana w oborze**	**Rasa**	**Żywienie**	**Interakcja ($A_i \times B_j$)**
Mleko (kg)	LSM	12,1 ^{AB}	18,3 ^{A}	17,9 ^{B}	15,3 ^{AB}	19,8 ^{A}	18,7 ^{B}	<0,001	<0,001	0,143
	SEM	0,53	0,59	0,80	0,59	0,73	0,95			
Tłuszcz (%)	LSM	4,2 ^{Ab}	3,65 ^{A}	3,81 ^{b}	4,54 ^{AB}	3,93 ^{A}	3,95 ^{B}	<0,001	<0,001	0,140
	SEM	0,05	0,06	0,08	0,06	0,07	0,09			
Białko (%)	LSM	3,48 ^{ab}	3,1 ^{a}	3,1 ^{b}	3,8^{AB}	3,34 ^{Ac}	3,46 ^{Bc}	<0,001	<0,001	0,337
	SEM	0,03	0,03	0,05	0,03	0,04	0,05			
Przeżuwanie (min/dzień)	LSM	507 ^{AB}	475 ^{AC}	551 ^{BC}	459 ^{AB}	436 ^{AC}	482 ^{BC}	0,000	0,000	<0,001
	SEM	0,89	0,98	1,25	1,03	1,20	1,52			
Pobieranie paszy (min/dzień)	LSM	343 ^{Ab}	461 ^{AC}	350 ^{bC}	350 ^{AB}	499 ^{AC}	372 ^{BC}	<0,001	0,000	<0,001
	SEM	1,05	1,16	1,48	1,22	1,42	1,80			
Brak aktywności (min/dzień)	LSM	403 ^{AB}	278 ^{AC}	360 ^{BC}	418 ^{AB}	293 ^{AC}	380 ^{BC}	<0,001	0,000	0,179
	SEM	0,98	1,08	1,38	1,14	1,33	1,68			
Aktywność fizyczna (min/dzień)	LSM	192 ^{AB}	231 ^{AC}	213 ^{BC}	218 ^{a}	216 ^{b}	210 ^{ab}	<0,001	0,000	<0,001
	SEM	0,77	0,85	1,09	0,89	1,04	1,31			

PHF – polska holsztyńsko-fryzyjska, BS – brunatna szwajcarska, LSM – średnia najmniejszych kwadratów, SEM – błąd standardowy średniej, interakcja ($A_i \times B_j$) – stały wpływ interakcji między rasą a sposobem żywienia. Średnie (dla rasy bydła w wierszu) oznaczone tymi samymi literami różnią się istotnie na poziomie: aa, $p \leq 0{,}05$; AA, $p \leq 0{,}01$.

Analiza statystyczna wykazała istotne różnice ($p < 0{,}001$) między badanymi rasami. Rasa BS charakteryzowała się zarówno wyższą wydajnością, jak i zawartością tłuszczu i białka w porównaniu do rasy PHF. Podobne wyniki uzyskali Horn i wsp. (2013) oraz De Haas i wsp. (2013) wykazując, że krowy rasy BS produkowały mleko o wyższej zawartości tłuszczu i białka w porównaniu z rasą HF. Analiza wpływu sezonu na kształtowanie się parametrów użytkowych wykazała istotne różnice. W sezonie zimowym krowy charakteryzowały się niższymi wydajnościami, jednakże ich mleko wyróżniała wyższa zawartość tłuszczu i białka w porównaniu do sezonu letniego. Podobne wyniki uzyskali Hanu i wsp. (2014) oraz Bar i wsp. (2020), którzy również zaobserwowali obniżenie zawartości białka, tłuszczu i kazeiny w okresie żywienia letniego. Analiza interakcji sezonu żywienia i rasy nie wykazała istotnych różnic.

Przeprowadzone badania wykazały istotne statystycznie różnice w zachowaniu krów przebywających na pastwisku oraz w oborze (tabela 3). Średni czas pobierania zielonki pastwiskowej wynosił 460 minut dziennie. Natomiast krowy spędzały średnio 346 minut dziennie na pobieraniu siana oraz 360 minut dziennie na pobieraniu świeżo ściętej zielonki pastwiskowej, dostarczanej na stół paszowy. Znacząca dysproporcja między tymi dwiema grupami jest efektem różnic w dostępności pożywienia oraz mechanicznych aspektach pobierania paszy. Krowy na pastwisku owijają językiem kępy trawy, a w miarę skracania jej długości proces ten staje się bardziej wymagający, co przekłada się na wydłużenie czasu pobierania zielonki pastwiskowej (Pérez-Prieto i wsp., 2011). Ważne jest jednak podkreślenie, że zachowanie krów w oborze podlega także wpływowi interakcji z pracownikami oraz fluktuacji cyklu świetlnego. Pobudzający efekt sztucznego oświetlenia stymuluje krowy do aktywności w rejonie stołu paszowego (McCarthy i wsp., 2007; Soca i wsp., 2014). Te zróżnicowane czynniki składają się na kształtowanie behawioru krów, zarówno w kontekście dostępu do pożywienia, jak i w reakcji na manipulacje oświetleniowe, w sposób złożony i wielowymiarowy.

Podczas analizy behawioru bydła badanych ras tj. – polskiej holsztyńsko-fryzyjskiej oraz brunatnej szwajcarskiej, – wykazano statystycznie istotne różnice w ich zachowaniu, które były determinowane przez interakcję genotypu i środowiska. Przeprowadzona analiza statystyczna wykazała, że różnice behawioralne między krowami rasy PHF i BS we wszystkich okresach żywienia były statystycznie istotne ($p < 0,001$). Niezależnie od pory karmienia, krowy rasy PHF spędzały więcej czasu na przeżuwaniu, w porównaniu do krów rasy BS. Natomiast rasa BS spędzała więcej czasu na pobieraniu paszy, w porównaniu do krów rasy PHF. Czynności związane z aktywnością fizyczną i brakiem aktywności dla obu ras były również statystycznie istotne. Badania wykazały, że podczas żywienia pastwiskowego krowy rasy PHF wykazywały większą aktywność w porównaniu do krów rasy BS. Odwrotna zależność wykazana została podczas żywienia zimowego, gdzie wyższa aktywność lokomotoryczna wykazana została u krów rasy BS. Dostępna literatura naukowa prezentuje ograniczoną liczbę doniesień dotyczących behawioru tych ras w systemie ekologicznym/ekstensywnym. Braun i wsp. (2013) wykazał, że czas pobierania paszy przez BS wynosił średnio 445 min/dzień, podczas gdy czas przeżuwania 388 min/dzień. Wartości te wykazują pewną rozbieżność w porównaniu z wynikami badań własnych, w których średni czas pobierania paszy i przeżuwania w okresie zimowym wynosiły odpowiednio 366 min/dzień oraz 462 min/dzień dla rasy BS. Różnica ta może być związana z wyższą wydajnością krów w eksperymencie przeprowadzonym przez Brauna i wsp. (2013, 2015), gdzie wyższa wydajność u krów skorelowana była ze zwiększonym pobraniem suchej masy. Z powyższej analizy wynika, że obserwowane różnice w zachowaniu krów rasy BS stanowią rezultat interakcji między ich wydajnością a poziomem pobrania suchej paszy.

W analizie alokacji czasu u krów w różnych fazach laktacji, wykazano istotne różnice, uwzględniające zarówno wpływ czynnika rasowego, jak i sezonu żywienia ($p < 0,001$). Wykazano, że czas poświęcany na aktywność pobierania paszy w okresie żywienia zimowego wykazywał istotny wzrost w miarę postępu laktacji. W szczególności, krowy znajdujące się w zaawansowanej fazie laktacji zarówno w przypadku rasy brunatnej szwajcarskiej, jak i polskiej holsztyńsko-fryzyjskiej, przeznaczały średnio o 19 minut więcej czasu na pobieranie paszy, w porównaniu do krów w początkowej fazie laktacji. Analogiczne zależności zaobserwowano podczas żywienia krów świeżą runią pastwiskową w oborze. Czas spędzony na pobieraniu paszy wykazał istotny wzrost wraz z postępem fazy laktacji, a krowy w końcowej fazie laktacji spędzały średnio 21 minut więcej przy stole paszowym, w porównaniu do krów w początkowej fazie laktacji. Ponadto, nie wykazano istotnych statystycznie różnic w czasie spędzonym na pobieraniu paszy między badanymi grupami krów podczas żywienia pastwiskowego. Obserwowane wydłużenie czasu pobrania paszy wraz z postępem laktacji kontrastuje z wynikami uzyskanymi przez Løvendahl i Munksgaard (2016), którzy odnotowali najdłuższy czas pobierania paszy przez zwierzęta w początkowej fazie laktacji. Należy jednak podkreślić, że krowy w cytowanym badaniu osiągnęły wydajność wynoszącą ponad 30 kg/dzień, a w prezentowanym doświadczeniu 16 kg/dzień - co implikowało niższe zapotrzebowanie energetyczne, nawet we wczesnej fazie laktacji.

Publikacja 3

Grodkowski, G., Sakowski, T., Puppel, K., & Baars, A. (2018). Comparison of different applications of automatic herd control systems on dairy farms – a review. **Journal of the Science of Food and Agriculture**, *98,* 5181–5188 **(35 pkt., IF 2,463)**.

Głównym celem niniejszego opracowania było zgromadzenie informacji dotyczących potencjału wynikającego z wdrożenia nowoczesnych systemów monitorowania w czasie rzeczywistym stad bydła mlecznego. W ramach analizy dokonano szczegółowej oceny różnych rodzajów urządzeń, metod ich instalacji oraz oceny ich użyteczności w kontekście hodowli zwierząt. Ponadto podjęto próbę określenia perspektyw wykorzystania tych systemów w szybkiej diagnostyce schorzeń.

Powszechnie wiadomo, że w czasie rui behawior krów istotnie się zmienia. Kiddy (1977) wykazał, że liczba kroków wykonywanych na godzinę przez krowę w rui jest około 2 do 4 razy większa, niż w przypadku krów nie będących w rui. Jak donosi Sakatani i wsp. (2012), zimą wzrost aktywności fizycznej krów w rui wyniósł 400%, a latem tylko 175%. Było to spowodowane stresem cieplnym, który może mieć wpływ nie tylko na zmniejszenie widocznych oznak, ale może również skutkować przesunięciem cyklu jajnikowego. Czynność chodu krowy można mierzyć za pomocą krokomierza, urządzenia elektronicznego przyczepianego do nogi zwierzęcia lub innej części ciała, lub innego akcelerometru, który mierzy przyspieszenie i wykorzystuje algorytmy do obliczania aktywności fizycznej krowy i pozwala oszacować najlepszy czas na inseminację. Krokomierze oparte na naturalnym zachowaniu zwierząt nie mogą być stosowane we wszystkich systemach utrzymania zwierząt. Roth (1987) wykazał, że aktywność krów wzrosła o 93% w okresie rui, gdy krowy były trzymane w oborach wolnostanowiskowych. Jednak znacznie mniejszy wzrost aktywności, rzędu 14-20%, zaobserwowano w oborach uwięziowych. Dlatego pełny potencjał krokomierzy można osiągnąć tylko poprzez wykorzystanie obór wolnostanowiskowych jako środowiska pomiarowego. Innymi zmianami behawioralnymi mającymi miejsce w czasie rui jest zmniejszenie czasu przeżuwania około 14-24%. Ta cecha również może być mierzona za pomocą akcelerometrów instalowanych na szyi lub w małżowinie usznej i być wykorzystana w algorytmach wykrywania zachowań rujowych. Dokładności uzyskiwane przez różne systemy przeznaczone do wykrywania rui przedstawiono w tabeli 4.

Tabela 4. Porównanie skuteczności detekcji rui przy użyciu różnych urządzeń elektronicznych (opracowanie własne).

Źródło	**Nazwa systemu**	**Typ mierzonego zachowania**	**Miejsce montażu czujnika**	**SE**	**SP**	**Dokładność detekcji**
Brunassi i wsp. (2010)	S.A.E Afikim	Aktywność fizyczna, Odpoczynek	Noga	84	98	88,1
Cavalieri i wsp. (2003)	Heat-Seeker®TX, Bou-matic	Ruja	Zad	81,4	-	-
Cavalieri i wsp. (2003)	Tail Mark	Ruja	Ogon	91,3	-	-
Cavalieri i wsp. (2003)	Heatwatch, DDX Inc., Denver, CO	Ruja	Zad	85,7	-	-
Dolecheck i wsp. (2015)	Track a Cow	Aktywność fizyczna,	Noga	100	91	91
Dolecheck i wsp. (2015)	CowManager SensOor	Aktywność, fizyczna, Odpoczynek, Pobieranie paszy, Przeżuwanie	Małżowina uszna	100	99	99
Dolecheck i wsp. (2015)	HRTag	Przeżuwanie, Aktywność fizyczna	Szyja	100	96	97
Dolecheck i wsp. (2015)	IceQube	Aktywność fizyczna	Noga	100	100	100
Hockey i wsp. (2010)	Nedap Agri B.V., Groenlo,	Aktywność fizyczna	Noga	79,4-94,1	90-98,2	-
Kamphuis i wsp. (2012)	AR collars	Aktywność fizyczna, Przeżuwanie	Szyja	76,9	99,4	82
Kamphuis i wsp. (2012)	AO collars	Aktywność fizyczna	Szyja	62	99	77

SE – czułość, SP – specyficzność

W celu identyfikacji kulawizny, w ramach oceny lokomocji bydła, wykorzystuje się mierzalne cechy chodu oraz zmiany behawioru krów. Walker i wsp. (2008) wykazali, że krowy dotknięte kulawizną wykazują wydłużony czas przebywania w pozycji leżącej, ograniczoną aktywność ruchową oraz zmiany w zachowaniu w okresie rui. Kulawizna prowadzi do większej asymetrii między kończynami w kontekście szerokości, długości kroku, czasu trwania kroku oraz czasu podparcia, w porównaniu z krowami zdrowymi (Maertens i wsp., 2011). Natomiast Flower i wsp. (2005) wykazali, że zdrowe krowy wykazują wyższą prędkość chodu (1,11 ± 0,03 vs. 0,90 ± 0,05 m/s, średnia ± SEM), krótszy czas trwania kroku (1,26 ± 0,03 vs. 1,48 ± 0,05 s) oraz dłuższe kroki (139,5 ± 2,1 vs. 130,0 ± 3,2 cm) w porównaniu z krowami z owrzodzeniami podeszwy. Dodatkowo, zaobserwowano, że krowy z oceną lokomocji na poziomie 4 lub 5 wykazują ograniczoną aktywność w trakcie karmienia oraz niższe spożycie paszy w porównaniu z krowami o ocenie lokomocji 1. Wczesna identyfikacja kulawizny, również przed przeglądem weterynaryjnym, stanowi kluczowy aspekt skutecznego leczenia oraz minimalizacji strat finansowych.

Efektywna detekcja kulawizny u krów stanowi kompleksowe wyzwanie, jednak na współczesnym rynku istnieją dostępne rozwiązania techniczne umożliwiające osiągnięcie tego celu. Badania przeprowadzone przez Alsaaoda i wsp. (2012) wykazują, że zastosowanie pomiarów krokomierza ALT w połączeniu z zaawansowanymi algorytmami uczenia maszynowego stanowi obiecującą strategię w kontekście detekcji kulawizny u krów – model osiągnął poziom trafności detekcji wynoszący 76%. Dodatkowo wnioski płynące z badań przeprowadzonych przez Van Hertem i wsp. (2013) wskazują, że czujniki umieszczone na szyi mogą być również wykorzystywane do wykrywania kulawizny. Zespół badawczy opracował i zweryfikował model matematyczny do wykrywania kulawizny klinicznej w oparciu o istniejące dane z czujników, które były powiązane z zachowaniem i wydajnością krów w komercyjnej farmie mlecznej. Model regresji logistycznej wykazał czułość 0,89 i specyficzność 0,85.

Monitorowanie zachowań okołożywieniowych bydła to ważne narzędzie w ocenie zdrowotności stada. Skrócenie czasu przeżuwania u krów może sygnalizować zbliżający się okres wycielenia (Schirmann i wsp., 2013), stres cieplny lub zaburzenia metaboliczne (Soriani i wsp., 2013). Jednak samo monitorowanie czasu przeżuwania nie wystarcza do postawienia pełnej diagnozy. Sterrett i wsp. (2014) wykorzystali dane dotyczące przeżuwania, leżenia, aktywności ruchowej oraz temperatury ciała do identyfikacji subklinicznej hipokalcemii i ketozy. Natomiast Soriani i wsp. (2012) wykazali, że krótki czas przeżuwania przed wycieleniem skutkuje większą podatnością na choroby po wycieleniu. Ponadto, Steensels i wsp. (2017) potwierdzili, że informacje o przeżuwaniu, aktywności fizycznej i wydajności mlecznej pozwalają na wczesną diagnostykę ketozy z precyzją 76% i czułością 90%.

Publikacja 4

Grodkowski, G., Szwaczkowski, T., Koszela, K., Mueller, W., Tomaszyk, K., Baars, T., & Sakowski, T. (2022). Early detection of mastitis in cows using the system based on 3D motions detectors. **Scientific Reports**, 1–11 **(140 pkt., IF 4,997)**.

Sieci neuronowe

Zarówno budowa modeli neuronowych, jak i estymacja parametrów modeli regresji logistycznej przebiegała według zasady od ogółu do szczegółu. Oznacza to, iż przy tworzeniu obu rodzajów modeli w pierwszej kolejności przyjęto dane pochodzące z najliczniejszego zbioru PHF-BS. Dla głównego zbioru danych PHF-BS optymalną siecią okazała się topologia neuronowa typu MLP: 16-12-1 (MultiLayer Perceptron) posiadająca 16 neuronów w warstwie wejściowej, 12 neuronów w warstwie ukrytej oraz 1 neuron w warstwie wyjściowej.

Wartości poszczególnych błędów uzyskanych dla tego modelu: uczenia, walidacji, testowania oraz odpowiadające im parametry jakości w połączeniu z wskaźnikiem AUC przedstawiono w tabeli 5.

Tabela 5. Zestawienie wytworzonych modeli neuronowych, wartości błędów, jakości i AUC dla poszczególnych zbiorów.

Zbiór danych	Model	Błąd uczczenia	Błąd walidacji	Błąd testowania	Jakość uczenia	Jakość walidacji	Jakość testowania	Wskaźnik AUC
PHF-BS/3735	MLP 16:12:1	0,17991	0,20510	0,20439	0,76981	0,77623	0,78778	0,8433
PHF/1989	MLP 15:19:9:1	0,19748	0,22938	0,22105	0,80100	0,81489	0,80080	0,8593
BS/1746	MLP 15:12:8:1	0,16327	0,17153	0,16704	0,75945	0,81693	0,81651	0,8255
PHF-CO/1224	MLP 14:9:6:1	0,23445	0,23097	0,26526	0,75817	0,75163	0,78758	0,8645
PHF-PA/765	MLP 14:4:1	0,17351	0,20270	0,20257	0,79634	0,78010	0,76440	0,8793
BS-CO/1032	MLP 14:5:1	0,14431	0,10568	0,14961	0,7539	0,73643	0,79070	0,8012
BS-PA/714	MLP 14:4:1	0,11687	0,22309	0,14989	0,76750	0,79330	0,79213	0,8569

Małe oraz zbliżone wartości błędów RMS dla zbiorów treningowego, walidacyjnego oraz testowego świadczą o dobrych właściwościach generalizacyjnych wytworzonych ANN, a to oznacza dobre zdolności klasyfikacyjne.

Kluczowymi zmiennymi w procesie klasyfikacji *mastitis* przy wykorzystaniu modeli neuronowych dotyczących zbiorów PHF-BS, PHF, BS (obejmujące osobniki obu ras oraz zwierzęta przynależne do jednej z ras) były zmienne jakościowe, m.in. grupa żywieniowa oraz lokalizacja. Równie istotne były zmienne ilościowe pochodzące z systemu wykorzystujące czujniki ruchu 3D, estymatory związane ze stanem jedzenia oraz z jedną z form aktywności odrębną dla jednego modelu BS.

Regresja logistyczna

Analiza przeprowadzona na zbiorze danych obejmującym zmienne ciągłe pochodzące z systemu czujników ruchu 3D w kontekście zachorowania na *mastitis* w populacji krów prowadzi do kilku istotnych wniosków. Wyniki wskazują na istotny wpływ aktywności ruchowej na prawdopodobieństwo zachorowania na *mastitis*. W szczególności, zmienna reprezentująca czas aktywności związany z pobieraniem paszy wykazała istotność w prawie wszystkich analizowanych modelach. Niemniej jednak kierunek tego wpływu nie jest jednoznaczny i może różnić się między modelami. Obserwowane sprzeczności w kierunku wpływu aktywności ruchowej oraz długości braku aktywności mogą wynikać ze złożonej interakcji między badanymi zmiennymi. Wieloczynnikowy charakter tego zjawiska skutkuje trudnościami w sformułowaniu ogólnych wniosków dotyczących wpływu analizowanych zmiennych na *mastitis*. Warto zauważyć, że oddziaływanie to może być specyficzne dla poszczególnych modeli.

Spośród zmiennych jakościowych zmienną w sposób istotny wpływającą na szansę zachorowania na *mastitis* okazała się zmienna „grupa żywieniowa”. We wszystkich analizowanych modelach ,z wyjątkiem opartego na zbiorze BS-PA, krowy z grupy 3 (końcowa faza laktacji) miały wyższą szansę na zachorowanie, niż krowy z grupy 1 (grupa 1 była tu poziomem odniesienia). Dla modelu BS-PA odnotowano odwrotną zależność; szansa na zachorowanie malała (-3,423). Wpływ grupy żywieniowej 2 na *mastitis* był mniej jednoznaczny z perspektywy analizowanych modeli. Z kolei czynnik „pierwsza laktacja" miał istotny wpływ w połączeniu z innymi zmiennymi na prawdopodobieństwo zachorowania. Na podstawie danych w tabeli 6 można zauważyć, że zmienna „pierwsza laktacja", jako wpływająca istotnie na zmienne zależne, została włączona tylko do modeli odnoszących się do krów rasy PHF i miała różny kierunek wpływu.

Tabela 6. Wyniki szacowania parametrów regresji logistycznej.

Współczynniki regresji	PHF-BS	PHF	BS	PHF-CO	PHF-PA	BS-CO	BS-PA
Akty śr	-0,200**	-0,295**					
Akty śr^2			-0,052**				0,312**
Akty_w śr	-0,443**		-1,667**			-1,093**	3,542**
Akty_w śr^2		-0,037**					
Jedze śr	-0,496**	-0,790**	-1,029**		-0,579**	-0,281**	2,996**
Jedze śr^2	0,009**	0,018**			0,015**		
Przez śr				0,362**			2,499*
Spocz śr			-1,224**	0,385**		-0,81**	2,755**
Spocz śr^2			0,012**			0,016*	
Grupa ż_2	0,179	-1,742**	2,384**	-1,304	-19,967	2.625*	-2,335**
Grupa ż_3	2,137**	1,597**	3,769**	1,572**	1,455**	4,308**	-3,423**
Pierw_1	0,432*	0,393**		1,299**	-0,994*		
Lokaliz_1	-0,946**	-0,458*	-1,133**	-	-	-	-
Lokaliz_2	0,238	0,167		-	-	-	-
Rasa_1		-	-	-	-	-	-
Wyraz wolny	4,613**	6,576**	40,524**	-17,9213**	2,165	10,731**	-157**

* oznacza istotność na poziomie 0,05; **oznaczają istotność na poziomie 0,01

Tabela 7. Klasyfikacja przypadków dla zbioru PHF-BS.

	Próba ucząca			V-krotna walidacja krzyżowa		
	Sklasyfikowane chore	Sklasyfikowane zdrowe	Procent poprawnych	Sklasyfikowane chore	Sklasyfikowane zdrowe	Procent poprawnych
Obserwowane chore	154	55	74	159	50	76
Obserwowane zdrowe	707	2819	80	840	2686	76

Tabela 7 przedstawia efekty klasyfikacji z regresją logistyczną i punktem odcięcia π_0 = 0,079, określone za pomocą wskaźnika Judena dla testu próbnego dla zestawu HF-BF i walidacji w tym samym zbiorze danych (π_0 = 0,067). Dokładność w tym modelu przy tak określonych punktach odcięcia wynosiła ACC = 0,7960, SE = 0,7368, SP = 0,7995, dla walidacji odpowiednio ACC = 0,7617, SE = 0,7608, SP =0,7618.

Reasumując, zaprezentowane modele neuronowe i regresji logistycznej wykazały podobną zdolność klasyfikacyjną zwierząt zdrowych i z zapaleniem wymion, zbudowanych na podstawie przetworzonych danych płynących z systemu informatycznego współpracującego z czujnikami ruchu 3D oraz wzbogaconych zmiennymi jakościowymi. Informują nas o tym zbliżone wartości współczynnika AUC, będącego wspólnym wskaźnikiem jakości klasyfikacji dla obu rodzajów modeli. Należy nadmienić, że dla wszystkich modeli wykazany został zbliżony charakter krzywej ROC.

W obu podejściach odnotowano istotny wpływ tych samych zmiennych jakościowych: grupy żywienia oraz lokalizacji. Wykazano niejednakowy wpływ rasy na rozpoznawanie *mastitis*. Ta zmienna była istotna dla modelu neuronowego, natomiast nie pojawiła się w regresji logistycznej. Podstawą budowy obu modeli był zbiór PHF-BS.

W przypadku istotnych zmiennych ciągłych, opisujących aktywność zwierzęcia trudno w obu wariantach dla wszystkich modeli doszukać się prawidłowości, co jest wynikiem stwierdzonej korelacji. W modelach neuronowych i regresji logistycznej wykazany został istotny wpływ czasu poboru paszy na rozpoznanie *mastitis*. Pozostałe zmienne ciągłe, istotne z perspektywy powstałych modeli neuronowych charakteryzowały się losowym rankingiem. Natomiast w regresji logistycznej nie stwierdzono jednoczesnego wpływu wszystkich zmiennych ciągłych. Ich zbiory istotne dla poszczególnych modeli, były zróżnicowane.

Analizując literaturę naukową dotyczącą wykrywania zapaleń u krów, można odnaleźć wiele publikacji opisujących potencjał wykorzystania pomiarów oporności mleka oraz liczby komórek somatycznych jako narzędzi diagnostycznych (Norberg, 2004; Kamphuis i wsp., 2008; Langer i wsp., 2014). Cavero i wsp. (2006; 2007; 2008) zastosowali różne podejścia analizy tych samych danych opartych na liczbie komórek somatycznych. Modele oparte na logice rozmytej, lokalnie ważonej regresji wielomianowej i sieciach neuronowych osiągnęły różne poziomy SE i SP, co wskazuje na istotność wyboru metody analizy w kontekście diagnozowania zapaleń. Jensen (2016) wykorzystał zróżnicowane parametry, takie jak wydajność mleczna, przewodność mleka, zawartość tłuszczu, białka, liczba komórek somatycznych oraz masa ciała krów, aby stworzyć algorytm przetwarzania i kategoryzacji danych w czasie rzeczywistym. Ich model osiągnął wysoki poziom AUC (0,81) oraz satysfakcjonujące wartości SE i SP. Podobne wyniki uzyskali Post i wsp. (2020), którzy w swoim badaniu do klasyfikacji krów wykorzystali zarówno dane pochodzące z hali udojowej (ilość wydojonego mleka, przewodność, przepływ mleka, liczbę komórek somatycznych) oraz dane związane z pobraniem paszy i ogólną aktywnością krowy. Spośród wielu testowanych modeli najlepsze dopasowanie modelu wynosiło AUC 0,79. W obu badaniach, w wykorzystanych modelach najwyższe rangi uzyskiwały informacje o liczbie komórek somatycznych.

5 Podsumowanie i wnioski

Rolnictwo ekologiczne jest prawnie uregulowane w wielu krajach, w tym także w Polsce. Ograniczenia i wytyczne dotyczące produkcji mleka oraz hodowli krów w ramach rolnictwa ekologicznego mają na celu promowanie zrównoważonego i przyjaznego środowisku rolnictwa, a także zapewnienie wyższego poziomu dobrostanu zwierząt. W ramach niniejszej dysertacji doktorskiej przeprowadzono analizę porównawczą zdolności adaptacyjnych dwóch ras bydła: polskiej holsztyńsko-fryzyjskiej oraz brunatnej szwajcarskiej do warunków produkcji ekologicznej.

Badania prowadzone w kierunku analizy behawioru krów wykazały, że jest on niezwykle złożony i determinowany przez szereg czynników, takich jak skład i forma podawanej paszy, sposób jej dostarczania, wydajność, rasa oraz faza laktacji. Otrzymane wyniki podkreślają znaczenie uwzględniania naturalnych wzorców zachowań krów podczas zarządzania stadem, szczególnie w przypadku wypasu pastwiskowego, gdzie cykliczne zmiany w dostępie do pożywienia wpływają na codzienną aktywność zwierząt. To zagadnienie niesie za sobą istotne implikacje dla efektywnego zarządzania bydłem i utrzymania optymalnych warunków hodowli.

Analiza danych pochodzących z zastosowanych czujników umożliwiła identyfikację charakterystycznych wzorców zachowań, które potencjalnie wskazują na obecność problemów zdrowotnych i reprodukcyjnych w stadzie. Skuteczna implementacja tych zaawansowanych narzędzi może znacząco przyczynić się do poprawy dobrostanu zwierząt, ograniczenia strat ekonomicznych oraz usprawnienia ogólnego zarządzania gospodarstwem.

W świetle cytowanych wcześniej prac naukowych, obecnie ograniczona jest dostępność badań wykorzystujących dane behawioralne krów do konstrukcji modeli matematycznych służących do wykrywania *mastitis*. Niemniej jednak wiele istniejących prac naukowych sugeruje istotne zmiany w behawiorze krów ze zdiagnozowanym *mastitis*. Otrzymane wyniki również potwierdzają istotność uwzględnienia cech behawioralnych w modelach matematycznych wykorzystywanych do klasyfikacji krów zdrowych i chorych na *mastitis*.

Rozwój bezinwazyjnych metod ciągłego monitorowania parametrów produkcyjnych i behawioralnych stwarza dla rolnictwa ekologicznego nowe możliwości. Zwłaszcza w zakresie szybkiego diagnozowania schorzeń, co przekłada się na szybsze wdrażanie leczenia a tym samym ograniczenie stosowania środków farmakologicznych, w szczególności antybiotyków.

Na podstawie uzyskanych wyników sformułowano następujące wnioski:

1. Rasa krów stanowi istotny czynnik etiologiczny kształtujący poziom parametrów użytkowych mleka oraz behawior krów:
    - Behawior krów rasy polskiej holsztyńsko-fryzyjskiej oraz brunatnej szwajcarskiej w warunkach pastwiskowych i alkierzowych wykazał istotne różnice w alokacji czasowej. Krowy rasy BS niezależnie od miejsca przebywania i rodzaju zadawanej paszy więcej czasu spędzały na pobieraniu paszy oraz mniej przeżuwały w porównaniu do krów rasy PHF.

- Krowy rasy BS charakteryzowały się zarówno wyższą wydajnością, jak i zawartością białka i tłuszczu w mleku w porównaniu do krów rasy PHF.

2. Analiza behawioru krów stanowi kluczowy element wczesnej diagnostyki *mastitis*:

   - Analiza alokacji czasowej potwierdziła istotny wpływ aktywności ruchowej, zwłaszcza czasu pobierania paszy, na ryzyko zachorowania na *mastitis* u krów.

3. Badania wykazały, że zarówno bydło rasy polskiej holsztyńsko-fryzyjskiej, jak i brunatnej szwajcarskiej, wykazuje zdolność adaptacyjną do ekologicznego systemu produkcji mleka. Obydwie rasy mogą być wykorzystywane w ekologicznych gospodarstwach mlecznych, co potwierdza możliwość wdrożenia zrównoważonego podejścia do hodowli i produkcji mleka.

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7 Zbiór publikacji naukowych wchodzących w skład dysertacji doktorskiej pt. „Przydatność dwóch ras bydła mlecznego (polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej) w ekologicznym systemie produkcji na podstawie analizy jakości mleka i dobrostanu krów”

animals

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Review

Organic Milk Production and Dairy Farming Constraints and Prospects under the Laws of the European Union

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Simple Summary: Consumers are increasingly choosing organic farming products. Such behavior is mainly dictated by the conviction that organic farms do not use pesticides or antibiotics, and that animals are provided with the best living conditions. This review discusses issues related to the comparison between organic and conventional dairy cattle housing systems in terms of welfare assessment, breed selection, and product quality. It has been shown that cows kept in organic systems usually have better welfare compared to conventional breeding. However, it is worth bearing in mind that conventional farms can also provide better animal welfare through, for example, the use of pasture grazing, which is voluntary in conventional farming, but mandatory in organic farming. The pasture feeding of cows has been shown to affect the taste of milk, but regarding consumer preference, this is a personal preference. Reducing the use of antibiotics in ecology has a positive impact on the technological quality of milk; it is also an additional incentive to use preventive measures to reduce the incidence of mastitis. In the future, it is expected that the proportion of land that is unsuitable for the production of crops for human consumption will increasingly be used for cow grazing.

Abstract: In recent years, there has been rapid development in organic farming. When choosing organic livestock products, consumers are guided by the conviction that animals are provided with the highest welfare standards and access to pasture. The purpose of this article was to trace the principles of organic farming prevailing in the EU with regard to milk production and cattle breeding. The principles of organic production are universal and their application is not limited to certified farms. Organic certification is intended to assure the consumer of the quality and method of production. Due to additional requirements imposed by law, organic cows are usually kept in better welfare conditions compared to conventional cattle, but this is not the rule. The altered taste and texture of organic milk and its products compared to conventional products mainly depends on the presence of pasture greens in the cows' diet. Therefore, milk from conventionally kept, pasture-grazed cows may have similar characteristics and composition. Organic farms tend to have lower milk yields compared to conventional farms due to the lower consumption of concentrate feed. In the future, it is expected that the proportion of land that is unsuitable for the production of crops for human consumption will increasingly be used for cow grazing.

Keywords: organic production; cow; cow behavior; animal welfare

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1. Introduction

Currently, in the livestock sector, progressively more attention is being paid to ensure that animals have the best possible welfare—which is being achieved by providing better housing conditions and avoiding diseases through veterinary prevention. This trend has led to the rapid development of various types of production standards, the main goal of which is to produce high-quality products, with special attention to animal welfare. One of the most popular standards associated with animal welfare and the production of quality food without antibiotic residues is the organic farming certification.

Organic farming is not a new way of producing food. Its development dates back to the early twentieth century in German- and English-speaking countries. This trend was a form of criticism of the industrial revolution prevailing at the time [1,2]. The main pioneer of this type of farming was J. von Liebig. He created the concept of a closed system of agriculture based on growing crops using atmospheric carbon and nitrogen, as well as soil minerals. Initially, the organic farming initiative was not very popular. The breakthrough came in the 1970s, when, along with growing concerns about the quality of the food products we bought, there was great interest in this method of growing crops and raising animals. Many countries, in response to this great interest, introduced various subsidies for the promotion of organic food, especially in the European Union, where this support is now implemented under the Common Agricultural Policy (CAP) program [3].

Currently, both in Europe and around the world, organic farming is in a period of rapid development. The amount of land certified as organic land is increasing every year. In 2019, 72.3 million hectares of land were certified worldwide, which accounted for 1.5% of all crops. In Europe, meanwhile, the percentage of organic land accounted for 3.3% of all crops. In the last decade, the area utilized by organic crops increased by 102.4% worldwide, while in Europe, the increase came to 64.8%. The poultry sectors saw the fastest growth. The total stock of broilers and laying hens increased by 110% between 2010 and 2019. The organic milk sector also experienced dynamic growth. Dairy and beef cattle populations increased by 81% over a similar period [4].

In different countries around the world, regulations for organic farming may vary. Organic products produced in one country may not have an organic status when exported to another country with different legal requirements. Within the European Union, organic farming laws are unified and strictly sanctioned. At the level of community law in European Union, the most important legal document relating to organic production is Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on the Organic Production and Labeling of Organic Products and Repealing Council Regulation (EC) No. 834/2007 [5]. This document defines what an organic product is, and specifies the objectives and principles of organic production. In Chapter II, Articles 4 and 5 of the aforementioned regulation, there are provisions stating the need to ensure high levels of welfare standards for animals, i.e., the ability to meet the behavioral needs characteristic of the animal species. In addition, the legislator draws attention to the need to use rare or local breeds that are threatened with extinction. Other requirements for organic farming are as follows: limiting the use of allopathic medicinal products, prohibiting the use of milk replacers, and limiting routine procedures that cause pain, such as the dehorning of cattle and the castration of bulls. In an organic system, the areas available to animals are also increased compared to conventional systems, the use of a tethered system is limited, and there must be bedding in resting areas. In addition, animals must have freedom of movement and, in the summer season, go out to pasture. Table 1 shows the main requirements for organic dairy farming in the EU.

Many of the requirements imposed in the organic system are also voluntarily implemented on farms keeping cattle in conventional systems. Measures willingly implemented by conventional farmers include increasing the area available for animals in the barn, access to pasture, and [3] the use of natural bedding litter. Undoubtedly, government subsidies for welfare conditions and some dairies' preference for buying milk from pasture-grazed cows are incentives for such measures. However, this is not the norm, and non-certified organic products can be made from a mix of raw material from high welfare and pasture-access barns and from lower welfare barns. This situation is unacceptable to many customers. Organically certified food gives the consumer confidence that specific requirements are met at every stage from production; from the production of raw material to the retail sale of the finished product.

Table 1. Main requirements for the organic farming of dairy cattle in the EU.

	What Is Allowed or Prohibited in Organic Farming	Regulation
Breed selection	Local breeds preferred	REGULATION (EU) 2018/848, Annex II part II point 1.3.2 point d
		REGULATION (EU) 2018/848, Annex II part II point 1.3.3
Welfare	The need for high levels of welfare and conditions so natural behavior can be exhibited	REGULATION (EU) 2018/848, pkt. 44
Insemination	Allowed	REGULATION (EU) 2018/848, Annex II part II point 1.3.2
Estrus stimulation	Allowed on a case-by-case basis as a form of treatment	REGULATION (EU) 2018/848, Annex II part II point 1.3.2, point b
Multiple Ovulation and Embryo Transfer (MOET)	Prohibited	REGULATION (EU) 2018/848, Annex II part II point 1.3.2, point c
Animal cloning	Prohibited	REGULATION (EU) 2018/848, point 23
Tethering or isolation of livestock	Allowed on a case-by-case basis after obtaining permission (maximum of 50 animals)	REGULATION (EU) 2018/848, Annex II part II point 1.7.5
Access to pastures	Required	REGULATION (EU) 2018/848, Annex II part II point 1.7.3
		REGULATION (EU) 2018/848, Annex II part II point 1.9.1.1 point e
Litter-free animal housing	Prohibited	REGULATION (EU) 2018/848, Annex II part II point 1.9.1.2 point b
Feed composition	At least 60% of the dry matter in daily rations must consist of roughage, fresh or dried fodder, or silage	REGULATION (EU) 2018/848, Annex II part II point 1.9.1.1 f
GMO feeds	Prohibited	REGULATION (EU) 2018/848, Art. 11, point 1
Dehorning	Allowed in justified cases	REGULATION (EU) 2018/848, Annex II part II point 1.7.8
Castration	Physical castration will be allowed in order to maintain the quality of products and traditional production practices	REGULATION (EU) 2018/848, Annex II part II point 1.7.10
	Required use of anesthesia during castration procedure	REGULATION (EU) 2018/848, Annex II part II point 1.7.9
Milk replacers	Prohibited	REGULATION (EU) 2018/848, Annex II part II point 1.4.1. sub point g
	90 days after birth for bovine and equine animals	COMMISSION IMPLEMENTING REGULATION (EU) 2020/464 Ch. II, sect. 1, Art 2, point a
Use of antibiotics	Prophylactic use of antibiotics is prohibited	REGULATION (EU) 2018/848, pkt. 43
		REGULATION (EU) 2018/848, Annex II part II point 1.5.1.3
	Antibiotic treatment authorized when necessary to treat disease entities	REGULATION (EU) 2018/848, Annex II part II point 1.5.2.2

Table 1. *Cont.*

What Is Allowed or Prohibited in Organic Farming	Regulation
The withdrawal period for the use of an antibiotic is twice as long as specified in Article 11 of Directive 2001/82/EC	REGULATION (EU) 2018/848, Annex II part II point 1.5.2.5
It is forbidden to use more than three antibiotic treatments for a single animal within 12 months	REGULATION (EU) 2018/848, Annex II part II point 1.5.2.4.

All of the above restrictions aim to ensuring the best possible welfare for the animals, the ability to express their natural behavior, and the production of high-quality food. Such an approach involves making some compromises between animal freedoms, product quality, and production profitability. The purpose of this article was to trace the principles of organic farming prevailing in the European Union with regard to milk production and cattle breeding. The main objectives of organic farming will be described, such as the selection of individuals for the organic system, ensuring high animal welfare, access to pasture, and the impact of this production system on milk. The organic system will be compared with the rules prevailing on conventional farms.

The literature was selected based on keywords related to the topic of this paper in several bibliographic databases of the Warsaw University of Life Sciences including Web of Science and Scopus.

2. Welfare

2.1. Welfare Evaluation

In both organic and conventional production, ensuring high animal welfare is given priority. In the case of organic production, welfare has been listed as one of the main goals of this farming system. The challenge proves to be measuring welfare, taking into account the needs of different breeds living in different environments. In the past, veterinarians and farmers conceived of animal welfare primarily in terms of animal health and performance, and paid less attention to behavioral aspects [6]. Currently, much attention is being paid to psychological issues such as the social relations among individuals in a herd, the occurrence of inbreeding, and the availability of barn space.

Discrepancies in the definition of the term welfare can be seen by comparing the perceptions of consumers and breeders. For the consumer, the conviction of better living conditions for organic animals relative to conventional production is the main reason why they buy the usually more expensive organic products [7]. Consumers prioritize animal access to the outdoors, overall natural behavior, and good animal treatment [8]. This is due to non-farmers' tendency to anthropomorphize animals. For producers, on the other hand, it is more important to keep animals healthy and minimize the pain they experience [9]. Thus, welfare is a complex issue and the way it is perceived may vary across different social groups [10]. It was therefore necessary to create a general definition of well-being. Currently, one of the most widely used definitions is that published by the World Organization for Animal Health (OIE): "Animal welfare means the physical and mental state of an animal in relation to the conditions in which it lives and dies. An animal experiences good welfare when the animal is healthy, comfortable, well nourished, safe, not suffering from unpleasant states such as pain, fear and distress, and is able to express behaviors that are important for its physical and mental state" [11].

Various types of protocols have been developed so that the welfare of animals on farms can be assessed. These are questionnaires that broadly assess the welfare of an entire herd by describing health, comfort, social relations, and access to pasture. The protocols currently used on dairy cattle farms are as follows: AssureWel, Farmers Assuring Responsible Management (FARM), and the Welfare Quality Network (Welfare Quality®, EU-project). To perform this assessment reliably, the person conducting the audit requires adequate knowledge and experience. Nevertheless, drafting a welfare assessment protocol can tell us a lot about the condition of animals. Wagner et al. [12] compared the welfare of cows on conventional and organic farms using the Welfare Quality® protocol. The averaged results suggest that organic farms did indeed maintain cows at higher levels of welfare, but that there were also farms that were significant outliers in this regard. Similar results were obtained in another study using the same protocol, but the authors noted that the positive effect of pasture grazing may not occur when other animal needs are not met [13].

These types of protocols are helpful for gaining general knowledge about animals, for example, a cow's condition at a specific time. However, their welfare can be altered as a result of various external factors, for example, the periodic lack of access to feed or increased temperature in the barn. Thanks to the miniaturization of technology, it is possible to obtain increasingly accurate data not only about the environment in which the animals live but also about the behavior of the cows themselves and even the conditions inside their bodies [14]. One example of improving cow welfare with the use of automation is the monitoring of conditions in the barn and the appropriate control of fans, sprinklers, and other infrastructure that manages the microclimate in the barn [15,16]. This can largely prevent conditions within the barn that cause heat stress in the animals. Another example of welfare monitoring is the use of sensors that measure cow behavior, such as CowManager SensOor (Agis Automatisering BV, Harmelen, the Netherlands), RumiWatch (RWS; Itin and Hoch GmbH, Liestal, Switzerland). Sensors of this type allow fairly accurate monitoring of the amount of time cows spend taking feed, chewing, and moving. Some sensors are able to monitor the location of a specific cow in the barn, such as Smartbow (Smartbow/Zoetis LLC, Weibern, Austria). This makes it possible to learn about the natural behavior of cows and quickly alert farmers to abnormal situations. It is possible to quickly detect lameness, udder inflammation, and metabolic diseases, often even before there are clinical signs [17,18].

In addition to issues that are easy to measure, there are also aspects that are difficult to quantify, such as the human–animal relationship or the effects on animal behavior of any kind of barn automation. These aspects, from a behavioral point of view, are still poorly understood, although it has been shown that negative interactions with humans can cause timidity [19] as well as lower animal productivity [19,20]. Progressive automation has increasingly reduced the need for contact with animals, however, many activities must still be performed manually, making human–animal interaction unavoidable. It is important that this contact is appropriate right from birth. Krohn et al. [21] and Jago [22] have shown that positive human contact with calves a few days after birth can influence later interactions with handlers. Therefore, an important part of maintaining high levels of animal welfare is the proper training of farm personnel in animal handling.

Another interesting welfare issue is access to elements that enrich the animal's environment. An example of such an element would be a brush that allows animals to groom themselves. In the wild, cows groom themselves using tree trunks. This is a natural form of behavior for coping with stress [23]. In the barn, cows do not have access to this method, which can lead to all sorts of undesirable behaviors. DeVries et al. [24], in their study, showed that cows have a very strong need to groom themselves by scratching. Seven days after installing a mechanical brush in the pen, the scratching time had increased more than 500%. The need to scratch has been shown to be just as strong as the need to take feed [25]. Providing a scratching device for calves in a group pen also had a positive effect by reducing inactivity time. In addition to grooming activities, calves spent more time taking feed [26].

There is still no method to unambiguously determine cow welfare. Breeders wishing to improve the welfare of their animals should work on many levels. Using welfare assessment protocols helps give a general understanding of the condition of the animals and infrastructure, enabling breeders to find areas that need attention. On the other hand, sensors that monitor behavior will enable a faster response to disease states and perinatal problems and allow the precise control of microclimates. Only a comprehensive approach to the evaluation of welfare in the barn environment, by combining living condition assessments with the behaviors of individual animals in the herd, could provide the opportunity to study the welfare of animals and quickly react to the occurrence of a number of factors that can impact the welfare of animals.

2.2. Procedures That Cause Pain

As herbivores, cattle do not manifest the pain they feel [27]. This behavior is a way of defending against predators, who usually focus their attention on the weakest animal in the herd that is under attack. By not manifesting pain, such animals do not stand out from the herd and do not attract the attention of potential predators. The nature of masking pain symptoms may, mistakenly, give the impression that cattle are insensitive to pain [27,28]. Hence, recognizing and assessing the intensity of perceived pain in cattle based on behavior is difficult.

Pain-inducing procedures such as castration in beef cattle, removal of horn bundles in calves, and dehorning of adult cows, are partially restricted under organic farming regulations ((EU) 2018/848 Annex II to points 1.7.10 and 1.7.8) [5]. Organic production allows these procedures to be performed only in certain situations. In the case of dehorning, it is necessary to justify the need for this treatment and, on this basis, in certain cases, the appropriate permit is issued. As for castration, this physical procedure is permitted in cases justified by the maintenance of product quality; but must be performed using anesthetics, similarly to in conventional farms. In conventional herds, dehorning and castration are not restricted, and in the case of calves, dehorning can be performed without anesthesia. Current recommendations include the administration of analgesics to all animals, for all surgical procedures, and for the removal of horns and horn buds. However, it is still not a legal requirement. Restricting the use of these practices means there are less cattle that have to suffer the pain involved in these procedures, but, as a result, there is the increased risk of suffering due to, for example, the incidence of disease or skin damage that results from horned cows fighting over hierarchy issues. Therefore, additional recommendations are needed on farms where the aforementioned procedures are not used.

The dehorning process is very common in conventional herds. According to a study [29] performed in the EU, it is carried out on as many as 81% of herds. The main reason for performing this procedure is cited as increasing the safety of handlers as well as the safety of the animals themselves, mainly in cases of free-range housing, where fighting occurs over hierarchy. Stafford and Mellor [30], in a comprehensive review paper, point out that all methods of calf dehorning cause pain that persists long after the anesthetic—if one was used—wears off. Because of the prevalence of this practice and the pain that calves experience during and after the procedure, dehorning has been highly criticized by animal rights organizations such as PETA (People for the Ethical Treatment of Animals’). Therefore, despite legal restrictions on organic production, the execution of the aforementioned procedures is met with public resistance. As a result, the concept of selecting individuals with a “hornlessness” gene has emerged. Hornless animals have always existed in cattle populations, but intensive selection for productive traits drove this gene out of the population. This situation is particularly evident in the Holstein breed, where selection for dairy traits is the strongest [31]. Consequently, the limited number of hornless individuals limits the possibility of more effective breeding work using hornless bulls that have high genetic potential.

Another solution for obtaining hornless individuals is the use of genetic engineering methods. Such methods have significant potential for producers and can increase animal welfare [32], meanwhile, the public is rather distrustful of genetic modification. A survey conducted by Funk et al. [33] found that 57% of the general public consider genetically modified foods unsafe. In addition, when it comes to the possibility of applying these solutions to organic farming, it is possible to implement the selection of individuals that have a naturally occurring hornlessness gene, while the conduct of molecular techniques themselves on organic cattle are legally prohibited in ((EU) 2018/848 Article 2(f) [5]. Currently, organic farming regulations do not prohibit the use of insemination of semen from conventional bulls that were born using molecular techniques. Thus, outstanding individuals from conventional breeding can pass on their traits to animals that will be kept under organic conditions.

There remains the question of ensuring the safety of the handlers and the horned animals themselves. The presence of horns changes the behavior of cows in a herd. In hornless herds, the hierarchical structure is mostly influenced by the weight of the cow, which can fluctuate, leading to constant hierarchical changes. The presence of horns means that the dominant cow, regardless of body weight, can maintain its status in the herd [34]. This allows for a more stable hierarchical structure. The presence of horned animals also affects the infrastructure of the barn; and this should be taken into account when designing the barn, especially in relation to feed ladders and herding. Horned cows, both out on pasture and indoors, need more space compared to hornless animals [35]. A lack of adequate space causes increased competitiveness in the herd resulting in skin damage due to fighting. The most prone areas are where the animals are crowded together, i.e., in herds and in the waiting area to the milking parlor. Irrgang et al. [36] showed that increasing the space to more than 1.7 m^2 per cow in the waiting area in front of the milking parlor had a beneficial effect on horned-herd behavior.

One of the concepts of organic farming is to promote farms that are diversified in their activities. Hence, if a farm is engaged in milk production, it is natural for a separate branch to be beef production based on bull fattening. This is especially justified when choosing local breeds often used for dairy and beef. A castration procedure is associated with beef production. Castrated males (bullocks) exhibit higher meat quality as aggressiveness, sexual behavior, and fights for dominance are reduced after the procedure and thus there is a much lower risk of bruising and injury [37]. In addition, the intramuscular fat content and tenderness of the meat increase after castration [38], all of which favorably affects the quality of the beef obtained from even a typical dairy breed. On the other hand, castration reduces the average daily weight gain and feed conversion [39].

Castration can be carried out in several ways: the surgical removal of the testicles, crushing the seminal vas deferens, or cutting off the blood supply to the testicles with a permanently placed rubber band. In addition, there are also pharmacological methods that are not approved for use in the organic system. Several studies have shown that regardless of the choice of method, the castration procedure causes pain [40–42]. The severity and duration of this pain is dependent on many factors and increases with age, weight gain, and the testicular size of the calves [43]. Surgical castration has been shown to be more painful, as evidenced by increased plasma cortisol levels [43]. The solution is to administer painkillers; however, when their effects wear off after a few hours, the calves continue to experience pain.

Bretschneider [44] showed that observed stress reactions indicated that the younger the calf being castrated, the less stressful the procedure, and that the stress associated with castration was independent of the method used. The author indicated that the best method of castration was to use a bloodless method based on the use of a rubber band. Similar conclusions were reached by Becker et al. [45].

Based on literature reports and the organic farming requirements, it can be concluded that the castration of calves should be carried out at about 4–6 weeks of age, and the application of a rubber ring above the testicles should be chosen method—this approach reduces the suffering of calves to a minimum.

3. Grazing

3.1. Behavior on Pasture

It is widely believed that pasture grazing has a positive effect on cow health and behavior [46,47]. Cows on pasture are able to fully manifest their natural behavior by interacting with other the individuals of the herd, lying down in any body position, or naturally consuming forage by selectively feeding on the selected plant species [48,49]. However, some of these positive effects have been shown to disappear as the distance traveled by cattle from barn to pasture increases [50]. Forcing cows to stay in the pasture during hot weather or other adverse conditions also negatively affects their welfare [51].

Research suggests that the cattle's motivation to stay on pasture is uneven throughout the day. Dairy cows typically prefer to stay indoors during the day, especially when temperatures and humidity are high, and, instead, spend most of their time on pasture at night [52]. A similar relationship is observed for rainy days, when cows spend more time indoors [53]. Crump et al. [54] presented evidence that being on pasture is perceived by cows as being something pleasant. Similar conclusions were reached by Sharma et al. [55], who, by examining cortisol levels in cow hair, showed that there was a negative association between cortisol concentrations and access to paddocks. Lower levels of this stress hormone in cows that have access to paddocks indicate less stress and, therefore, better animal welfare.

Cattle are herd animals and exhibit complex social behavior and a need to interact with each other. At the very top of the herd hierarchy are one or two dominant cows; while below this is a slightly larger group of sub-dominant cows. The middle part of the social pyramid is occupied by the largest group of subordinated cows. The very last level of the hierarchy falls to marginal individuals, where animals are sick or old. The behavior and movement of the herd is most influenced by the most dominant cow. Activities such as foraging, ruminating, or moving around the pasture are initiated by the most dominant cow, which is successively joined by the rest of the herd. Cows mimic the activities performed by herd leaders, even when they physiologically do not feel the need to do so. This mechanism is referred to as allelomimetic behavior. It has been shown that synchronous behavior is strongest in semi-natural systems such as pasture systems. Here, cows have enough space to freely establish a hierarchy and avoid dominant individuals. In buildings, on the other hand, synchronous behavior is much less pronounced [56], especially when overstocking forces some competition for resources. The desynchronization of group behavior that occurs in buildings is associated with reduced lying time and more frequent changes in lying location. Therefore, conducting observations of behavioral synchronization in the herd can be an indicator of the natural behavior of cows [57,58].

The behavior of cows, in the absence of struggles for resources, changes depending on the time of day. Cows are crepuscular animals and are particularly active at sunrise and sunset. Hence, periods of increased forage intake fall mainly around sunrise and sunset [59,60].

However, pasture is not always the best place for forage intake. High-yielding cows that have access to pasture and whole-meal feed (TMR) located in the barn prefer TMR feed [61]. It is more accessible and easier to consume than green fodder [62,63]. As a result, high-yielding cows can consume more feed with a high concentration of energy by which they are less likely to suffer from energy deficiencies.

Some authors claim that TMR feed can even endanger animal welfare under certain circumstances. This is related to the natural desire to manipulate the tongue while picking out blades of grass. On pasture, especially one that is diversified in terms of vegetation, cows are able to have a varied diet. On the other hand, in the barn and with TMR feed imposed, the cow cannot, and should not, be able to sort through the feed. This often leads to frustration, increased stress levels [64], and stereotypies [65]. Additionally, it has been shown that cows fed on pasture do not develop overgrown molars [66].

3.2. Risk of Heat Stress

The grazing season largely coincides with a period of high temperatures, which are forecast to get hotter every year [67]. Cows, as large-bodied animals, have an unfavorable body volume to skin surface area ratio; because of this, they have difficulty with heat exchange. Due to the ever-increasing lactation capacity, the fermentation processes in the rumen generate even more heat energy. As a result, cows are prone to heat stress, which causes a decrease in productivity, reproductive problems, and, in extreme cases, collapse [68]. It also affects milk quality by lowering its technological suitability [69]. It is commonly claimed that heat stress in cattle occurs when the temperature humidity index (THI) exceeds 72 points [70]. The occurrence of heat stress is influenced by a number of factors, including air movement, sunlight, and coat length and/or color. Dark-coated cows (including Holstein Friesians) are more susceptible to heat than light-coated cows [71].

Through evolution, cattle have developed several mechanisms to cope with high temperatures. One that is easily observed is to reduce feed intake. Lower feed intake reduces the intensity of the exogenous fermentation processes occurring in the rumen, which in turn leads to a decrease in performance [72]. It has been shown that in high-yield cows, reduced feed intake during early lactation increases the negative energy balance, which in turn can lead to effective insemination problems [73]. Increasing temperature causes blood vessels in the skin to dilate, and increased sweating and panting [74].

In an attempt to adapt to the rising temperatures, cows change their behavior by reducing their time lying down in favor of staying upright. The standing position increases the surface area for heat dissipation and minimizes the contact with the heated ground [75]. However, increased time spent standing puts significant strain on the limbs and leads to a greater risk of lameness. If there is access to shaded areas on the pasture, cows are eager to use it. It has been shown that cows' motivation to obtain a place in the shade increases with increasing ambient temperature and solar radiation [76]. Tuyttens et al. [77] showed that access to shade on the pasture enabled high milk yields to be maintained in contrast to cows without access to shade, in which there was a decrease in milk yield. There are various methods of dealing with high temperatures in closed systems where cows do not go out to pasture. Mainly, these involve efforts to ensure the best possible ventilation of the facility through curtain walls and mechanical ventilation. Sprinkler systems are also often installed. In the case of cows on pasture, many engineering solutions are not possible; however, it is possible to provide shaded areas that can accommodate the entire herd. Shade can be provided by sheds or clusters of trees, which are particularly valuable from the point of view of biodiversity. An interesting idea was presented by Kendall et al. [76], who provided sprinklers and shade for cows before afternoon milking. The use of both shade and sprinklers 90 min before afternoon milking was shown to provide an effective, immediate reduction in the body temperature of dairy cows grazing on pasture.

Different breeds of cows respond differently to elevated temperatures. Pereira et al. [78] proved that, among the four breeds they studied (Alentejana, Limousine, Holstein Friesian, and Mertolenga), the Holstein Friesian breed was the fastest to show signs of heat stress, while the Portuguese Mertolenga breed showed the highest resistance to high temperatures.

4. Feed Base and Productivity

One of the main tenets of organic farming is to combine local crop production with livestock production. In dairy cow nutrition, European organic standards require the use of roughage at a rate of at least 60% of daily dry matter intake and access to pasture during the summer. The use of feed additives, milk replacers, and hormones is limited. An extension of the organic system is the Bio Suisse standard, in which the main feed base is grass, grass silage, or hay, while concentrated feed can only account for 10% [79]. Consequently, organic systems are highly dependent on the environment and require animals that are well adapted to local conditions.

Dairy cows in organic and conventional pasture systems face constantly changing conditions, both climatic and nutritional. Grazing cattle are exposed to sunlight and high pasture temperatures, and during the summer they travel considerable distances from barn to pasture. Twice a year there is a change in the feed ration (pasture in summer and winter based on hay and silage), which forces a change in the rumen's microbiome [80,81]. In addition, the composition of pasture forage itself changes and depends on the plant species, developmental stage, and soil and climatic conditions [82]. Spring forage has a high forage value and is juicy and readily taken up, while in later growth stages, its fiber content increases, which reduces the intake and digestibility. The type of grazing itself also affects the later quality of the pasture. An excessively low density of cows results in the selective grazing of the forage by which plants end up at different stages of growth [83].

By comparing the forage base available in organic and conventional systems, it can be concluded that, in organic systems, the energy concentration of forage is much lower than in conventional systems [84,85]. This is mainly due to the limited use of corn silage and the use of hay in winter feed, which is in line with the general assumptions of organic farming. The lack or low proportion of energy feeds in the ration is also due to their high price and the poor availability of components certified for organic farming. For organic milk production to be profitable, most feed must be produced on the farm [86]. In contrast, growing energy feed crops such as corn under organic conditions is extremely difficult due to the many constraints placed upon it [87].

This organic model for feeding cattle, although driven by economic reasons, is part of the general principle of linking animals to the land. Cattle mainly use perennial pastures and grasses grown on lower grade arable land. As a result, cows do not compete for acreage with human food production. On the other hand, in order to obtain higher yields, it is necessary to add cereals that can also be used as human food [88].

Maintaining high-yield cows under organic system conditions poses a number of challenges; the most important of which is the provision of high-energy feed during the first phase of lactation. Consequently, there is a high risk of creating a negative energy balance in high-yield cows, which in turn leads to declines in reproductive indices [89,90]. In addition, cows on organic farms are more prone to ketosis [91].

A diet that has limited energy also has an effect on the milk yield of animals, meaning that organic farms tend to have lower productivity compared to conventional farms [92,93]. These differences are significant, with organic herds having a 9–35% lower milk yield than conventional herds [84,94–96]. Van Vuuren and Van den Pol-van Dasselaar [97] calculated that a grass-only diet can support milk production levels of 22–28 kg per cow per day. Increased milk yields have been shown to result in the risk of more frequent hoof problems. Studies by other authors have been consistent and they also see a link between yield and hoof disease which is associated with poor animal welfare [98,99]. In organic farming, any disease unit—especially recurrent ones—can force the farmer to remove such a cow from the herd.

Feed conversion is also important in grazing systems. It has been shown that different breeds are able to utilize the pasture forage to different degrees. Prendiville et al. [100] has shown that grazing Jersey cows required 7%–8% less forage for every kilogram of milk fat and protein produced compared to HF (Holstein-Friesian) cows. This effect is particularly evident in the limited forage intake that can occur on pasture. Spaans et al. [101] also obtained similar results.

5. Breeding

When considering the selection of a breed for an organic system, special attention should be paid to the breed's genetic traits and selection indexes. Due to the nature of organic production, there is the need for animals to be hardy and suitable for grazing on outdoor pasture systems [102]. Currently, most countries do not use a separate performance evaluation system for organic animals. This is due to the small number of animal populations and the liberal regulations on reproductive techniques. In organic agriculture, the use of estrus synchronization, the induction of superovulation, and embryo transfer is prohibited for animals that were granted organic status. However, the use of insemination with semen from non-organic bulls is allowed, and thus these bulls can come from embryo transfer. Delaby et al. [102] has shown that the complete exclusion of the linkage of multiple ovulation and embryo transfer (MOET) to organic production would result in a significantly large loss in genetic gain in organic population.

The lack of a separate evaluation for organic animals promotes the use of Holstein Friesian cows, which, due to their popularity and performance in intensive production systems in many countries, are also the dominant breed in organic systems [103–105]. As previously shown, it is not an optimal breed for organic production. Due to years of selection for production traits, many health traits have significantly deteriorated, including hoof health, udder health [106], and fertility [107].

As a result, there are increasing attempts to create a separate index that takes into account genotype–environment interactions. Demonstrating the existence of genotype–environment interactions within a given feature results in individuals of the same genotype behaving differently depending on the environment. This means that the same individual's index can change depending on the environment. When animals are genetically adapted to certain conditions, they will be more productive and production costs will be lower [108].

In the literature, it is increasingly common to find papers describing the probability of a genotype–environment interaction comparing conventional and organic systems [109–111]. The occurrence of such an interaction would indicate that bulls selected as sires may perform well in intensive systems but would not be suitable for organic systems. An example of this would be milk yield, which is influenced by many genes. If it is found milk yield is dependent on different sets of genes depending on the environment in which the cows are housed, it is possible that the bull rankings would vary from system to system. Robertson [112] suggested that a genetic correlation of less than 0.80 should indicate a significant genotype–environment interaction. Table 2 shows the results of work on estimating the heritability of various traits, depending on the livestock housing system and genetic correlations.

Table 2. Genetic correlations and heritability in the same traits between organic and conventional and conventional pasture production systems.

Trait	Breed	Genetic Correlation	Heritability, Organic System	Heritability, Conventional Pasture System	Heritability, Conventional System	Citation
Length of productive life	German Holstein	0.65–0.66	0.09–0.18		0.03–0.12	[109]
	Swedish Holstein	>0.88	0.13		0.09	[113]
	Swedish Red	>0.96	0.18		0.13	[113]
Milk yield	Netherlands Holstein	0.8	0.70		0.48	[104]
	Austrian Fleckvieh		0.63		0.59	[114]
	Swedish Holstein	0.95–1	0.27		0.35	[115]
	German Holstein	0.59–0.82	0.43–0.44		0.36–0.48	[109]
	Brown Swiss	0.95				[116]
	Canadian Holstein	0.93		0.31	0.37	[117]
	American Holstein	0.89		0.19	0.2	[118]
Fat yield	Holstein Friesian	0.97	0.58		0.39	[104]
	Brown Swiss	0.95				[116]
	Canadian Holstein	0.88		0.35	0.39	[117]
	American Holstein	0.88		0.19	0.23	[118]
Protein yield	Holstein Friesian	0.78	0.59		0.39	[104]
	Brown Swiss	0.93				[116]
	Canadian Holstein	0.94		0.3	0.36	[117]
	American Holstein	0.91		0.17	0.2	[118]

Research does not give a clear answer regarding which traits are correlated with the environment; however, it does indicate that, under certain conditions, such interactions do occur. Zhang et al. [111] showed the existence of a genotype–environment interaction for fertility traits. Similar results were obtained by Liu et al. [110] when measuring the number of inseminations needed for successful fertilization in conventional and organic heifers. Nguyen et al. [119] confirmed the possibility of selection for heat stress resistance. This type of study, it is important to have a large number of individuals and to collect as much information as possible about them. Shabalina et al. [109] partially confirmed the validity of breeding work according to the production system, but stressed the need to obtain more data from organic herds.

Nauta et al. [104] showed that with the further tightening of organic farming regulations, the magnitude of genotype–environment interactions was likely to increase. Therefore, animals selected for maintenance in conventional systems may not be suitable for organic systems.

6. Milk Quality

Organic production should ensure a high-quality product. Consumers also perceive organic milk to be superior in many respects to conventionally produced milk. The quality of milk can be evaluated in terms of consumer safety, technological quality, and consumer sentiment. There are standards in the legislation that state the minimum parameters that must be met when dairies receive raw material. These include temperature, somatic cell counts (SCC), bacterial counts, and antibiotic residues below the levels specified in Regulation (EC) No 853/2004 [19].

In the context of milk quality, one of the most important and common problems is the health of the mammary gland (mastitis). A direct indicator of udder health is the number of somatic cells per milliliter of obtained milk. The European standard allows a maximum of 400,000 somatic cells per ml of pooled milk (Regulation (EC) No. 853/2004) [19], but this level is considered too high and indicates a high frequency of mastitis in the herd. It has been shown that the optimum level for this indicator is approximately 200,000/mL of pooled milk [120], however, even in this case, some cows show signs of mastitis [121]. Mastitis is a common disease and occurs in both organic and conventional herds. There are conflicting reports in the literature showing that the incidence of the disease varies between conventional and organic systems. Some authors show a less frequent incidence of mastitis in organic cows compared to conventional cattle [122–124], while other authors show no difference in the frequency of mastistis between the two animal housing systems [125]. The incidence of mastitis is influenced by many factors that affect both housing systems, including barn hygiene, milking hygiene, and proper treatment. There are also specific factors: conventional farms that are focused on high productivity often show elevated SCC rates, as udder health is correlated with milk yield. High-yield cows may be at higher risk of udder inflammation [126]. On the other hand, incompetent use of pasture, including in the organic system, also leads to an increased risk of mastitis [127]. The way to improve herd health is to increase milking hygiene and to cure sick cows [128].

In addition to the legal aspects, udder health affects the technological quality of the raw material. Inflammation causes real economic losses related to milk yield and the veterinary costs incurred for treatment. The effective treatment of the clinical form of mastitis requires the use of antibiotics. A common practice is to administer broad-spectrum antibiotic agents. Such actions contribute to the development of antibiotic resistance in pathogens, which, in the long term, will promote the development of further inflammation that is difficult to treat [129,130].

When mastitis occurs, it is important to detect it quickly and implement specific treatments. According to Regulation 2018/848 Annex II, Part II, points 1.5.1.3 and 1.5.2.2 [5], the use of antibiotics should be avoided, but if it is necessary, specific targeted antibiotic treatments can be implemented. These actions ensure less drug use and shorter treatment time, resulting in a shorter withdrawal period, which in organic farming is twice as long as in conventional farming. In less acute cases, alternative treatments are worth considering. Angelopoulou et al. [131], in their work, showed that prebiotics and bacteriocins (in particular, nisin) could be used to treat subclinical inflammation. Another alternative may be the use of silver, gold or chitosan nanoparticles in the prevention and treatment of mastitis [132,133]. Currently, this is a novel approach and the formulations are in the experimental phase. Based on the published results, it can be assumed that commercial nanoparticle-based formulations will be developed in the future. However, it should be remembered that the process of registering an agent as a veterinary drug is complicated and lengthy.

In addition to veterinary costs, mastitis causes changes in milk composition, especially within the casein protein fraction [134]; this in turn negatively affects its cheese-making performance [135]. This is particularly important for farms that use the milk to make cheese and fermented products. Even small antibiotic residues that are below the acceptable standard have been shown to negatively affect milk processing and especially cheese making [136,137]. The problem of antibiotic residues in conventional milk is common in some parts of the world, mainly developing countries. However, in developed countries (EU, USA), this problem also occurs, although to a lesser extent [138]. In the EU in 2019, a survey was conducted to detect antibiotic residues in milk: 9555 samples of cow's milk were tested, and the number of non-compliant samples was 0.12%. However, three positive samples of chloramphenicol were detected (one sample in three states), although the use of this antibiotic is banned for veterinary use. Studies relating to the prevalence of antibiotic residues in organic milk are sparse, however, Welsh et al. report that studies conducted in the US have proven the absence of antibiotic residues in organic milk [139].

Milk quality is significantly affected by how cows are fed. Grass and herbs are important natural sources of fatty acids and vitamins. Milk from pasture-grazed cows has been found to have higher levels of polyunsaturated fatty acids (PUFAs) including conjugated linoleic acids, vaccenic acid, and omega-3 fatty acids, compared to animals fed TMR feed [140,141]. This type of milk is also characterized by a higher vitamin A and E content. This effect is significantly influenced by the quality of the grass, as FA (fatty acid) concentrations in fresh green fodder vary depending on plant species, season, and sunlight intensity. Leaves and young plants have higher FA concentrations than the plants of a later growth stage. Diet-related changes in the milk's FA composition can affect the sensory characteristics of milk and milk products. This is due to the different structure of fatty acids, which affects their physical characteristics. In milk, palmitic (characterized by high melting point) and oleic (characterized by low melting point) acids are found in the highest concentrations. Their relative concentrations affect the texture of the milk [142]. It has been shown that milk from grazing cows has a slightly altered texture, being creamier and having a higher intensity of grassy flavor [143] compared to milk from cows fed TMR. Some differences can also be seen in dairy products. O'Callaghan et al. [144] found that butter from grass-fed cows scored highest in terms of appearance, taste, and color when compared to butter from TMR-fed cows. Coppa et al. [145] showed that even the intensity of grazing and the composition of the pasture sward influenced the appearance and taste of cheese. Cheese from pasture-grazed cows had a more intense color and was creamier compared to cows kept in the barn.

Of course, consumer preferences in terms of taste and eating sensation vary widely. Taste sensations are strongly influenced by the temperature at which the products are consumed: the higher the temperature, the more noticeable the differences in taste and aroma [146]. It should be remembered that most of the differences between conventional milk from cows fed TMR feed and milk from organic cows or conventional cows on pasture are seasonal and due to the feed base. Winter feeding, even when based on hay, does not provide the same concentrations of vitamins and fatty acids as green fodder. When grass wilts in the field, before silage or hay is prepared, there is a loss of polyunsaturated fatty acids [147].

7. Conclusions

Organic and conventional pasture-based farming is expected to continue to grow. This is due to pressure from the public, who perceive grazing as being a necessary element of the welfare of cattle. Based on the studies of cow behavior, however, it should be noted that the increase in average annual temperature and the associated risk of heat stress in cattle is a significant threat.

On the other hand, ranchers recognize the economic benefits associated with grazing. Pasture is the cheapest feed base for ruminants, especially at a time of increasing competition for acreage for grain production. The increasing human population needs more and more food and thus acreage for the production of high-energy feed crops may decrease in the future. Some animal species such as poultry and pigs absolutely require cereals to maintain production, while cows and other ruminants can utilize feed that is unsuitable for humans. Therefore, by limiting milk production, cattle can be successfully raised on lower-quality land without competing for acreage for grain production.

Holstein Friesian cows, due to their adaptation to high milk yields, may not be the optimal breed for extensive milk production. Based on current research and review papers, it is difficult to find specific factors that predispose any cow breeds for use in organic systems [148,149]. This is due to the high variability in breeds, climatic conditions, and nutrition. However, work is constantly underway to find traits suitable for organic or grazing systems. This provides some hope that, in the future, there will be a separate selection index for organic cows.

An important factor motivating consumers to buy organic products is the belief that antibiotics are not used in breeding. This is not entirely true, because, in the case of an acute disease entity, the health of the animal is paramount and antibiotic treatment should be implemented.

The marketing of organic products as coming from animals of indigenous breeds, characterized by high welfare, and the concomitant negative perception of conventional agriculture by some members of the public, have allowed organic to grow rapidly. The continued tightening of regulations related to the use of antibiotics, hormones and pesticides have brought conventional agriculture ever closer to the organic system. In many cases, two well-managed farms do not differ in terms of welfare or product quality, and are only distinguished by the fact that one of them is certified as organic. In the future, it is likely that even stricter standards will develop to make competition with conventional agriculture possible.

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Comparison between the Behavior of Low-Yield Holstein-Friesian and Brown Swiss Cows under Barn and Pasture Feeding Conditions

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Simple Summary: Cows are usually kept in indoor housing. They receive daily feed of similar composition at fixed times. A regular daily routine means that the cows' behavior during the day is usually similar and does not vary from day to day. Cows grazing on pasture, however, must adapt their behavior to the changing composition of the grasses. The study was conducted on 64 Holstein-Friesian (HF) cows and 54 Brown Swiss (BS) cows between August 2016 and October 2017. The animals were equipped with sensors measuring the time spent on feed intake, rumination, physical activity, and rest. In winter, the cows were fed mainly on hay, while in summer, they took forage from pasture or freshly cut forage distributed in the barn. The study also showed behavioral differences between the HF and BS breeds. HF cows, regardless of location or forage type, spent more time foraging and chewed less than BS cows. A similar relationship was observed across all the lactation groups being studied.

Abstract: Cow pasturing poses many logistical and nutritional problems. Animals have more difficulty accessing pasture feed and require more time to consume the equivalent amount of dry matter compared to total mixed ration (TMR) feed from a feed table. The study was conducted during August 2016–October 2017 on 64 Holstein-Friesian (HF) cows and 54 Brown Swiss (BS) cows. All animals were equipped with CowManager sensor devices, and the cows' behaviors were recorded: time spent on feed intake, rumination, physical activity, and rest. In winter, cows were mainly fed hay, while in summer, they took forage from the pasture or freshly cut forage provided in the barn. The study showed that the time of day had a significant ($p < 0.001$) effect on the cows' feeding behaviors. The study also showed behavioral differences between HF and BS breeds. HF cows, regardless of the location and type of feed provided, spent more time on feed intake and chewed less compared to the BS breed. These differences were observable in all studied lactation groups. Animals were most willing to take forage two hours before sunrise and two hours before sunset and showed an increased willingness to take feed immediately after leaving the milking parlor.

Keywords: cows' behavior; pasture; organic production; Holstein-Friesian; Brown Swiss

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1. Introduction

Pasture is the natural environment for dairy cattle. It is an environment where animals have the opportunity to express natural behavior, interact with other individuals, lie down in different body positions, and selectively take up pasture forage. Access to pasture also has a positive impact on animal health and increases overall welfare [1]. It has been shown that cattle housed on pasture are less likely to develop mastitis [2,3] and lameness [4]. Despite the beneficial effects animals derive from pasture, the number of farms using this method is currently declining in Europe. This is related to the intensification of both animal and crop production [5]. In Europe, the Holstein breed is still the most popular breed, with many years of selection aimed at improving traits related to milk yield. Pasture feeding, despite its many advantages, is not suitable for high-yield cows due to the relatively low energy value of green fodder compared to TMR feed. Therefore, grazing is used mainly by small farms that employ pasture as a form of cheap feeding scheme during the summer season. However, there are countries in the world that base a significant part of their dairy production on pasture grazing. Two examples are New Zealand [6] and Ireland [7]. These countries have introduced parameters into their cattle selection indexes that take into account pasture use, the seasonality of calving, and longevity. Consequently, the genetic traits of Irish and New Zealand cows are adapted to a pasture-based feeding model, as opposed to the common genotype of high-yield Holstein-Friesian cows that require intensive feeding.

As the intensity of dairy production has continued to increase over recent years, consumers have started to pay increasing attention to the welfare conditions of the animals from which the products they buy are derived. For the consumer, it is important that dairy cows are provided with the highest possible welfare, including the opportunity to go out to pasture [8]. In response to this demand, various agricultural certification schemes are becoming increasingly popular. Examples include the organic farming system [9] and Bio Suisse [10]. Having a product certified under these schemes gives the customer the assurance it has been sourced from animals that have been provided with high levels of welfare and access to pasture. Therefore, it is possible that increasing numbers of large dairy cattle farms will start using pasture grazing over the next few years. However, it should be noted that the introduction of pasture feeding involves many changes, not only in the organization of the farm itself, but also in the behavior and circadian rhythm of the cows themselves.

The behavior of dairy cows housed in a free stall barn is fairly stable; the total duration of activities spent on fulfilling basic behavioral needs per day varies from 20 to 21.5 h in a 24 h period, of which 5–5.5 h is for eating, 12–14 h is for resting (lying down), 10 h is for ruminating, 30 min is for drinking water, and 1.5 h is time spent in passageways and on other social behaviors [11]. Conditions in the barn are usually stable. Cows receive a compositionally similar feed at the same times of day, every day. Small changes in the structure of the TMR feed can result in slight increases or decreases in feed intake times, which are generally imperceptible in the overall behavior of the cows. The situation changes when the cows go out to pasture. Pasture forage is more difficult to take up, its composition changes throughout the year, and the cows are exposed to changing weather conditions.

Despite the variable conditions, and it being more difficult to intake pasture forage, cows are happy to stay on the pasture. Many works relating to behavior and welfare have highlighted the strong motivation that cows have to stay on pasture when given the choice between pasture and barn. This is not a simple relationship, and this choice is influenced by a number of factors, including weather conditions, vegetation stage, time of day, and milk yield [12–14]. Animals housed on pasture change their behavior compared to cows housed in barns. This is related to greater opportunities for social interaction and the different form of forage intake. Pasture fodder is more difficult for the animals to access and, therefore, intake activities tend to take longer than for the easily accessible TMR feed [15,16]. Keeping cows on pasture for most of the day can also cause changes in their circadian cycles. Cattle are crepuscular animals, showing increased activity around sunrise and sunset [17]. On pasture, the diurnal rhythm is undisturbed, unlike the conditions in the barn, where the lights are on during the winter season several hours after dark as well as before sunrise. As a result, nighttime in the barn lasts only a few hours. In addition, the presence of attendants in the barn also affects animal behavior.

It has been shown that, as the growing season progresses and the composition of the pasture sward changes, the cows' preferences also change. Cows are most likely to take fresh spring forage, whereas, when the quality of forage deteriorates as the season progresses, cattle prefer to take the readily available and high-energy TMR feed [13]. The motivation of cattle to take in sufficient energy is very strong; hence, cows with lower productivity are more likely to stay on pasture compared to high-yield cattle, which prefer the readily available TMR feed [12]. Atmospheric conditions, and especially the temperature humidity index (THI), can also influence the cows' preference for housing. At high THI indices (THI >72), cattle seek shelter and prefer a shaded barn, whereas, if the temperature remains within the comfort limits, cattle prefer to stay on pasture.

Failure to provide cows with opportunities to express their natural behavior can result in reduced productivity and increased stress levels in the herd [18]. Hence, careful monitoring of the animals' circadian behavior is essential to optimize production systems [19]. Knowledge about the activities of individual cows results in valuable information about their health status. These days, cows are equipped with many different types of sensors to measure some of their specific behaviors, such as number of steps, chewing time, or time spent on feed intake. Depending on the model, these sensors are mainly used to detect estrus and lameness. There is a growing body of work demonstrating the possibility of using cow behavior monitoring for the early detection of mastitis, metabolic diseases, or heat stress [20,21]. Most of this type of research focuses on assessing the behavior of high-yield Holstein cows kept in barns, but there is little work comparing the feeding behaviors of cows of different breeds or cows kept less intensively. Companies involved in the production of monitoring systems for herd management are also increasingly implementing additional types of functionality into their equipment, including for the detection of different types of disease and alarms warning of the possibility of heat stress. Such systems usually work well under barn conditions where the cows' behavior is comparable from day to day and any deviation from the norm can indicate the onset of a disease entity. Under pasture conditions, cow behavior is not stable and can change depending on many factors. In order to be able to implement such solutions in grazing barns, it is first necessary to know the specific behavioral characteristics of cows of different breeds in different conditions and environments. The results of the few works that describe this issue indicate that animal behavior differs significantly depending on production potential, feeding regime, and breed. O'Connell et al. [22] compared the behavior of HF cows that had high and low production potentials. They indicated that cows with high potential had shorter grazing periods, higher feed intake rates, and spent more time ruminating compared to HF cows with lower production potential. McCarthy et al. [23] showed that cows specifically selected for pasture feeding (New Zealand Friesian) grazed longer, but had lower pasture sward grazing rates compared to HF cows. Prendiville et al. [24] showed that there were differences in ruminating time between HF and Jersey (JE) breeds, with HF cows spending more time ruminating than JE cows. Failure to account for differences in the behavior of cows of different breeds housed in different environments can result in erroneous alerts generated from automated herd monitoring systems. An example of this is the difficulty in detecting heat in cows housed on pasture and associated with greater physical activity compared to cows in barn conditions [25].

The purpose of this study was to investigate the differences in the behavior of Holstein-Friesian and Brown Swiss cows under organic production conditions. Three methods of feeding were considered: pasture-based feeding, hay-based feeding in the barn, and fresh grass provided on the feed table in the barn. Demonstrating the differences and/or similarities in the daytime behavior of cows of different breeds may help to better organize production, especially in an organic system where cows usually have large areas of pasture available. It could also be the basis for further research into new systems for detecting behavioral changes in individual animals in the herd, which would contribute to the earlier detection of disease entities and thus improve the welfare of cows.

2. Materials and Methods

2.1. Location of the Experiment

The research was conducted on a certified organic, biodynamic farm in Juchowo, located in West Pomeranian Voivodship (Poland). The farm keeps Brown Swiss (BS) (about 120 head) and Holstein-Friesian (HF) (about 250 head) dairy cattle in a free-stall box system (for lactating cows) and a free-stall deep litter system (for dry cows). The average herd performance during the study was about 6500 kg of milk per standard lactation, with an average fat content of 4.21% and protein content of 3.32%. Cows were milked twice a day on a Happel 2 × 16 herringbone-type milking parlor. The morning milking started around 5:00 a.m., and afternoon milking started at 4:00 p.m. Cows were admitted to the hall according to their associated lactation group, starting with the group that were in the first stage of lactation. The parlor was equipped with built-in ICAR-certified milk yield measuring equipment installed in the collection manifolds for each station. The fat and protein content information came from monthly tests conducted as part of the herd's milking performance evaluation carried out by the Polish Federation of Cattle Breeders and Milk Producers.

The way in which the animals were fed depended on the season. During the winter, it was based on *ad libitum* hay with the addition of concentrated feed and vitamin and mineral supplements. Hay distributed on the feed table was not crushed or mixed with other feeds. During the grazing season, whenever possible, the animals went out to pasture to take in pasture fodder. The cows were grazed on pastures in a rotational system with technological grouping, taking into account the stage of lactation. The pasture stocking rate was about 10 cows per hectare. The botanical composition of the pastures and their productivity is shown in Figure 1. The pastures were distributed on slightly undulating terrain with hills whose relative heights did not exceed 5 m. The time spent on the pasture depended on weather conditions (temperature and rainfall). When conditions were favorable, the animals spent approximately 20 h a day on pasture, going down to the barn only for milking. After milking, they received a concentrated feed supplement, the amount of which depended on the cows' stage of lactation (from 6 to 8 kg at the beginning of lactation, 3 to 4 kg during the middle phase of lactation, and 1 kg at the end of lactation—feed concentrate per cow per day). The concentrated feed ration consisted of oats, lupine, and barley, and mineral additives in the form of sea salt, fodder chalk, and mixed vitamins and minerals. The feed concentrate was divided into two portions: one given after the evening milking and the other after the morning milking. In cases where the weather conditions were unfavorable, the animals were fed with cut, green fodder (which had not been crushed or mixed with other feed) delivered to the feed table in the barn.

2.2. Data Collection

The experiment began in August 2016 and lasted until October 2017. From the herd, 118 cows (64 HF breed and 54 BS breed) were randomly selected. The selected animals varied in age and stage of lactation. Group size data are presented in Table 1. The body condition score (BCS) was assessed using the BCS-5 method described by Edmonson et al. [26]; the average BCS for the cows was 3.0–3.4. During the study, the cows were under veterinary care.

Table 1. Group size and milk yield of cows selected at the beginning of the experiment.

		First Stage of Lactation		Medium Stage of Lactation		Last Stage of Lactation	
		HF	BS	HF	BS	HF	BS
Number of animals		23	18	23	18	22	18
Milk yeld (kg/day)	LSM	22.1	24.2	15.1	14.3	8.5	9.8
	SEM	0.72	0.81	0.75	0.78	0.51	0.55

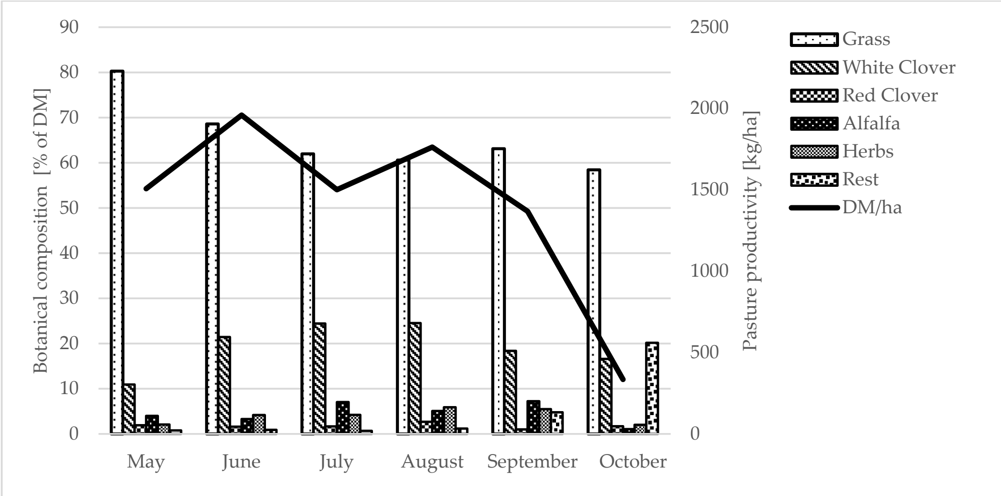

Figure 1. Botanical composition and productivity of pastures.

The animals were fitted with CowManager sensor devices from Agis Automatisering BV, Harmelen, the Netherlands. The sensors were installed according to the manufacturer's recommendations on the left auricle. The sensors measured cows' activity using accelerometer-measured acceleration in three directions (3D). The data were then transmitted to a router and then further to the system provider's servers, where an algorithm classified the data into individual activities (feed intake, rumination, rest, low physical activity, high physical activity). While the animals were in the pasture, out of range of the router, the data were stored in the device's memory and exported to the Internet during milking in the milking parlor where the router was located.

At the start of the experiment, this was still a new system, and there were no papers available in the scientific literature dealing with the validation of this device. Therefore, before starting data collection, the system was calibrated to adjust its sensitivity to the specifics of the herd. This consisted of making visual observations of a selected cow's behavior at one-minute intervals over a period of one hour and comparing them with data from the CowManager system. After 56 h of observations, covering different individuals, the following coefficients of determination were obtained, which allowed for the concordance between the questionnaire's records and the system readings: feed intake R2 = 0.86, rumination R2 = 0.97, and rest R2 = 0.94 [27]. It was assumed that the system was sufficiently accurate in classifying the different types of cow behavior. Currently, other works validating this system also confirm its applicability to this type of research [28–30].

The height of the pasture sward during the summer season was measured once a week using a Jenquip EC10 Platemeter, with measurements being taken using the envelope method at every 10 m. A minimum of 30 measurements were taken for each pasture each time, from which the average height of the pasture sward was drawn. In order to determine the amount of dry matter in the pasture grass, a representative sample of grass was taken every two weeks from each of the pastures and meadows used in the experiment. Determination of forage dry matter content was carried out by drying it at 70 °C. The analysis of the dry matter content in the hay given to cows during the winter period was carried out in the same manner.

The results obtained from the CowManager sensors were grouped into packets, each corresponding to a particular hour. The data packets (1 packet = 1 h of measurement) contained the total number of minutes spent by the cow on a particular activity per hour. The data were additionally supplemented with, among other things, information on the various types of disease entities that were detected by the veterinarian. Information concerning lameness and the occurrence of estrus were also included in the created database. As a result of the experiment, which ran from August 2016 to October 2017, more than 960,000 data records were collected.

2.3. Statistical Analysis

Due to the significant behavioral changes that occur during the onset of various disease entities, estrus, and the periparturient period, such animals were not included in the statistical analysis. Data collected during the two transition periods from winter to summer feeding and the transition from pasture to winter feeding were also excluded from the analysis. During these periods, the time spent by the animals on pasture was gradually lengthened (in spring) and gradually shortened (in autumn). Any frequent changes in the feed ration during these periods could affect the behavior of the cows; hence, these data were not included in the statistical analysis. The final analysis included 181 days of winter feeding, 108 days of pasture feeding, and 64 days of grass feeding in the barn. Excluded from the analysis were 24 days of grass feeding in the barn during rainy days and 75 days of transitional feeding.

In order to analyze the overall behavior of cows in different lactation phases and feeding regimes, hourly data were summed to obtain the total amount of time spent performing a given activity by a single animal per day (min/day). Complete data were used to analyze the effect of milking time on cow behavior.

Statistical analysis was carried out using IBM SPSS 23 software. A mixed model with multiple variables was used for the calculations.

$$Y_{ijk} = \mu + A_i + B_j + C_k + (A_i \times B_j) + (A_i \times C_k) + (B_j \times C_k) + (A_i \times B_j \times C_k)\ e_{ijk}$$

where Y_{ijk} is the dependent variable, A_i is the breed effect (where $i = 1$ or 2, in which 1 = HF, 2 = BS), B_j is the feeding effect (where $j = 1$–3, in which 1 = winter feeding, 2 = pasture season, and 3 = fresh grass in the barn), and C_k is the lactation stage effect (where $k = 1$–3, in which 1 = first stage of lactation, 2 = middle stage of lactation, and 3 = last stage of lactation); $(A_i \times B_j)$ is the fixed interaction effect between breed and feeding; $(A_i \times C_k)$ is the fixed interaction effect between breed and stage of lactation; $(A_i \times B_j \times C_k)$ is the fixed interaction effect between breed, feeding, and stage of lactation; and e_{ijkl} is the random error.

The triple interaction was not cosidered in the results as it was not significant. The analysis of the covariance structure presented the UN structure as the covariances between the repeated measurments below and above the diagonal. Spearman's correlation was used to evaluate the relationship between the amount of dry matter in the feed ration and the time spent on intake. For multivariable comparison, Fisher's LSD test was applied.

3. Results

The analysis of the effects of breed and diet on cow behavior and milk quantity and composition showed significant differences. BS cows had higher yields compared to HF cows in terms of both milk quantity and fat and protein content (Table 1). The high standard deviation numbers are due to a failure to include the effect of the lactation phase in the analysis. This was due to insufficient data on the composition and quantity of the obtained milk.

The behavioral differences between HF and BS cows for all the analyzed feeding scenarios were also statistically significant ($p < 0.001$). Regardless of the feeding season, cows of the HF breed spent more time ruminating compared to the BS breed. In contrast, the BS breed spent more time on feed intake compared to HF cows. Activities related to physical activity and inactivity for both breeds were also statistically significant, but the differences found in chewing were not as large as those for rumination and feed intake. Nevertheless, it was shown that during pasture feeding, the HF breed cows showed more activity compared to the BS breed cows. The opposite situation was observed during winter feeding, where higher locomotor activity was observed in BS cows (Table 2).

Table 2. Effect of breed and feeding system on milk yield and cow behavior. HF—Holstein-Friesian, BS—Brown Swiss, LSM—least squares mean, SEM—standard error of the mean, and ($A_i \times B_j$) is the fixed interaction effect between breed and feeding. Means (for cattle breed in the row) marked with the same letters differ significantly at: lowercase letters, $p \leq 0.05$; uppercase letters, $p \leq 0.01$.

		HF			**BS**			***p*-Value**		
	LSM /SEM	**Winter**	**Pasture**	**Fresh Grass in Barn**	**Winter**	**Pasture**	**Fresh Grass in Barn**	**Breed**	**Feeding**	**Interaction ($A_i \times B_j$)**
Milk (kg)	LSM	12.1^{AB}	18.3^{A}	17.9^{B}	15.3^{AB}	19.8^{A}	18.7^{B}	<0.001	<0.001	0.143
	SEM	0.53	0.59	0.80	0.59	0.73	0.95			
Fat (%)	LSM	4.2^{Ab}	3.65^{A}	3.81^{b}	4.54^{AB}	3.93^{A}	3.95^{B}	<0.001	<0.001	0.140
	SEM	0.05	0.06	0.08	0.06	0.07	0.09			
Protein (%)	LSM	3.48^{ab}	3.1^{a}	3.1^{b}	3.8^{AB}	3.34^{Ac}	3.46^{Bc}	<0.001	<0.001	0.337
	SEM	0.03	0.03	0.05	0.03	0.04	0.05			
Ruminating (min/day)	LSM	507^{AB}	475^{AC}	551^{BC}	459^{AB}	436^{AC}	482^{BC}	0.000	0.000	<0.001
	SEM	0.89	0.98	1.25	1.03	1.20	1.52			
Eating (min/day)	LSM	343^{Ab}	461^{AC}	350^{bC}	350^{AB}	499^{AC}	372^{BC}	<0.001	0.000	<0.001
	SEM	1.05	1.16	1.48	1.22	1.42	1.80			
Not Active (min/day)	LSM	403^{AB}	278^{AC}	360^{BC}	418^{AB}	293^{AC}	380^{BC}	<0.001	0.000	0.179
	SEM	0.98	1.08	1.38	1.14	1.33	1.68			
Active (min/day)	LSM	192^{AB}	231^{AC}	213^{BC}	218^{a}	216^{b}	210^{ab}	<0.001	0.000	<0.001
	SEM	0.77	0.85	1.09	0.89	1.04	1.31			

The dry matter content of pasture green fodder and grass provided in the barn varied throughout the year from 14% to 20% and depended on the weather conditions and vegetation stage. Hay fed to cows during the winter period had between 88% and 90% dry matter. The correlation coefficient between the feed's dry matter content and time spent by cows eating was −0.382 ($p < 0.001$).

Comparing groups of cows at different stages of lactation also showed significant differences in behavior by breed and feeding season ($p < 0.001$) for all the analyzed groups. Time spent on feed intake during winter feeding increased as the lactation stage progressed. Animals in the final stage of lactation spent an average of 19 min longer at the feed table for the BS breed and 21 min for the HF breed, when compared to cows in the initial stage of lactation. A similar relationship was observed when cows were fed fresh grass in the barn. During pasture feeding, the differences between groups were insignificant (Figure 2).

When analyzing changes in the circadian cycle, the cows were divided by breed, lactation phase, and location (pasture or barn). It was found that, both for cows housed in the barn and cows grazing on pasture, the feed intake peak occurred around one hour after milking. A similar increase in feed intake was found for both the morning and evening milking. Morning milking started at around 5:00 a.m., while afternoon milking started at 4:00 p.m. Cows entered the parlor according to their lactation grouping, starting with those at the beginning of their lactation and, hence, the shift in peak feed intake in each group (Figure 3).

A succession of increased forage intake activity can be observed around 11 a.m., after which there is a decrease in the cows' interest in forage. Cows of both breeds, regardless of whether they were on pasture or in the barn, spent the least amount of time on feed intake in the hours before the evening milking and during the night. The influence of the night period is particularly evident in the case of cows on pasture, which between 9 p.m. and 1 a.m. hardly took up any forage at all, but, instead, spent a lot of time ruminating (Figure 4).

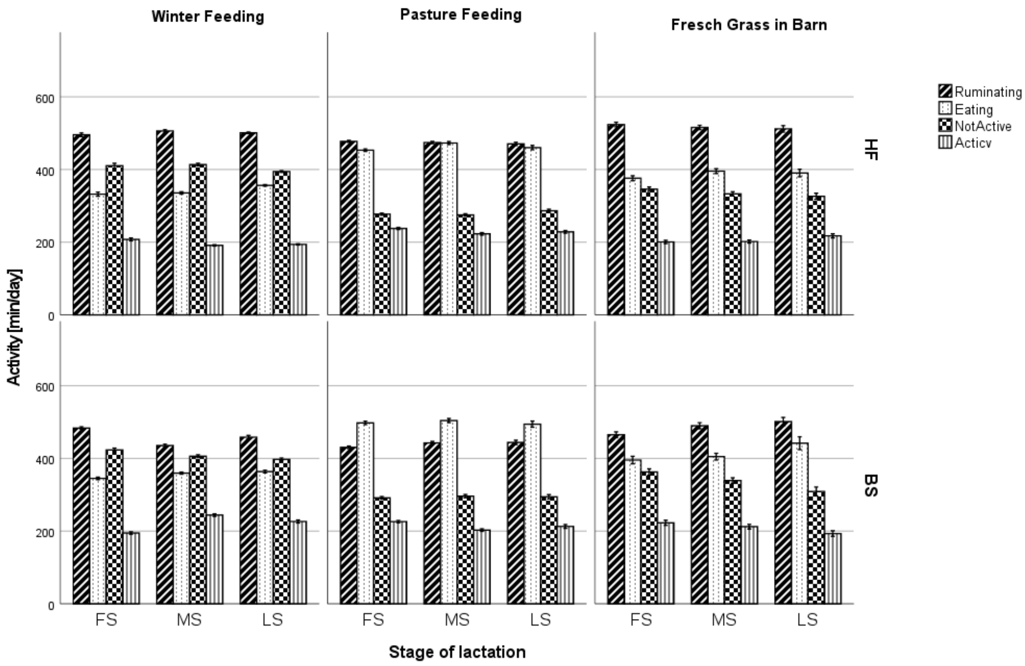

Figure 2. Effect of breed, feeding regime, and stage of lactation on cow behavior. FS—first stage of lactation, MS—middle stage of lactation, LS—last stage of lactation, HF—Holstein-Friesian, BS—Brown Swiss. Data are presented as least squares means with a standard error of the mean. Statistical differences between cow breed groups at $p < 0.001$, stage of lactation at $p < 0.001$, and feeding system at $p < 0.001$.

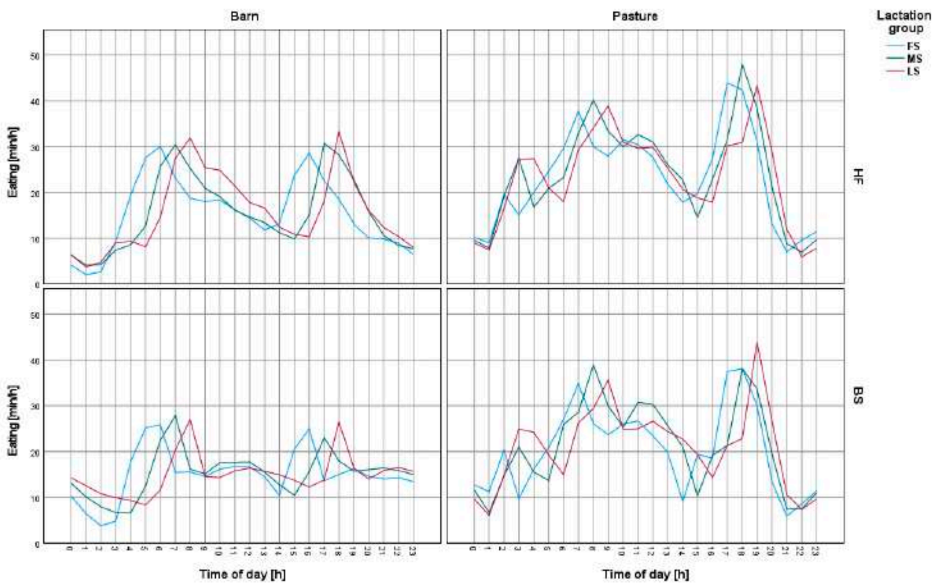

Figure 3. Changes in feed intake intensity on a daily basis for Holstein-Friesian and Brown Swiss cows on pasture and in the barn. FS—first stage of lactation, MS—middle stage of lactation, LS—last stage of lactation, HF—Holstein-Friesian, BS—Brown Swiss. Morning milking started around 5:00 a.m. and afternoon milking started at 4:00 p.m. Cows were admitted to the hall according to their associated lactation group, starting with the group of cows in the first stage of lactation.

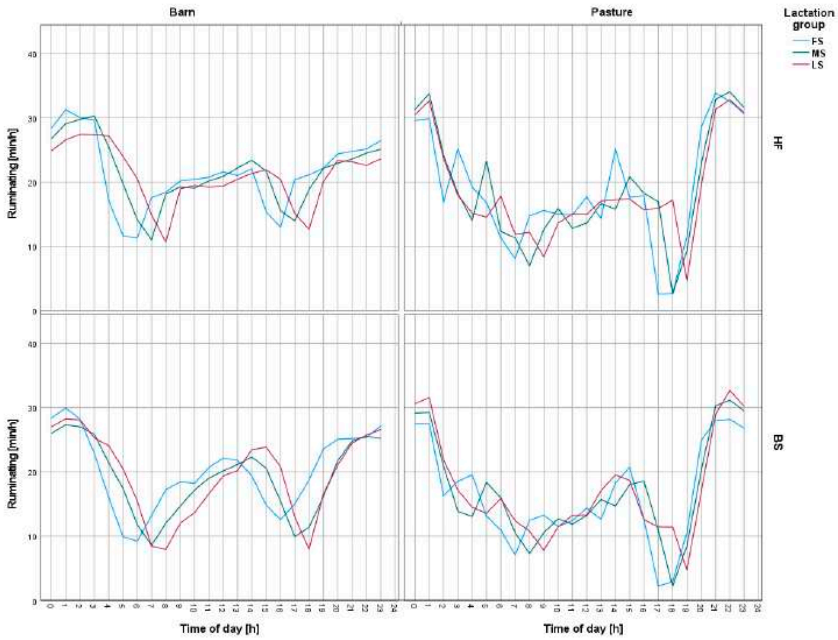

Figure 4. Changes in ruminating intensity on a daily basis for Holstein-Friesian and Brown Swiss cows on pasture and in the barn. FS—first stage of lactation, MS—middle stage of lactation, LS—last stage of lactation, HF—Holstein-Friesian, BS—Brown Swiss. Morning milking started around 5:00 a.m. and afternoon milking started at 4:00 p.m. Cows were admitted to the hall according to their associated lactation group, starting with the group of cows in the first stage of lactation.

4. Discussion

The time spent by cows on individual activities can vary depending on the factors involved, for example, milking time, frequency and time of feeding [31], and the type of feed and its fineness [32,33]. In the present study, the cows' time budgets were analyzed in relation to their diet (summer feeding—pasture, summer feeding—fresh grass in the barn, winter feeding—hay), lactation group (FS, MS, LS), and breed (HF, BS).

It is known that the time spent on pasture intake varies with the restrictions placed on the amount of time animals spend on pasture during the day. The cows' motivation to take forage from the pasture is very strong, so reducing the time that the pasture is accessible increases the intensity of forage intake and reduces the time spent on other activities, such as resting and ruminating [34]. In this study, the focus was on analyzing natural behavior without restrictions on access to pasture. The animals studied were on pasture for approximately 20 h per day. The greatest changes in behavior were shown between cows housed on pasture with those in the barn. Pasture forage intake times averaged 460 min/day; while in contrast, the time spent by cows picking up feed from the feed table averaged 346 min/day for hay and 360 min/day for freshly cut pasture forage delivered to the feed table. This large difference between the two groups is due to the lower availability of forage on the pasture and the different physiology involved in forage intake. When cattle take forage from the pasture, they wrap their tongues around clumps of grass and tear them off. This method makes feeding increasingly difficult as the length of grass becomes shorter, resulting in cows spending more time on eating activities [35]. Fodder on the feed table can be taken in larger bites, which significantly reduces the time needed to satisfy hunger.

The results obtained in this experiment concerning the time taken by cows to take up forage correspond to some of the results obtained by other authors. Perez [35], in his work, recorded 430 min of grazing per day when access to pasture was limited to 9 h per day. Soca et al. [34] observed 486 min/day with unrestricted grazing. Other authors observed much higher values for forage intake time. RG Pulido and JD Leaver [36] obtained a figure of 541 min/day, but this experiment was conducted on pasture with a sward height of up to 9 cm. In a study by Rossi et al. [37], cows were grazed on pastures that had different yields: 2100 and 2800 kg d.m./ha. The animals spent 552 and 462 min/day on forage intake, respectively. In contrast, R. Prendiville [24], during a study on the behavior of HF and JE cows, obtained average pasture forage intake times of 648 min/day. This value is significantly higher than the study in question, especially considering the similar average productivity of the cows (about 16.9 kg/day). The authors pointed out that the increased intake time was probably influenced by the height of the pasture sward. This ranged from 10.9 to 11.4 cm before grazing and 5.3 to 4.9 cm after grazing. In the present study, the grass height oscillated around 12 cm during the summer and 7 cm at the beginning and end of the grazing season. The minimum recorded value after grazing was 5 cm, at the beginning of May and in October. These measured sward heights are similar to measurements made by McCarthy et al. [23], who reported an average pasture forage uptake time of 504 min/day, with average sward surface heights before and after grazing of 22.8 and 7.9 cm, respectively. Therefore, when comparing pasture forage intake times and pasture sward height, the results are consistent with other authors, although this parameter is highly variable and dependent on sward height and animal performance.

Cows housed in barns are usually fed with TMR feed. Many authors have carried out studies on TMR feed intake times, with very divergent results: from 168 min per day [38] to 210–300 min per day [15,39]. Nevertheless, compared to pasture-grazing cattle, cows on TMR feed spend significantly less time on feed intake. In the current study, no TMR feed was given to any of the groups under study. Cows in the winter period received a feed consisting of hay fed *ad libitum*. For this period, the average feed intake time was 346 min/day. This is longer than in the studies cited above and is probably due to the fact that feed intake time was also influenced by feed structure and dry matter content. Forage with a high content of structural fiber (NDF) is taken up more slowly than forage that is more finely ground [40]. In addition, hay tends to have a significantly higher dry matter content compared to TMR feed.

Analyzing the behavior of cows with respect to their stage of lactation showed slight increases in feed intake time as lactation progressed. This result is in contrast to that obtained by Løvendahl and Munksgaard [41], who recorded the highest feed intake times for cows in the early stage of lactation. However, it should be emphasized that the cows in the cited study were high-producing animals, which produced more than 30 kg of milk per day. In the experiment presented here, the cows produced an average of only 16 kg of milk per day, making their energy requirements, even in the early stage of lactation, much lower than high-yielding cows. It appears that high milk yields can also affect other types of cow behavior that are not related to feed intake, such as lying time and movement within the barn [42]. In contrast, a study by Munksgaard et al. [43] found no differences in feed intake time for cows at different stages of lactation with an average yield of about 26 kg milk/day.

In the present study, the average rumination time for cows on pasture was 480 min/day, which was similar to results obtained by Watt et al. [44], who, in their study, showed that cows with permanent access to pasture usually ruminated for 487 min/day. Similar results were also found in a meta-analysis by Perez-Prieto and Delagarde [16], who showed that cows grazing on pasture ruminated between 380 and 477 min/day, with a milk production above 30 kg/day. Polock et al. [45], on the other hand, in a study conducted on high-yielding HF cows, showed that the average rumination time was 330 min/day.

It has been shown that the behavior of cows is dependent on where they are housed. The behavior of the animals housed in barns can be influenced by the workers carrying out their daily duties and the associated disruption due to the light cycle. When the lighting is on, it can stimulate cows to be more active in the feed table area. In the barn where the study was conducted, daily animal handling activities typically lasted from 5 a.m. to 9 p.m., which could significantly affect natural circadian behavior. In the case of the animals that spent most of their time on pasture, the rhythm of the solar day was not disturbed by artificial lighting because, during the summer, the animals participating in the experiment went out to the pasture before sunset and returned for morning milking after sunrise. The behavior of animals in barns is also influenced by the cyclical distribution of feed. It has been proven that the moment when the feed is given is a strong stimulus for the animals to take up the feed [46].

The time of day was also significant in relation to the time at which the cows ruminated. Similar to other works [47,48], in the present study, the majority of observed ruminating time also occurred at night. As with feed intake, the cows on pasture showed greater diurnal behavior changes than cows housed in the barn.

Both HF and BS breeds are typical dairy breeds characterized by high production. However, each of these breeds have been genetically improved in different ways. HF cows were improved mainly to produce large quantities of milk in an intensive farming environment, whereas the BS breed was improved mainly to produce high-quality milk for cheese production [49,50]. The results of selection have also led to different weather condition sensitivities. It has been demonstrated that BS cows are better adapted to high temperatures compared to the HF breed [51]. The current work did not focus on evaluating the milk yield of the HF and BS breeds; however, under extensive organic production conditions, it was shown that the BS breed produced milk with significantly higher fat and protein content compared to the HF breed.

An analysis of the behavior of the two breeds in the study indicated significant differences in their behaviors according to location and diet. There are few reports in the literature on the behavior of BS and HF breeds when they are fed extensively. Braun et al. [46] showed that BS cows fed hay *ad libitum* with an average milk production of 20–25 kg spent 445 min/day on feed intake and 388 min/day on rumination. The quoted results differ from those obtained in the current experiment, in which the times for feed intake and rumination during the winter season were 350 min/day and 459 min/day, respectively. The higher feed intake time observed by Braun et al. [46] may be due to the higher productivity of the cows—as productivity increases, the average dry matter intake increases. In another study, also conducted on BS cows fed hay with silage, it was shown that cows took up feed for an average of 316 min/day [47]. This result is more in line with the forage intake times for BS cows during winter feeding in the present study (350 min/day).

Another example of a similar study is a work by Graf et al. [48], who, for BS cows that grazed all day and night on pasture, measured average forage intake times of 532 min/day and rumination times of 344 min/day, with an average yield of 17.6 kg/milk. Again, despite the similar performance of the animals, the results differ significantly from those observed in this study for BS cows on pasture feeding (499 min/day for forage intake and 436 min/day rumination). In contrast, for HF cows fed on pasture, other authors reported forage intake times averaging 522 min/day [52], that is, 497–520 min/day depending on grass height [53]. In contrast, observed rumination times averaged 464–533 min/day [53]. The HF cows in the present study spent slightly less time grazing (461 min/day) compared to the results of the other authors, while they spent a similar amount of time ruminating (475 min/day).

By comparing the two studied breeds, it was demonstrated that BS cows spent more time on feed intake and less time on rumination compared to HF cows. Similar results were obtained by Hanada et al. [54], who also studied BS cattle. Casasús et al. [55], studying the behavior of BS and Pirenaica heifers, also showed that BS animals spent significantly more time on feed intake compared to the Pirenaica breed.

5. Conclusions

Cow behavior is very complex and can be influenced by factors such as the structure of the supplied feed, the way in which it is supplied, animal performance, and the feeding regime. The study showed behavioral differences between HF and BS breeds. HF cows, regardless of the location and type of feed provided, spent more time on feed intake and chewed less compared to the BS breed. These differences were visible in all studied lactation groups. The presented results testify to a need to take the natural behavior of cows into account in herd management, especially when keeping animals under pasture conditions where cyclical changes in feed rations change their daily behavior.

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Institutional Review Board Statement: The Second Ethics Committee for Animal Experimentation in Warsaw of the Ministry of Science and Higher Education (Poland) reviewed and approved all procedures. All cows were handled in accordance with the regulations of the Polish Council on Animal Care, and the Warsaw University of Life Sciences Care Committee reviewed and approved the experiment and all procedures carried out in the study, approval number: WAWA2/086/2018.

Data Availability Statement: All data generated or analyzed during the study are included in this published article. The datasets used and/or analyzed in the current study are available from the corresponding author on reasonable request.

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Comparison of different applications of automatic herd control systems on dairy farms – a review

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ABSTRACT

Recent years have seen the rapid development of different devices which can be helpful in the daily work of livestock farmers. The growing size of livestock herds has led farmers to lose individual contact with their animals, while behavioral studies show that breeders can effectively and precisely monitor a herd of up to 100 cows. This was the main motivation for this study, which aims to identify and test various electronic devices which provide useful herd management data, including estrus detection, individual activity and body temperature measurement, monitoring rumen pH levels, milk quality and content as well as milk temperature and somatic cell count measurements. Some devices can detect the metabolic status of animals with a reasonable level of precision. Contemporary animal farms are offered a large number of systems for monitoring the behavior of the animals in the herd and helping to identify those that are intended for insemination or are too active or excessively apathetic. Monitoring devices support herd management and help to reduce costs through the early detection of animal diseases and nutritional problems. This review aims to compile and summarize the information currently available on the use of automatic herd control systems on dairy farms, as well as to discuss the interpretation of the results, providing a useful diagnostic tool in nutritional evaluations of dairy herds.

Keywords: cow; herd control system; detection; estrus; lameness

INTRODUCTION

Behavior is one of the most commonly used and sensitive indicators of animal welfare. Breeders can make a relatively detailed assessment of the health of animals or the optimal time for insemination based on behavior. However, visual observation of the herd carries some important limitations. In large barns, estimating cow health and determining the time of insemination is often impossible. It involves a considerable amount of work and the need to log observations in detail. Moreover the evaluation of normal cattle behavior patterns and individual health status is difficult to accomplish owing to the animals' response to human interaction. Cattle behavior may be altered by contact with people and exposure to processing procedures such as restraint in a squeeze chute.[1] Presently in dairy farming, there is a trend toward the automation of processes to reduce manual labor and its associated costs. Automated systems enable dairy farmers to manage larger herds with lower labor requirements.[2]

The first sensors to find use in dairy herds were devices allowing the easy identification of individual animals. In the early 1970s, John Bridle at the National Institute of Agricultural Engineering in Silsoe (UK) developed a system which was tested at an experimental farm.[3] In 1976, DACA, a Dutch firm, manufactured and installed the first computerized feeding control system, developed in Wageningen. The successful introduction of such systems on the market encouraged many other companies to develop a similar approach. In 1977, NEDAP, another Dutch firm, began to produce transponders. In the last 20 years, over two million transponders were sold all over the world.[4]

To improve cow management in large dairy herds, sensors have been developed that can measure physiological, behavioral and production indicators for individual cows. Previously, a sensor was defined as a device that measures physiological or behavioral traits for an individual cow and enables the automated, on-farm detection of changes in parameters that are related to changes in the cow's health, requiring intervention from the farmer.[5]

Recent years have seen the rapid development of different types of sensors. There are currently many different devices capable of measuring multiple physiological and behavioral traits on the market. For example, sensors can be used to detect estrus,[6–8] clinical mastitis[9] and lameness.[10–12] Such systems can also be used to measure time of chewing[13] and monitor the pH of the rumen, a useful indicator of metabolic problems.[14,15] In recent

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years, technological advances have increased the popularity of robotic automatic milking systems (AMS) with built-in sensors, such as weighing platforms to monitor the growth of cows[16] or milk conductivity sensors.[17] After the introduction of AMS by the first commercial farms in the Netherlands in 1992, the rapid development of this technology followed, and by 2009 the number of farms using AMS had increased to more than 8000, 90% of which were located in Western Europe.[2]

The above examples show that modern milk production needs new technologies that provide farmers more control over their animals. The aim of this article is to gather information on the untapped potential for the use of new real-time herd monitoring systems on dairy farms, as well as to discuss the interpretation of the results, providing a useful diagnostic tool in dairy herd nutrition. The following study will examine different types of devices, their modes of installation and their usefulness in livestock farming. The study will also highlight the issues involved in the implementation of new monitoring systems.

OPERATING PRINCIPLES AND INSTALLATION OF SENSORS

The market currently offers many different devices for measuring activity. The first group comprises leg-mounted sensors that measure the overall physical activity of the cow, the number of steps taken and sometimes the time spent lying down and standing still (e.g. AfiTag, CowAlert, CowScout S Leg, Crysta-Heat, IceTag3D, RumiWatch, Track a Cow). The next group includes sensors mounted on the head and neck. They too can measure physical activity, but also time spent chewing, feed intake levels and time at rest (e.g. Alpro, CowManager SensOor, HeatBox, HR-Tag, Hi-Tag, Heatime, HeatPhone, MooMonitor, CowScout S Neck). The last group includes devices installed on the tail, in the vagina and on the back of the cow and are designed to detect only heat or calving time.

In their review, Rutten *et al.*[5] divided measuring devices which have been described in scientific publications into four categories: (I) techniques that measure behavioral traits (e.g. activity); (II) interpretations that summarize changes in sensor data (e.g. decrease in activity) to produce information about the cow's status (e.g. lameness); (III) integration of information where sensor data are correlated with additional data (e.g. economic data) to produce advice (e.g. whether to treat a cow or not); and (IV) the farmer making a decision or the sensor system making the decision autonomously (e.g. when to contact the trimmer or veterinarian). Raw data from these sensors are sent to a computer where they are processed using special algorithms and returned to the breeder in the form of clear diagrams and alerts. Depending on the system, data from the sensor can be sent to the computer in several ways. Some devices need constant communication with routers placed in the barn and provide data at regular intervals. Others may collect data from the whole day and connect to a router located in the milking hall. From this receiver, the data are automatically forwarded to a central computer which can then send updates to a smartphone via the GSM network or upload data to the internet.

Depending on the algorithm, the sensors are capable of different levels of accuracy, and more complex devices that are able to measure multiple different cow activities are typically the most accurate. Through data processing, the computer recognizes readings that correspond, for example, to rumination or walking. The easiest activity to recognize is the transition from lying to standing upright. It is far more difficult to distinguish the transition from standing to walking and vice versa.[18] Robert *et al.*[19] showed that the accelerometer's ability to distinguish between the lying and standing position is very accurate, approximately 99%, but its ability to recognize walking was significantly lower (67.8%). Alsaaod *et al.*[20] tested a novel algorithm to monitor locomotor behavior of loose-housed dairy cows based on the output of the RumiWatch pedometer (ITIN + HOCH GmbH Fütterungstechnik, Liestal, Switzerland). The authors reported that the ratio of correctly detected events or bouts was 1 for stand-ups, lie-downs, standing bouts and lying bouts and 0.99 for walking bouts.[20]

The most promising devices are those that measure the greatest number of different parameters. It has been proven that, on the basis of minor behavioral changes, it is possible to predict the occurrence of osteoarthritis and other developing diseases. Work on the algorithms of these devices is currently still under way. The developers aim to create an algorithm which, based on a broad range of data, will provide a clear picture of the status of the herd.[21,22]

Sensors of the current generation are very small and generally comfortable for the animals. Notwithstanding, some sensors can be painful at the start, while some leg- and tail-mounted sensors may cause skin irritation when fitted for a long time. That is why, after the installation of a pedometer sensor, cows were found to shake their legs and try to remove the device. Thus, for the first few days, the device will show an increase in time spent standing and a decrease in time spent lying down. The acceptance of new devices will be of special importance in the case of CowManager SensOor. This device is mounted on the ear and requires the piercing of the skin, as in the case of an ordinary tag. Until the wound has healed, the cow will feel discomfort, which can lead to inaccurate results.

The above systems have other limitations to keep in mind. Van Hertem *et al.*[21] showed that the neck activity measurement by head movements could be dependent on the production group of the cow. The distance between the cowshed and the milking parlor was not the same for each group. Therefore the activity was different in each group when the cows walked to the milking parlor three times per day. If the sensor measures the number of steps, the entire barn floor should be made of the same material. Platz *et al.*[22] showed an increase in the stride length of cows housed in rubber-floored barns compared with concrete-floored barns.

ESTRUS DETECTION

In mammals, estrus is a behavioral symptom and strategy to ensure that the female is mated close to the time of ovulation. Estrus is an external and visible sign of ovulation, an internal and invisible event. For a long time, these specific behaviors have helped farmers to determine the best time for insemination. Traditionally, estrus detection is performed by visual observation of the dairy herd, a very time-consuming and inaccurate method. Many studies have investigated estrus detection by visual observation.[23,24] Many authors focused on the most visible sign: standing heat. However, research results on the basis of this method are highly divergent, from 90%[23] detected estrus to less than 50%.[25–27] With improving herd productivity, the number of undetected estrus cases also increases, which in turn causes economic losses. Senger[28] reported that the annual losses resulting from incorrect heat detection in the USA amount to more than US$300 million. Furthermore, the duration of estrus in the case of high-yielding dairy cows has been markedly reduced in recent years.[29] According to Dobson *et al.*[30] the shortening of the visible symptoms of heat is largely associated with increasing milk yields, with the simultaneous deterioration of the health of cows. For this reason, it seems to be indispensable to adapt new methods to determine the correct time to perform insemination. Different methods for the detection of estrus have been described by Firk *et al.*[6] During the estrous cycle, many changes occur in the cow's body, most of which can be measured and the resulting data used to select the optimal time for insemination.

Currently, breeders have various types of automatic tools for detecting standing heat, body temperature and activity and automated systems to measure milk progesterone levels. This technology is much more effective in comparison with visual observation. The heat detection rate of most systems is above 80%, although some are capable of detection rates greater than 90%.[31]

One of the characteristic traits that can be automatically measured is the increase in physical activity that occurs during estrus. Kiddy[32] reported that the number of steps taken per hour by a cow in estrus is about two- to fourfold higher than in diestrus. As reported by Sakatani *et al.*,[33] in winter the increase in the physical activity of cows in heat was 400% and in summer only 175%. This was due to heat stress, which may not only have an effect on the reduction of visible signs but also result in a shift in the ovarian cycle.

The walking activity of a cow can be measured using a pedometer, an electronic device which is attached to the animal's leg or other part of the body, or with an accelerometer, which measures acceleration and uses algorithms to calculate the physical activity of the cow, making it possible to estimate the best time for insemination.[34–36]

Pedometers which are based on the natural behavior of animals cannot be used in all animal housing systems. Roth[34] showed that the activity of cows increased by 93% during estrus when the cows were housed in free stall barns. However, a much lower activity increase of 14–20% was observed in the case of tie stall barns. Therefore the full potential of pedometers can only be attained through the use of free stall barns in breeding.

The accuracy of the current generation of pedometers ranges from 49 to 90% and may depend on many environmental factors.[35] Brehme *et al.*[36] used the ALT pedometer in their study. The identification rate of cows 'positively in heat' was >90%, while the proportion of 'false positive' cows was approximately 10%. Similar results were obtained by Brunassi *et al.*[37] They studied the effectiveness of the SAE Afikim® pedometer installed on 98 Holstein Friesian cows. This device can efficiently detect 84.2% of all true estrus cases.

Kamphuis *et al.*[38] carried out an experiment that compared two activity collars. The first device was used to monitor only physical activity (AO collars) and the second to measure activity and rumination characteristics (AR collars). These devices were used to predict the occurrence of estrus in cows staying on pasture. The authors obtained the following results: the AR collars achieved 76.9% sensitivity, 99.4% specificity and 82.4% positive predictive value, whereas the AO collars achieved 62.4% sensitivity, 99.3% specificity and 76.6% positive predictive value.

Observation of rumination time can be another method of heat detection. Many publications report that rumination time on the day of estrus decreases by about 14–24%.[39] Reith *et al.*[40] also reported that it is possible to use HR-Tag sensors to detect estrus. On the day of estrus, activity increases on average by 38.7%, whereas data of daily rumination time were on average reduced by 19.6% (83 min day^{-1}). The proportion of estrual cows with increased activity was 76.5%. In contrast, 86.2% of all cows showed decreased rumination time during estrus. Similar results were reported by Pahl *et al.*[41] using the same measurement system.

Body temperature is another trait that can be helpful in assessing the time of estrus. The body temperature of cows in heat increases and this change can be used to determine the optimal time of insemination. Geers *et al.*[42] reported that the normal body temperature of cows is 38.6 °C. During the estrus cycle, this temperature changes significantly. Piccione *et al.*[43] found that rectal temperatures, though not measured automatically, displayed an even greater increase during estrus (1.3 °C). Similar observations were made by Fisher *et al.*,[44] who measured the vaginal temperature of Holstein cows, 21 of which had induced estrus and 12 were non-lactating, and recorded a mean temperature increase of 0.48 °C (ranging from 0.40 to 3.22 °C) at the time of the luteinizing hormone (LH) peak. The same authors developed a model based on vaginal temperature to estimate the time of the LH surge. Fisher *et al.*[44] suggest that the LH peak could be predicted to within a 6 h margin of error in 76% (16/21) of cows in estrus. The interval between the LH peak and ovulation amounts to 29 h on average[45] and enables the use of body temperature changes during the ovulation phase to create electronic devices which can be useful in heat detection.

Some currently available accelerometers are equipped with a thermometer. Dolecheck *et al.*[46] used CowManager SensOor and detected a significant increase in ear temperature during estrus, but their readings were not consistent. Moreover, the authors emphasized that the temperature of the ear to a large extent depends on external factors, and readings from the SensOor system cannot be used for the detection of estrus.

Several devices currently available on the market allow for the continuous measurement of cow body temperature. These may be in the form of intravenous bolus or vaginal inserts, for example (Thermochron Type SL, KN Laboratories, Osaka, Japan). The body temperature increase may be used to predict estrus, but it is a method susceptible to external conditions. According to Sakatani *et al.*,[33] the cow's body temperature changes with season. While it was possible to detect body temperature increases before the onset of heat in winter, this was not possible in summer. These fluctuations were caused by heat stress.

Table 1 shows a comparison of the effectiveness of heat detection using different devices. Most devices are very accurate in detecting the time when the cow should be fertilized: their efficacy is above 90%. The table shows that there are two heat detection systems that work by dye smudging placed on the back of the cow (HeatSeeker, TailMark). Each cow has a small container of dye attached to its back, which bursts when another cow jumps on it. Such systems also demonstrate high accuracy, but they require that each cow be examined at least twice a day.

CALVING TIME PREDICTION

Predicting calving time is a key factor in modern livestock farming (Table 2). With proper monitoring of the pregnancy and anticipation of calving time, it is possible to transfer the cow to the maternity pen (at the latest on the day of pre-calving). Cows are very willing to calf at night when no work is being done in the barn and no staff are present. This is highly problematic, because in the case of complications the breeder will not be informed and the resulting delay in intervention may result in the death of the calf. This situation is very common, because according to Lombard *et al.*[53] as many as 51% of primiparous dams and 29% of multiparous dams may require human intervention immediately prior to calving following significant changes in the concentration of hormones such as estrogen and progesterone in the cow's body. Moreover,

Table 1. Comparison of effectiveness of heat detection using different electronic devices

Name of device	Type of animal activity	Point of attachment	Sensivity (%)	Specifitity (%)	Accuracy of detection (%)	Literature source
SAE Afikim	Active resting	Leg	84	98	88.1	Brunassi *et al.*[37]
HeatSeeker	Standing heat	Back/rump	81.4	–	–	Cavalieri *et al.*[47]
TailMark	Standing heat	Tail	91.3	–	–	Cavalieri *et al.*[47]
HeatWatch	Standing heat	Back/rump	85.7	–	–	Cavalieri *et al.*[47]
Track a Cow	Active	Leg	100	91	91	Dolecheck *et al.*[46]
CowManager SensOor	Active Resting Eating Ruminating	Ear	100	99	99	Dolecheck *et al.*[46]
HR-Tag	Ruminating Active	Neck	100	96	97	Dolecheck *et al.*[46]
IceQube	Active	Leg	100	100	100	Dolecheck *et al.*[46]
Nedap Agri BV, Groenlo	Active	Leg	79.4–94.1	90–98.2	–	Hockey *et al.*[48]
AR collars	Active Ruminating	Neck	76.9	99.4	82	Kamphuis *et al.*[38]
AO collars	Active	Neck	62	99	77	Kamphuis *et al.*[38]

cow behavior is changed so that 4–10 days before calving the cow begins to look for a quiet place away from the herd. Such behavior is apparent in pasture with less than one cow per hectare.[54] In free-standing barns, this behavior will be less noticeable.[55] In the final 6 h period before calving, the cow spends less time lying down, more time in standing bouts and shows more physical activity.[56] At about 2–4 h before birth, there is a decrease in physical activity and the cow adopts a lateral lying position with its head rested.[56,57]

Another significant indicator of impending calving is a reduction in time spent on feed intake and rumination. In the last stage of pregnancy, there is a decrease in feeding time. This decrease amounts to 66 min on average over the last 24 h.[58] In the last 6 h, there is a 57% decrease in feed intake compared with rumination time during the dry period.[13] Rumination is also good indicator of calving time. The average reduction of rumination time on calving day is about 70% compared with rumination time during the dry period.[59] Moreover, cows stopped ruminating 123 ± 58 min (mean ± standard deviation) before calving and restarted 355 ± 194 min later.[60]

There are currently many different devices for detecting calving time. They work by detecting behavioral and physical changes occurring several days before calving. Behavioral changes such as increased physical activity can be measured using simple accelerometers that are typically used to detect heat. Tracking changes in feed intake and rumination requires more complex equipment such as SensOor, Hi-Tag or HR-Tag. Their primary function is to detect heat or symptoms of cow diseases.

There are also devices dedicated to detecting calving cows. The simplest solution is the iVet Birth Monitoring System with temperature biosensor. It is used to remotely transmit information about the upcoming birth. The biosensor is introduced in advance to the vaginal sheath. In the early stages of labor, it is pushed outward by the growing calf. The decreasing temperature of the biosensor generates a signal warning that the cow is close to birthing. Data can be sent from the sensor to the farm in the form of SMS messages. The next, more advanced device is Moocall. The Moocall system considers the frequency of contractions to determine when the calf will most likely be born and sends an SMS notification. The message is usually sent 1 h before birth at the time of the initial phase of contraction. Some devices require a small surgical procedure during the installation. For example, the C6 Birth Control sensor needs to be sewn onto the vulvar lips. Dedicated devices are very sensitive and detect the start of calving with almost 100% accuracy.

LAMENESS DETECTION

Lameness can be defined as the clinical manifestation of painful disorders mainly related to the locomotor system and resulting in impaired movement or deviation from normal gait or posture.[61] Lameness is one of the most common diseases in dairy herds and has become a significant problem for animal welfare, herd management and productivity. The occurrence of lameness leads to financial losses resulting from the cost of cattle treatment, lower milk production and reduced reproductive performance. To identify abnormal gait or lameness, some gait characteristics are used in the locomotion scoring of cattle. Walker *et al.*[62] reported that lame cows often spend more time lying down, walk less and show changes in their estrous behavior. Lame cows showed more asymmetry between left and right limbs in step width, step length, step time and stance time compared with non-lame cows.[63] According to Flower *et al.*[64] healthy cows walked faster (1.11 ± 0.03 *vs* 0.90 ± 0.05 m s^{-1}, mean ± standard error of mean), had shorter stride durations (1.26 ± 0.03 *vs* 1.48 ± 0.05 s) and longer strides (139.5 ± 2.1 *vs* 130.0 ± 3.2 cm) compared with cows with sole ulcers. Cows with a locomotion score of 4 or 5 spend less time feeding and consume less feed (dry matter intake) than those with a locomotion score of 1–3.[65] Additionally, Telezhenko and Bergsten[66] reported that moderately lame cows had a smaller step angle compared with non-lame cows on concrete flooring, while there were no significant differences between lame and non-lame animals when they walked on yielding surfaces. Furthermore, limb diseases cause significant decreases in milk production.[67] Early detection of lameness (even before visual inspection) is important for effective treatment and makes it possible to reduce financial losses to a minimum, enables the cow to quickly return to health and prevents the lameness from developing into a chronic condition. Many researchers claimed that sensitive accelerometers can detect subtle differences which appear in the behavior of cows in early disease states. The most frequent methods used

Table 2. Comparison of effectiveness of different electronic calving detection devices[49]

Calving signs detected	Type of sensor or technology	Device name	Place on/in cow
Tail raising and behavioral changes	Accelerometer or inclinometer	Alert'Vel (ALB Innovation)	Tail
		Calving Alert Set (Patura)	Tail
		SmartVel (Evolution XY)	Tail
		Moocall Sensor (Moocall)	Tail
Uterine and abdominal contractions	Pressure sensor	Agrimonitor (Databel Technics)	Abdominal harness
Fall in vaginal temperature and allantochorion	Temperature sensor	Radco (Verdor NV)	Vagina
		Vel'Phone (Medria)[a]	Vagina
		Vel'Box (Genes Diffusion)	Vagina
		Gyuonkei (NTT Docomo)	Vagina
Expulsion of calf	Temperature and light sensors	iVet (IVET)	Vagina
	Light sensor	Cow Call (Farmofy)	Vagina
	Mechanical signal	C6 Birth Control (Sisteck)[b]	Vulvar lips
	Mechanical signal + GPS antenna	GPS-CAL	Vulvar lips and collar
	Magnets	New Deal (Happy Foaling)	Vulvar lips

[a] Accurate prediction of calving 48 h: 82% for heifers and 100% for cows. Calf expulsion: 100% for heifers and 100% for cows.[50]
[b] Accuracy 95%.[51,52]

to detect lame cows include various types of visual interpretation of the locomotion of individual cows, i.e. visual locomotion scoring systems.[68] The problem with locomotion scoring is that this method requires experience to be conducted properly, is labor intensive as an on-farm method and the results are subjective.[69] There is evidence that lameness brings about significant changes in the behavior of cows. There is an increase in the time cows spend lying down[70] while mobility is reduced[71] and changes occur in weight distribution between the legs when standing.[72] These changes could be used for rapid detection of lameness. Several techniques have been proposed for automatic gait analysis, such as force platforms, electromyography, accelerometers and image-based technologies.

Kramer *et al.*[73] developed a fuzzy logic model for the classification of lameness based on the examination of the following variables: milk yield, dry matter intake, dry matter intake behavior (number of visits to the feeding trough, time spent at feeding troughs), water intake, activity and information about preliminary diseases as input data. They reported that when the block sensitivity was set to at least 70%, the accuracy of lameness detection ranged between 75.3 and 75.9%.

Basic methods of gait analysis have centered on the relation between limb/hoof events which are described in terms of footfall patterns or phase relationships between limbs.[61]

Pastell *et al.*[10] carried out an experiment in which they selected five sound and six lame cows. They fitted four three-dimensional accelerometers to each limb of every cow proximal to the fetlock joints. The accelerometers used an 869 MHz radio channel for transmitting the acceleration data, measured at 25 Hz with a sensitivity of 6 g. They found a significant difference in the symmetry of wavelet variance of the lame legs on level 1 wavelet detail, associated with changes over a 40 ms time scale. The most noticeable differences were detected in the final phase of the step when the hooves were hitting the floor.

Thorup *et al.*[74] carried out an experiment on four commercial farms where accelerometer data were derived from hind leg-mounted accelerometers (IceTag3D, IceRobotics, Edinburgh, UK) on 348 Holstein cows. The following information was collected by the accelerometers during the experiment: daily lying duration, duration of standing, walking duration, total number of steps and step frequency. Studies have shown that the lying duration of non-lame cows was 684 min day^{-1}, while this value increased by 40 min day^{-1} in the case of lame cows. On the basis of the obtained results, the authors concluded that the total acceleration while walking and walking duration seem to be particularly sensitive for the early detection of lameness. These results seem to be consistent with studies reported by Mazrier *et al.*[75] The authors indicated that lame cows are from 9 to 68% less active compared with healthy animals. In addition, nearly half of all lame cows showed a reduction in locomotor activity of 5% during the first 7–10 days prior to clinical symptoms.

Alsaaod *et al.*[76] reported that ALT pedometer measurements in combination with machine learning tools have the potential to detect lameness. Additionally, in the experiment, support vector machines with a radial basis function kernel have been used. In contrast to a prediction accuracy of 65% from the model derived for absolute values, this device predicts lameness with an accuracy of 76% using the deviation from normal behavior as feature. Van Hertem *et al.*[21] proved that neck-mounted sensors can also be used for lameness detection. They developed and validated a mathematical model to detect clinical lameness based on existing sensor data that were related to the behavior and performance of cows in a commercial dairy farm. All cows were equipped with behavior sensors (HR-Tag, SRC Engineers Ltd, Netanya, Israel) that measure neck activity and ruminating time. Moreover the cow's performance was measured with a milk yield meter in the milking parlor. The logistic regression model showed a sensitivity of 0.89 and a specificity of 0.85. In an experiment by Pastell *et al.*[77] four strain gauge balances were installed into a milking robot and used to measure the load of each leg, number of kicks and total time in the milking robot. The authors observed the changes in data and concluded that limb and hoof disorders can be detected using this system.

RUMINATION AND FEED INTAKE MONITORING

The monitoring of rumination times is potentially a very useful source of data about the health of the animals in the herd. Rumination is a clinical process characterized by regurgitation, re-mastication and re-swallowing. An important function of

Table 3. Comparison of effectiveness of different electronic devices in detecting chewing and rumination

Device	Traits monitored	Location	R^2	Literature source
Hi-Tag	Ruminating	Neck	0.77	Burfeind *et al.*[87]
CowManager SensOor	Active Resting Eating Ruminating	Ear	0.96	Grodkowski *et al.*[88]
Hi-Tag	Ruminating	Neck	0.87	Schirmann *et al.*[89]
RumiWatch	Jaw movements	Noseband	0.79	Zehner *et al.*[90]

rumination is to facilitate digestion, particle size reduction and subsequent passage from the reticulorumen, maintaining high levels of feed intake. Rumination also increases saliva secretion and improves rumen functionality, because saliva aids the buffering of volatile fatty acids produced by microbial digestion.[78]

Decreased ruminating time may indicate the onset of calving[58] and the occurrence of heat stress or problems with metabolism.[79] Cows with decreased dry matter intake in the pre-calving period have much higher odds of experiencing subclinical post-calving ketosis.[80]

The use of rumination time data can be effective in preventing the many negative factors occurring in breeding.

Rumination is typically monitored through visual observation conducted either live[81] or from video recordings.[82] These methods are labor-intensive and typically allow only a few cows to be monitored simultaneously. Direct methods of monitoring rumination are based on sensors which detect the movement of the jaw (i.e. strain or pressure gauges) attached to or built into a halter.[83] For their installation, the devices require full-head halters, an attachment that could be uncomfortable for the animals and influence the outcome of the experiment. Moreover, early versions of these systems required that the sensors be connected to a computer for data transmission via cables. These problems have since been eliminated and the sensors have become lightweight and wireless, such as those used in SensOor, Hi-Tag or HR-Tag.

It transpires that it is difficult to make a positive diagnosis about a cow's state of health solely on the basis of rumination data. While this requires more information about the animal's physical activity, all of the previously mentioned measuring systems are capable of making such measurements. Sterrett *et al.*[84] used rumination time, lying down time, neck activity (from HR-Tags) and reticulorumen temperature (from DVM boluses) and concluded that these parameters can be useful in identifying the early phase of subclinical hypocalcemia and ketosis. Soriani *et al.*[85] reported that cows with reduced ruminating time before calving maintained it reduced after calving and suffered a greater frequency of disease than cows with greater ruminating time in late pregnancy. In more recent research, Steensels *et al.*[86] showed that cows with ketosis can be detected 1 day sooner before veterinary diagnosis with a precision of 76% and a sensitivity of 90% based on chewing, physical activity and milk yield data.

Table 3 shows a comparison of the chewing readings from three popular devices. They provide a high accuracy of measurement and can be used to detect metabolic diseases when the appropriate algorithms are introduced.

BODY CONDITION SCORE

The body condition score (BCS) of a dairy cow is an assessment of the proportion of body fat that it possesses.[91] Changes in cows' BCS value have been found to be a predictor of breeding values for health traits such as mastitis or fertility traits.[92] BCS can be measured using visual indicators or a combination of visual and palpation of key bone structures[93] or by automatic BCS system.[94,95] Krukowski[94] demonstrated the potential for using Mesa Imaging AG's (Zürich, Switzerland) SwissRanger SR-3000 sensor for assessing BCS. The data showed that 100% of predicted BCS were within 0.5 points of actual BCS and 79% were within 0.25 points. Spoliansky *et al.*[95] tested automatic BCS using a low-cost three-dimensional Microsoft Kinect camera (version 1; Microsoft Corp., Redmond, WA, USA). The authors showed a mean absolute error of 0.26, a median absolute error of 0.19 and a coefficient of determination of 0.75, with 100% correct classification within one step for BCS classes.

CONCLUSION

Automatic heat detection systems are subject to continuous improvement. Sensors have become smaller while being able to measure a wider range of activities such as the cow's daily step count and time spent lying down, ruminating or eating. The devices that are able to measure the most traits tend to be more accurate and have more applications in today's livestock farms. Monitoring devices support herd management through the early detection of animal diseases and nutritional problems.

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Early detection of mastitis in cows using the system based on 3D motions detectors

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Mastitis is one of the major health problems in dairy herds leading to a reduction in the leading to a reduction in the quality of milk and economic losses. The research aimed to present the system, which uses electronic 3D motion detectors to detect the early symptoms of mastitis. The system would allow more effective prevention of this illness. The experiment was carried out on 118 cows (64 Holstein Friesian and 54 Brown Swiss). The animals were kept in free-stall barn with access to pasture. The occurrence of mastitis cases was noticed in veterinary register. Microbiological culture was taken from milk in order to confirm the development of infection. Data from motion detectors were defined as time spent by animals on feed intake, ruminating, physical activity and rest, and were expanded by adding information about feeding group, breed type and lactation number. During analyses, two approaches were used to process the same dataset: artificial neural networks (ANN) and logistic regression. The obtained ANN and the logistic regression models proved to be satisfactory from the perspective of applied criteria of goodness of fit (area under curve—exceed 0.8). Quality parameters (accuracy, sensitivity and specifity) of logistic regression are relatively high (larger than 0.73), whereas the ranks of significance of the studied variables varied across datasets. These proposed models can be useful for automating the detection of mastitis once integrated into the farm's IT system.

Mastitis is one of the most common conditions which affect herds of dairy cattle. The occurrence of undiagnosed cases of mastitis in herd leads to an increased average of somatic cells content in milk, which worsens its technological properties e.g. reduced thermostability of milk or reduced cheese yield. Mastitis milk has negative effect on milk-processing because of increased enzymatic activity, the effect of which is lower efficiency of butter and cheese. As Halasa et al.[1] reported this condition also causes an increase in cost of treatment and in labour cost. Average cost of treatment of a single cow affected by mastitis in Western Europe is about Euro 27–43. After including all costs associated with mastitis such as: losses in milk production, costs of treatment, possible slaughter and other complications, yearly cost per cow is—according to various authors—is from USD 71[2] to USD 435[3]. By reason of increased breeding intensity one can also observe higher and higher costs connected with mastitis resulting from, among other things, early removal of animals from the herd. It also should be highlighted that mastitis has negative impact on cattle well-being[4]. It is observed that cows affected by this condition are characterized by lower motion activity, lower feed consumption and social behaviour disorders[5]. That is why early diagnosis of mastitis can lead to cost reduction and improvement of animal well-being. Moreover, increasing number of large dairy farms hat that is observable both in the USA and Europe makes breeders invest in automated production solutions.

At present two methods are used to detect mastitis, namely specific electrical conductivity[6] and content of somatic cells in milk[7], although it is very often diagnosed by visual confirmation of clinical signs. Devices that are used to detect mastitis are attached to teat cups or are embedded in interceptors in milking halls. On the other hand, the sensor system can be perceived as valuable alternative or extension of production automation to help with of mastitis detection. It causes additional increase in costs and complications in barn fittings. In recent years there has been a rapid development of information and measurement systems, which use various types of

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Data set/count	Model	Learning error	Val. error	tst error	Learning quality	Validation quality	Testing quality	AUC
HF-BS/3735	MLP 16:12:1	0.1799	0.2051	0.2044	0.7698	0.7762	0.7878	0.8433
HF/1989	MLP 15:19:9:1	0.1975	0.2294	0.2211	0.8010	0.8149	0.8008	0.8593
BS/1746	MLP 15:12:8:1	0.1633	0.1715	0.1670	0.7595	0.8169	0.8165	0.8255
HF-CO/1224	MLP 14:9:6:1	0.2345	0.2310	0.2653	0.7582	0.7516	0.7876	0.8645
HF-PA/765	MLP 14:4:1	0.1735	0.2027	0.2026	0.7963	0.7801	0.7644	0.8793
BS-CO/1032	MLP 14:5:1	0.1443	0.1057	0.1496	0.7539	0.7364	0.7907	0.8012
BS-PA/714	MLP 14:4:1	0.1169	0.2231	0.1499	0.7675	0.7933	0.7921	0.8569

Table 1. List of created neural models, error values, accuracy and AUC for individual sets *MLP* multi layer perceptron, *AUC* area under curve.

motion detectors in order to support identification of behavioural patterns[8]. The above solutions serve to detect heat stress[9], lameness[10] and monitor time of ruminating[11]. Apart from the above, one can observe the use of systems based on other types of microcomputers, which allow to monitor pH in rumen, which is a good sign of problems with metabolism[12,13]. Other independent solution is the system of detecting mastitis during milking process[4], to which is included, among other things, advanced robotic milking. The aforementioned inflammatory condition of a cow's udder has a substantial influence on a cow's activity, which is also confirmed by other authors[4,5,14]. That is why it seems justified to claim that monitoring of cows' behaviour in herd can also serve as a diagnostic sign of mastitis. At present there are systems equipped with electronic motion detectors, which allow to recognize various forms of cows' behaviours. After appropriate processing and after building proper models, information coming from such detectors can be the basis for early prognosis of mastitis occurrence. Nowadays, a number of mathematical approaches are known, which allow to predict of the value of dependent binary variable, starting from regression methods[15], through stochastic modelling[16] and modelling with Artificial Neural Networks (ANN)[17].

The applied logistic regression model not only allows to determine if change in cow's behaviour had a substantial impact on pronouncing mastitis but also it will allow to identify which of the variables can be prognosis variables, which can be used to assess probability of mastitis development. An alternative approach to the signalled issue is the use of ANN, which is one of the methods of artificial intelligence. In recent years ANN has become popular to such an extent that now it is difficult to find a field of science, in which there were no endeavours made to make use of the effectiveness of this tool. ANN allow filtration of signals, elimination of noises, classification of images and steering robots. ANN is an effective tools, which allows reproducing complicated between properly selected input variables, and properly defined output variables. In cases with classification problems during generating models (testing, validation, verification), the factors which have impact on the quality of parameters in a network are: speed of learning, size of errors and generalization capability.

The main aim of the research was to verify the possibilities of building up classification models with statistical tools and methods of artificial intelligence based on data obtained from the systems based on 3D motion detectors. The above model would make it possible to detect health conditions such as mastitis at an early stage. Moreover, due to the increasing number of large dairy farms in both the USA and Europe, breeders are more likely to invest in automated production solutions.

Results

Neural modeling. The built of neural models as well as estimation of parameters concerning logistic regression models went according to the rule of top-down approach. It means that while creating both types of models, data coming from the biggest HF-BS set, were taken. The most optimal network for the aforementioned HF-BS set was neural typology type: 16–12-1 (Multilayer Perceptron) including 16 neurons in the input layer, 12 neurons in the hidden layer and 1 neuron in the output layer. Values of individual errors obtained for this model; learning, validation, testing and quality parameters corresponding to them in combination with AUC measurement were presented in Table 1.

In Table 1, characteristics of individual models were put together, namely the number of input neurons, the number of neurons in the hidden layer and the number of neurons in the output layer.

MLP neural models that were created are characterized by similar error values (of course slight differences can be noticed) from the perspective of classification of animals suffering from mastitis. Similar observations were made on the basis of AUC determining the surface area under ROC curse (Table 2). Creating models based on Statistica involved doing analysis of sensitivity of the obtained networks. Ranks of quantitative and qualitative variables together with their error quotient for individual MLP neural models were presented in Table 2. The sensitivity analysis is presented separately for the learning and validation set (Table 2). These indications are a valuable indicator of the correctness of a given assessment. The sensitivity is presented in the form of error ratio and rank:

- error ratio—it is a ratio of error to error obtained using all the independent characteristics; the greater the ratio, the greater the significance of given characteristics;
- rank—indicator characterizing numerical characteristics in order of decreasing error, where a rank of 1 is the most important for the network.

Data set Rank/error quotient	HF-BS	HF	BS	HF-CO	HF-PA	BS-CO	BS-PA
AV-TACTIV	**5/1.0750**	**5/1.0878**	10/1.0025	11/1.0044	7/1.0030	**3/1.0882**	7/1.1139
SD-TACTIV	14/1.0118	10/1.0379	14/0.9999	15/0.9997	6/1.0036	14/1.0020	**4/1.2963**
AV-ACTIV	9/1.0321	13/1.0233	12/1.0018	**4/1.0342**	15/0.9988	8/1.0290	14/0.9994
SD-ACTIV	8/1.0517	15/1.0042	15/0.9994	12/1.0024	13/0.9998	7/1.0343	13/1.0037
AV-HACTIV	15/1.0075	14/1.0098	**4/1.0257**	10/1.0048	**3/1.0081**	12/1.0102	**5/1.2174**
SD-HACTIV	11/1.0226	8/1.0534	8/1.0086	13/1.0006	11/1.0017	**4/1.0754**	**3/1.3453**
AV-INTAKE	13/1.0163	7/1.0609	13/1.0008	6/1.0173	**5/1.0045**	**2/1.1757**	11/1.0080
SD-INTAKE	**2/1.1185**	**2/1.1832**	**1/1.1250**	**5/1.0200**	9/1.0019	9/1.0237	**1/2.0641**
AV-RUMIN	16/1.0069	11/1.0376	7/1.0090	9/1.0060	14/0.9996	13/1.0036	9/1.0223
SD-RUMIN	10/1.0254	9/1.0532	11/1.0020	7/1.0119	8/1.0027	**5/1.0741**	8/1.0660
AV-REST	12/1.0201	12/1.0363	6/1.0098	8/1.0101	10/1.0018	11/1.0199	6/1.1902
SD-REST	6/1.0750	6/1.0628	**5/1.0109**	**3/1.0567**	**2/1.0149**	10/1.0208	12/1.0044
LOCAL	**3/1.1168**	**3/1.1605**	**3/1.0438**				
FEEDGR	**1/1.2456**	**1/1.1921**	**2/1.0584**	**1/1.1289**	**1/1.0201**	**1/2.8434**	**2/1.7219**
BREED	**4/1.1109**						
LACT	7/1.0671	**4/1.1251**	9/1.0059	**2/1.0749**	**4/1.0058**	6/1.0651	10/1.0133

Table 2. Ranks of variables with error quotient for seven neural models. *AV-TACTIV* average of total activity, *SD-TACTIV* standard deviation of total activity, *AV-ACTIV* average of activity, *SD-ACTIV* standard deviation of activity, *AV-HACTIV* average of high activity, *SD-HACTIV* standard deviation of high activity, *AV-INTAKE* average of feed intake, *SD-INTAKE* standard deviation of feed intake, *AV-RUMIN* average of rumination, *SD-RUMIN* standard deviation of rumination, *AV-REST* average of rest, *SD-REST* standard deviation of rest, *LOCAL* localization, *FEEDGR* feeding group, *BREED* breed, *LACT* lactation number (primiparous vs older cows). Significant values are in bold.

Logistic regression. The preliminary analysis (including estimation of correlation coefficients) was performed. In the process of selecting clarifying variables for logistic model within the frame of initial analysis, a correlation matrix was determined for continuous variables related to activity. For example in HF-BS set the highest positive correlation occurred between accumulative activity and activity (0.86), and negative correlation between time of taking feed and resting (−0.73) and between activity and ruminating (−0.54). Accumulative activity was also highly correlated with high activity (0.59) and ruminating (−0.54). Similar relations occurred in the remaining data subsets that were analysed. On account of correlations and occurrence co-linearity, accumulative activity was removed on this stage (Table 3). In case of HF-BS set in single analyses, where influence of each clarifying variable on logarithm of chance was researched, all variables with the exception of location had substantial influence on dependent variable. However, in multi-variable model, effect of location was significant. The tests that were done, which checked the linear relationship of logarithm of odds and independent variables, indicated curvilinear relationship in some cases. The above fact was the reason for adding variables of their squares to the set, which often resulted in elimination of variable itself, which was deemed unimportant and is presented in Table 3. Implementation of those variables substantially improved model matching. Estimation of logistic regression parameters for the seven datasets together with the importance of individual variables is presented in Table 3. However, measurements of matching quality and prediction, which show the adequacy of the created models, are presented in Table 4.

Only in model related to BS-PA set, extending average time of feed intake, had statistically significant effect i on diagnosing mastitis, in the remaining cases this effectwas negative. In majority of analysed models, variables related to motion activity or ruminating had a significant effects on detecting mastitis, for which a high rate of correlation was observed. Also in this case it is difficult to explicitly determine common direction of influence of those variables on all models. However, it seems that increase in motion activity results in lower chances of diagnosing mastitis. Similarly, longer period of motion inactivity, in case of the analysed models has different direction of influence. Those seemingly contradictory observations that are signalled above can result from accumulative activity of variables in individual models. It makes it hard to formulate general conclusions with reference to individual variables.

Among quality variables, feeding group variable had a substantial impact on probability of developing mastitis. In all the analysed models except the model based on BS-PA set, cows from group 3 were at higher risk of developing mastitis compared with cows from group 1 (group 1 was a level of reference). For BS-PA model, a reverse relationship was observed, a chance of developing mastitis was substantially decreased (−3423). Influence of feeding group 2 on developing mastitis is less explicit from the perspective of the analysed models. In turn, being in the first lactation had a substantial impact, combined with other variables, on probability of developing mastitis. On the basis of Table 3, it can be observed that first lactation variable, was deemed essential and added only to models concerning HF cows, and had a diversified direction of influence.

Variable	HF-BS	HF	BS	HF-CO	HF-PA	BS-CO	BS-PA
AV-ACTIV	−0.200**	−0.295**					
(AV-ACTIV)^2			−0.052**				0.312**
AV-HACTIV	−0.443**		−1.667**			−1.093**	3.542**
(AV-HACTIV)^2		−0.037**					
AV-INTAKE	−0.496**	−0.790**	−1.029**		−0.579**	−0.281**	2.996**
(AV-INTAKE)^2	0.009**	0.018**			0.015**		
AV-RUMIN				0.362**			2.499*
AV-REST			−1.224**	0.385**		−0.81**	2.755**
(AV-REST)^2			0.012**			0.016*	
FEEDGR-2	0.179	−1.742**	2.384**	−1.304	−19.967	2.625*	−2.335**
FEEDGR-3	2.137**	1.597**	3.769**	1.572**	1.455**	4.308**	−3.423**
LACT-1	0.432*	0.393**		1.299**	−0.994*		
LOCAL-1	−0.946**	−0.458*	−1.133**	–	–	–	–
LOCAL-2	0.238	0.167		–	–	–	–
BREED-HF		–	–	–	–	–	–
INTERCEPT	4.613**	6.576**	40.524**	-17.9213**	2.165	10.731**	– 157**

Table 3. Estimates of parameters of logistic regression equations. *AV-ACTIV* average of activity, *AV-HACTIV* average of high activity, *AV-INTAKE* average of feed intake, *AV-RUMIN* average of rumination, *AV-REST* average of rest, *FEEDGR-2* feeding group with milk yield over 11 kg milk per day, *FEEDGR-3* feeding group with milk yield less than 11 kg milk per day, *LACT-1* first lactation, *LOCAL-1* cows in the barn, *LOCAL-2* cows in the pasture, *BREED-HF* Holstein–Friesian breed. *p < 0.05. **p < 0.01.

Criteria Dataset/count	Rate R^2 Negelkerke	BIC	Hosmer Lemeshow's p-value	AUC
HF-BS/3735	0.237	0.367	0.801	0.8350
HF/1989	0.267	0.441	0.397	0.8439
BS/1746	**0.375**	**0.256**	**0.949**	**0.9140**
HF-CO/1224	0.321	0.461	0.395	0.8607
HF-PA/765	0.217	0.409	0.659	0.8252
BS-CO/1032	**0.297**	**0.234**	**0.972**	**0.8930**
BS-PA/714	**0.437**	**0.323**	**0.894**	**0.9270**

Table 4. Criteria of matching quality and prediction for individual datasets. *BIC* Bayesian information criterion, *AUC* area under curve. Significant values are in bold.

	Training dataset			Validation dataset		
	Classified as sick	Classified as healthy	Sensitivity	Classified as sick	Classified as healthy	Sensitivity
Observed (sick)	154	55	74	159	50	76
Observed (healthy)	707	2819	80	840	2686	76

Table 5. Classification of cases with logistic regression for HF-BS set. Accuracy in this model with cut-out points determined this way is ACC = 0.7960, sensitivity SE = 0.7368, and specificity SP = 0,7995, for validation respectively ACC = 0.7617, sensitivity SE = 0.7608, and specificity SP = 0.7618.

Different measurements of adequacy evaluation of models used in seven datasets were applied to the hierarchical structure (Table 4). Conformity of conclusions is the main argument to claim that the analyses were done correctly. In general, quantities of criteria that were obtained for all datasets, can be deemed satisfactory. It is true that ranks of matching according to various criteria are not identical, but still it is possible to claim that models for BS breed can be seen as better matched (values in grey). On the other hand, regression models describing HF and HF-PA sets of cows were matched to a lesser degree. It seems that low frequency of mastitis could substantially influence the model's adequacy in case of cows staying on grazing land. Cows with symptoms of mastitis are usually transported to barn. Model matching is not only dependent on a number of observations. Criteria values for the whole material (all together, 3735 observations of both breeds), correspond with this thesis/argument.

Table 5 shows classification effects with logistic regression and cut-out point of π_0= 0.079, determined with Juden's index for trial test for HF-BF set and for validation in the same dataset (π_0= 0.067).

Figure 1. View of the system's structure, transmission routes and data analysis.

Discussion

Data obtained directly from the system during the research and then enriched with additional information, were not a comfortable source of data allowing building up neural and statistical models because of their number (about 1 million records), their diversity and the fact that they were made available in the form of text file. Because of that, the data migration process was carried out, to structures embedded on SQL level Server 2017. Using possibilities of T-SQL language, actions were taken to improve data quality and indirect structure was created, which included aggregates obtained with grouping questions based on built-in statistical functions. Grouping was carried out based on the column cow's identifier and date. This additional relation together with merging substantially speeded up realization of questions, which were used to create sets used in the process of building up the aforementioned models. The process of generating datasets was not trivial because of the adopted research assumption. One of the aims was to determine a period of mastitis occurrence. The system contained only information about the day of diagnosing the disease. However, in the process of creating sets, a rule was adopted that three days before disease detection and two days after disease detection were to be considered as morbidity. The recognized periods in the form of unique dates, were one of the essential criteria in selection, during the process of creating datasets concerning sick animals and healthy animals. Another limitation in generating those sets included and taking into consideration only data coming from days when temperature and humidity index (THI) was lower than 72. According to research by Armstrong[18] and survey article by Polsky and Keyserlingk[19], a comfort threshold of THI for cows is 72. Additional conditions were adopted in the process of creating datasets concerning healthy animals. Only cows that did not show any morbidity symptoms during the whole period of research were assigned to this group. Cows suffering from other, concomitant diseases are characterized by substantial changes in behaviour in comparison with healthy cows a lot of days before diagnosis[14,20], for this reason, such cows were deleted from the dataset.

Before the research, the system shown in Fig. 1 was calibrated to adapt its sensitivity to specificity of the herd. It was made on the basis of observation of a selected cow's behaviour every minute for the period of one hour and then it was compared with data coming from the system. After 56 h of observations, including different cows, the following coefficients/rates of compliance determination of records in surveys and readings from the systems were obtained: taking up feed $R^2 = 0.86$, ruminating $R^2 = 0.97$, rest $R^2 = 0.94$[21]. It was agreed that the system classifies individual types of cows' behaviours in a sufficient way. The process of selecting optimal set of clarifying variables for a given model (model 1), was carried out with strategy of reverse steps, starting from model with all measured variables, which described behaviour of cows with concomitant quality variables. In another steps, irrelevant variables were eliminated. A detailed description of the procedure that was given by Hosmer and Lemeshow[22]. The idea of isolating learning test and trial test was abandoned because of small number of infection cases in the analysed sets. In order to evaluate a degree of model matching, a valuation technique was adopted based on v-repeated cross-testing[23]. Due to this strategy, there was possibility to evaluate quality of model matching without necessity of creating trial test.

Verification of the model included evaluating of: importance of variables and groups of variables, goodness of fit of the model with observed data and quality of prediction. The obtained error values, despite begin satisfied, made the authors build up another model on the basis of the previously signalled subsets, eliminating the influence of some factors (Table 1). It should be emphasized that in case of the remaining sets, MLP network turned out to be the best network. Low and similar RMS error values for training sets, validation sets and testing sets, prove that the generated ANNs have good generalization features and in turn it means good classification capabilities. Therefore both small RMS error and AUC rate values indicate that the proposed neural models used to detect mastitis on the basis of the accepted input variables are characterized by proper/adequate capability of knowledge generalization. They also indicate that the actions that were taken in the form of creating subsets as way of eliminating influence of some factor did not have substantial impact on changes during the process of classification improvement. Both RMS and AUC values showed negligible fluctuations (Table 2). The key variables in the process of ANN concerning sets HF-BS, HF, BS (including animals of both breeds and animal from just one breed), are quality variables, to which we include feeding group and location to a lesser degree. Quantitative variables extracted from the system with 3D motion sensors are equally important. These are quantities (estimators) connected with feed condition and one of the activity forms separate for one BS model.

The remaining models concerning subsets, where impact of breed and incomplete way of location (animals staying partially in barn were assigned to grazing land group) was consciously eliminated, had its root cause in limited number. From the perspective of gravity/importance of individual variables, some similarity was visible in connection with the previously analysed group. In this case, quality variable „feeding group" turned out to be still significant, and there was another quality variable „first lactation", which kind of „took the floor". In terms of gravity/importance, they are mostly separated from quantitative values coming from the system monitoring condition of animals' activity. However, it is not easy to notice any regularity out of 12 estimators concerning animals' conditions.

For the seven detailed datasets, the remaining five values related to activity were initially taken into consideration in further actions. However, the estimated coefficient of variance inflation factor for single variables counted in a couple of hundreds, clearly signalled the need for limiting the number of variables. Reduction of the number of continuous clarifying variables to four variables, substantially improved VIF coefficient, which were below 2.5. In the process of selecting reduced number of variables for single data sets, the authors took advantage of additional reverse step procedure. Selection of completely different set of variables caused model matching with similar characteristics, which is justified in correlation between variables (Table 3).

Analysing the results in Table 3, it can be observed that continuous variables coming from the system using 3D motion sensors had a substantial impact on evaluating the probability of developing mastitis. Variable, which turned out to be essential in almost all models, was time of activity related to taking feed, with the exception of HF-CO group. In this case, rest was an essential variable, which, as was already mentioned, was correlated with the eating variable. Despite the fact that this variable did not always show linear relationship with logarithm of odds, after including it as the second degree variable, it had a substantial influence on improving quality of model matching. It is worth noting the fact that for HF-BS model, built up on the basis of the set including both breeds, breed was not deemed essential as a variable used to recognize symptoms of mastitis. Different observations concern location variable, which has a substantial modifying effect. It refers to models marked HF-BS, HF and BS. To sum up, the presented neural models and models of logistic regression show similar capability of classification for healthy animals and for animals with mastitis. It should be added that the above models were built upon the basis of the processed data coming from the information system cooperating with 3D motion sensors and were enriched with quality variables. Similar AUC values, which are common classification quality rates for both models, prove the above assumption. It also should be noted that a similar character of ROC curve was obtained for all models. In both approaches the same quality variables concerning feeding group and location had a substantial influence on models. Being primiparous had a substantial importance only in relation to models built up on sets concerning HF cows. It was observed that breed had different impacts on detecting mastitis, with some surprise. This variable was important for neural model, but it did not appear/occur in logistic regression. HF-BS set was the basis for building up both models.

In case of essential continuous variables, describing animal's activity, it was very difficult to observe some regularity in both variants for all models, which is the result of the correlation that was found. However, we observe a substantial influence of time spent on feed taking on detecting mastitis in all neural models and in all models of logistic regression. All the remaining continuous variables are characterized by random rank from the perspective of neural models that were obtained. However, in logistic regression one cannot find a simultaneous influence of all continuous variables. Their sets, essential for individual models, are diversified/different. Currently, in the specialist literature, many publications describe the possibility of detecting mastitis by measuring resistance in milk or measuring the content of somatic cells in milk[24,25]. Cavero et al.[26–28] in those research, they used three different approaches for the same data, which allowed detecting mastitis on the basis of somatic cells in milk. They found the following SE and SP values respectively for models fuzzy logic, locally weighted polynomial regression and neural networks: SE 83%, 88% and 79% while SP: 76%, 67% and 61%. Jensen et al.[29] on the basis of data coming from many different sensors (among other things: milk yield, milk conductivity, fat and milk protein content, number of somatic cells in body mass), created an algorithm, which allows to process and categorize data in real time. Due to it, it was possible to match models on levels: AUC 0.81 and (SP 81% and SE 80%). Post et al.[30], who used in their research on cow classification data coming from milking room (volume of milk, conductivity, milk flow, somatic cell count) and data related to feed intake and general animal activity, which was measured with pedometers, obtained similar results. Among numerous models that were tested, the best matching was obtained for Extra Trees Classifier AUC 0.79. In both research with models that were selected, the highest ranks got the models with information about somatic cells.

Referring to the aforementioned works, it is currently difficult to find research that uses such a broad spectrum of data coming from motion detectors, describing behaviour of cows, in their mathematical models to detect mastitis. However, many works indicate changes in the behaviour of cows suffering from mastitis, which—as it was pointed out—can be the basis for classifying healthy and unhealthy/sick animals.

Conclusion

Generally, the applied neural and logistic regression models were satisfying. Small errors in the MLP neural models reflect their good generalization properties. While measurements of matching and prediction of regression models do not form the basis for their rejection. It is worth highlighting that in both approaches AUC with identical location of ROC curve (exceed 0.8).

The applied models indicated substantial differences in quality variables from the perspective of classification of animals suffering from mastitis: feeding group and location as well as continuous variables obtained from the information system determining period of time of various forms of animal activity. The diversified input of continuous variables in both types of models has its origin in the correlation between variables and imperfections of the information system cooperating with 3D motion sensors, despite their calibration. An attempt that was made to eliminate the impact of some variables by reducing database in the process of constructing both types of models did not substantially improve their classification. Nevertheless, the models, by their reproduction in the information structures, within the frames of a system based on 3D motions sensors or on the basis of the new system can be helpful in the process of detection of mastitis.

Methods

Research material and management. The research was conducted on the Juchowo ecological farm located in the West Pomerania Province in Poland. Brown Swiss cows (BS) and Holstein Friesian cows (HF) are housed on the farm with free-stall boxes (for cows in lactation phase) and free-stall boxes with deep bedding (for cows in dry period). Average productivity of the herd was 6500 kg of milk in standard lactation. Cows were milked once a day at different intervals.

In the winter, the cows were fed with hay ad libitum and supplementation in the form of feed concentrates. During grazing season, if it was possible, animals were grazing green fodder growing on grazing land, and in barn animals received supplementation in the form of feed concentrates. The amount of feed concentrates was dependent on lactation stage (from 6 kg at the beginning of lactation to 1 kg at the end of lactation of feed concentrate per cow per day). Food concentrate was divided into two portions and was given to animals after morning and afternoon milking. The experiment started in August 2016. 118 cows were randomly selected (64 HF milk cattle and 54 BF milk cattle). The recorded animals varied according to age and lactation stage.

Registration of behaviour and production traits. CowManager Sensor, CowManager B.V., were attached to the recorded animals. The sensors were installed in accordance with the producer's recommendations, on the left auricle. The sensors measured cows' activity with acceleration measurement registered by accelerometer in three dimensions (3D). Next the data were transferred to router and then to servers belonging to the system provider, where the algorithm classified data to individual activities (taking up feed, ruminating, rest, low physical activity, high physical activity). The behavioural records were grouped in packages corresponding to consecutive hours. Data packets (hours of measurements) included cumulative number of minutes spent by cow on a given activity. The data were combined with information about mastitis (51 cases), which was detected by veterinary surgeon or by taking culture from a cow suffering from udder inflammation. As a result of the experiment that was carried out, more than 960 thousands of records were collected, which were used to draw up neural and regression models, which allowed detection of inflammation of udder.

Implementation of criterion concerning feeding groups (lactation groups), which was reduced to three groups. This division depends on a daily milk production. Cows, which were 5 days after calving, were assigned to the first group. The daily effectiveness of milk production went down to about 20 kg. After this time, animals were assigned to the second feeding group. The daily effectiveness of milk production in this group went down to about 11 kg. Cows producing less than 11 kg of milk per day were assigned to the third group. On top of that, cows before calving, which were supposed to be dried, were also assigned to the last group. Data modification was also carried out, which involved giving some of the factors numerical values. Numerical and quality values used to build up the models included:

- status of animal—average and standard deviation;
  - rest,
  - feed intake,
  - ruminating,
  - activity,
  - high activity—heat behaviours and cattle rush
  - computed total activity
- breed;
- feeding group;
- location;
- lactation number;
- health group.

The dates of observations for each animal (with ID) were recorded. A total of 3785 records were included to build up the predictive models of mastitis occurrence under a previously signalled restrictions. The process of creating the aforementioned sets including the aforesaid factors was carried out with T-SQL language structures such as named, sub questions and unions, which were finally embedded in the procedures. They can act as elements of the future information system, supporting diagnosis of mastitis in dairy cattle.

ANN as well as the logistic regression models from the perspective of mastitis detection, was realized on the basis of seven datasets (Table 6). The first two datasets included data concerning all animals from a given breed irrespective of their place of location. On the hand, the next four disjunctive datasets included information about individual animals from two different breeds in two different locations (grazing land and barn). In the second case, during the process of creating a set related to the location called grazing land, a rule was adopted to assign only those animals, which stay in this location for a few hours per day or for 24 h. The last analysed set included combined data, where breed and location were added to the models as factors. Quantitative and quality variables adopted in creating models, were signalled previously. In case of qualitative variables such as lactation group and location, three levels were included, but the first group was a dichotomous variable.

Marking	Description
HF-BS[a]	cows of both groups (Polish Friesian Holstein and Brown Swiss) in both locations
HF[a]	Polish Friesian Holstein cows staying in all locations
BS[a]	Brown Swiss staying in all locations
HF-CO	Polish Friesian Holstein cows kept in barn
HF-PA[a]	Polish Friesian Holstein cows staying both on the grazing land or in barn
BS-CO[a]	Brown Swiss cows kept in barn
BS-PA[a]	Brown Swiss cows staying both on grazing land and in barn

Table 6. Datasets marking. Marked sets [a]in the process of building up logistic regression models, some variables had the form of quadratic function.

Methods of data analysis

Neural modeling. Creating neural models involves searching for a type of network that is adequate for the set goals. On this basis it is possible to test various types of neural networks on Statistica level such as: line network, probabilistic neural network (PNN), generalized regression neural network (GRRN) network, MLP network and networks with radial base functions (RBF). The structure of sets that were taken into consideration consisted of input variables and 1 nominal output variable. Creating learning sets is inseparably connected with generating the remaining sets; validation set and testing set. It is carried out according to standard schema 2:1:1, which determines the number of subsets in relation to the whole. The testing subset does not take part in generating the classification model, which is the model the authors deal with. Creating training set becomes the basis for learning process, where we try to minimize learning error by using various types of learning algorithms. Another step is to validate quality of a given neural model, as a result of which we obtain appropriate quality measurements. While the last verification are parameters obtained on testing set. Root Mean Square (RMS) error is a standard measurement of classification accuracy of the generated ANN. This measurement is defined as accumulative error made by network on datasets. It is calculated according to the following formula:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (y_i - z_i)^2}{n}}$$

where: n is the number of all cases in learning sets, y_i is the ith empirical value, z_i is the ith values determined by ANN.

Small values of RMS error can signify that MLP neural types are characterized by appropriate capability of generalizing knowledge in classification issues.

Logistic regression. Another alternative approach used in this work is logistic regression. Dependent variable, similar to output variable in neural models had dichotomous character: 1 (cow with mastitis) versus 0 (healthy cow). It is assumed that we observe n of independent pairs of forms $(\boldsymbol{x}_i, y_i)$, $i = 1, \ldots, n$, where $\boldsymbol{x}_i' = (x_{0i}, x_{1i}, \ldots, x_{pi})$ and $x_{0i} = 1$, means vector $p + 1$ of determined variable values for ith of this unit, and $y_i = 0$or1 means, the aforementioned realization of random variable Y_i .

In the model of logistic regression, the formula of conditional probability is determined:

$$P(Y_i = 1/\boldsymbol{x}_i) = \pi(\boldsymbol{x}_i) = \frac{e^{\boldsymbol{x}_i'\boldsymbol{\beta}}}{1 + e^{\boldsymbol{x}_i'\boldsymbol{\beta}}}.$$

After processing and finding the logarithm of the above formula we obtain:

$$logitP(Y_i = 1/\boldsymbol{x}_i) = ln\frac{P(Y_i = 1/\boldsymbol{x}_i)}{1 - P(Y_i = 1/\boldsymbol{x}_i)} = \boldsymbol{x}_i'\boldsymbol{\beta}.$$

The left side of the equation is called an odd of mastitis occurrence. In the processed model, we estimate the logarithm of chance and assume that it depends on a linear way of clarifying variables. Vector of parameters β in the model was estimated using the Maximum Likelihood method adopted by Hosmer et al.[31].

In the case of each independent variable that was analysed, a possible relation with the dependent variable was checked, and then a model with single variable was determined, and verification of its significance was carried out. Because of determinants of logistic regression, as part of initial analysis of data for continuous independent variables, a correlation matrix was determined. In order to diagnose the occurrence of collinearity, a variation inflation factor (VIF) was determined, which should not exceed 2.5[32].

The significance of variables in the model were examined by likelihood-ratio test (LR) and incremental chi-square statistic test and Wald's test[33]. Adequacy of model was verified with Hosmer and Lemeshow test[22], which compares distribution of expected numerical strength with the observed numerical strengths in groups. Pseudo R^2 Nagelkerke[34] was also used to select the best model. It is based on the likelihood function and describes an improvement of predictions in the model relative to model with only intercept. Pseudo R^2 measurements are much lower than classical determination coefficient R^2 in regression models, its typical value is 0.2 to 0.5[22].

Measurement value of Pseudo R^2 similar to classical R^2 increases if we add another variables to model, that is why verification of the degree of model matching was also carried out with Bayesian Information Criteria[35]. On the basis of SE and 1-SP values, a ROC (Receiver Operating Characteristic) curve was constructed for all possible cut-out points. ROC curve was used as a tool to evaluate and compare classification models between each other. Area under ROC curve marked as AUC, can be treated as measurement of discriminative quality of a given model[36]. AUC values ranged from 0 to 1. AUC value above 0.5 indicates classification better than random classification. In the process of selecting the cut-out point for classification, Jouden index J = SE + SP − 1 was used. The optimal point of cutting-out is when the Jouden index takes maximum value Jouden 1950. Apart from regression coefficients, odds ratio was also estimated.

An assumption of linear relationship between logarithms of odds and independent variables with logarithm likelihood test, which compares models with a given variable and quadratic variables, was checked.

Another stage of model verification is an evaluation of predictive ability of model With the use of the model we predict the probability of success if this probability is higher than the set value π_0, called cut-out point we assume that mastitis occurred $\left(\hat{y} = 1\right)$, otherwise mastitis did not occur $\left(\hat{y} = 0\right)$. In logistic model it is assumed that cut-out point is usually 0.5.

With low frequency of occurrence of a given case, a lower value of π_0 can be adopted, on the basis of the observed occurrence[37].

On the basis of the predicted values, a classification matrix was created, in which number of properly and improperly classified cases was given (TP—true positive) and (TN—true negative) vs. (FP—false positve) and (FN—false negative).

Measurements of quality classification were also determined, which are commonly used in diagnostic models, namely accuracy, sensitivity and specificity.

$$\text{Sensitivity} : SE = \frac{TP}{TP + FN} \quad \text{Specificity} : SP = \frac{TN}{TN + FP}$$

$$\text{Accuracy} : ACC = \frac{TP + TN}{TP + TN + FP + FN} = \frac{TP + TN}{N}$$

These calculations (for both methods) were performed in Statistica package programs (Statistica version 13.3).

Ethics approval and consent to participate. The authors confirm that the study was carried out in compliance with the ARRIVE guidelines. The Second Local Ethics Committee for Animal Experimentation SGGW of the Ministry of Science and Higher Education (Poland) reviewed and approved all procedures. The consent of the local ethical committee WAW 2/70/2016 dated 12.16.2016. All cows were handled in accordance with the regulations of the Polish Council on Animal Care, and the Warsaw University of Life Sciences Care Committee reviewed and approved the experiment and all procedures carried out in the study.

Data availability

All data generated or analysed during the study are included in this published article. The datasets used and/or analysed in the current study are available from the corresponding author on reasonable request.

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Sakowski

....

Podpis

Warszawa, dn., 07.08.2023r.

Dr hab. Kamila Puppel, prof. SGGW
Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

OŚWIADCZENIE

Niniejszym oświadczam, że Pan mgr inż. Grzegorz Grodkowski jest wiodącym autorem w poniższej publikacji.

Oświadczam, że w publikacji:

Grodkowski G. (60%), Gołębiewski M. (5%), Slósarz J. (5%), Grodkowska K. (5%), Kostusiak P. (5%), Sakowski T. (5%), Puppel K. (15%), (2023). Organic Milk Production and Dairy Farming Constraints and Prospects under the Laws of the European Union. *Animals*, 13(9):1457 **(100 pkt., IF 3,231)**, mój udział polegał na stworzeniu konspektu pracy, przeprowadzeniu korekty językowej powstałej pracy oraz pełnienia funkcji autora korespondencyjnego w cyklu wydawniczym.

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....

Podpis

Warszawa, dn. 01.08.2023 r.

Dr hab. Marcin Gołębiewski, prof. SGGW
Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

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....
Podpis

Warszawa, dn., 21.09.23

Dr inż. Jan Slósarz
Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

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Wyrażam zgodę na wykorzystanie powyższej publikacji w zbiorze publikacji, stanowiących dysertację doktorską Pana mgr inż. Grzegorz Grodkowskiego pt.: „Przydatność dwóch ras bydła mlecznego (polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej) w ekologicznym systemie produkcji na podstawie analizy jakości mleka i dobrostanu krów".

Jan Slósarz
....

Podpis

Warszawa, dn., 8.08.2023

Dr hab. Tomasz Sakowski, prof. IGBZ
Zakład Biotechnologii i Nutrigenomiki
Instytut Genetyki i Biotechnologii Zwierząt
Polskiej Akademii Nauk w Jastrzębcu

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Podpis

Warszawa, dn., 07.08.2023 r.

Dr hab. Kamila Puppel, prof. SGGW
Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

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....

Podpis

Warszawa, dn., 8.08.2023.

dr hab. Tomasz Sakowski, prof. IGBZ
Zakład Biotechnologii i Nutrigenomiki
Instytut Genetyki i Biotechnologii Zwierząt
Polskiej Akademii Nauk w Jastrzębcu

OŚWIADCZENIE

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Grodkowski G. (60%), Sakowski T. (15%), Puppel K. (10%), Baars T. (15%), (2018). Comparison of different applications of automatic herd control systems on dairy farms–a review. *Journal of the Science of Food and Agriculture*, *98*(14), 5181-5188 **(35 pkt., IF 2,422)** mój udział polegał na stworzeniu konspektu pracy oraz pełnieniu funkcji autora korespondencyjnego w cyklu wydawniczym.

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Sakowski
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Podpis

Warszawa, dn., 07.08.2023r.

dr hab. Kamila Puppel, prof. SGGW
Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

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....

Podpis

Witzenhausen, 22 Aug 2023

Data i miejsce
Date and place

Prof. Ton Baars

Department of Immunopharmacology

Utrecht University, Utrecht, The Netherlands

OŚWIADCZENIE

Niniejszym oświadczam, że Pan mgr inż. Grzegorz Grodkowski jest wiodącym autorem w poniższej publikacji.

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Wyrażam zgodę na wykorzystanie powyższej publikacji w zbiorze publikacji, stanowiących dysertację doktorską Pana mgr inż. Grzegorz Grodkowskiego pt.: „Przydatność dwóch ras bydła mlecznego (polskiej holsztyńsko-fryzyjskiej i brunatnej szwajcarskiej) w ekologicznym systemie produkcji na podstawie analizy jakości mleka i dobrostanu krów".

DECLARATION

I declare that Mr. Grzegorz Grodkowski, M.Sc. is the lead author in the following publication.

I declare that in the publication:

Grodkowski G. (60%), Sakowski T. (15%), Puppel K. (10%), Baars T. (15%), (2018). Comparison of different applications of automatic herd control systems on dairy farms–a review. *Journal of the Science of Food and Agriculture*, *98*(14), 5181-5188 **(35 pkt., IF 2,422)** my participation consisted of substantive support and proofreading of the resulting text.

I consent to the use of the above publication in the collection of publications constituting the doctoral dissertation of Mr. Grzegorz Grodkowski, M.Sc. under the title „Suitability of two breeds of dairy cattle (Polish Holstein-Friesian and Swiss Brown) in an organic production system based on analysis of milk quality and cow welfare".

....

Podpis
Signature

Poznań, dn. 9. sierpnia 2023 r

Prof. dr hab. Tomasz Szwaczkowski
Katedra Genetyki i Podstaw Hodowli Zwierząt
Uniwersytet Przyrodniczy w Poznaniu

OŚWIADCZENIE

Niniejszym oświadczam, że Pan mgr inż. Grzegorz Grodkowski jest wiodącym autorem w poniższej publikacji.

Oświadczam, że w publikacji:

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Tomasz Szwaczkowski
....
Podpis

Warszawa, dn., 23.08.2023

Prof. dr hab. inż. Wojciech Mueller
Katedra Inżynierii Biosystemów
Uniwersytet Przyrodniczy w Poznaniu

OŚWIADCZENIE

Niniejszym oświadczam, że Pan mgr inż. Grzegorz Grodkowski jest wiodącym autorem w poniższej publikacji.

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....

Podpis

22.08.2023 Poznań
....

Data i miejscowość

Dr Kamila Tomaszyk
Katedra Metod Matematycznych i Statystycznych
Uniwersytet Przyrodniczy w Poznaniu

OŚWIADCZENIE

Niniejszym oświadczam, że Pan mgr inż. Grzegorz Grodkowski jest wiodącym autorem w poniższej publikacji.

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Kamila Tomaszyk
....

Podpis

Witzenhausen, 22 Aug 2023

Data i miejsce
Date and place

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Department of Immunopharmacology
Utrecht University, Utrecht, The Netherlands

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Podpis
Signature

Warszawa, dn., 8.08.2023

dr hab. Tomasz Sakowski, prof. IGBZ
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Instytut Genetyki i Biotechnologii Zwierząt
Polskiej Akademii Nauk w Jastrzębcu

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Sakowski
....

Podpis

Załącznik 1. Autoreferat

Autoreferat

mgr inż. Grzegorz Grodkowski

Katedra Hodowli Zwierząt
Instytut Nauk o Zwierzętach
Szkoła Główna Gospodarstwa Wiejskiego
w Warszawie
Ciszewskiego 8, 02-786
Tel.: 602 869 936
e-mail: grzegorz_grodkowski@sggw.edu.pl

I. Wykaz opublikowanych prac naukowych oraz wskaźniki dokonań naukowych

A. Publikacje naukowe w czasopismach znajdujących się w bazie *Journal Citation Reports* (JRC)

1. Solarczyk, P., Sakowski, T., Gołębiewski, M., Slósarz, J., **Grodkowski, G.,** Grodkowska, K., Biondi, L., Lanza, M., Natalello, A., & Puppel, K. (2023). The Impact of Calf Rearing with Foster Cows on Calf Health, Welfare, and Veal Quality in Dairy Farms. Agriculture, 13, 1829 **(140 pkt., IF 3,600)**
2. Grodkowska, K., Gołębiewski, M., Slósarz, J., **Grodkowski, G**., Kostusiak, P., Sakowski, T., Klopcic, M., & Puppel, K. (2023). The Effect of Parity on the Quality of Colostrum of Holstein Dairy Cows in the Organic Production System. Animals, 13, 1–14 **(100 pkt., IF 3,231)**.
3. **Grodkowski, G**., Gołębiewski, M., Slósarz, J., Sakowski, T., & Puppel, K. (2023). Comparison between the Behavior of Low-Yield Holstein-Friesian and Brown Swiss Cows under Barn and Pasture Feeding Conditions. Animals, 13, 1–14 **(100 pkt., IF 3,231)**.
4. **Grodkowski, G**., Gołębiewski, M., Slósarz, J., Grodkowska, K., Kostusiak, P., Sakowski, T., & Puppel, K. (2023). Organic Milk Production and Dairy Farming Constraints and Prospects under the Laws of the European Union. Animals, 3, 1–20 **(100 pkt., IF 3,231)**.
5. Kostusiak, P., Slósarz, J., Gołębiewski, M., **Grodkowski, G**., & Puppel, K. (2023). Polymorphism of Genes and Their Impact on Beef Quality. Current Issues in Molecular Biology, 4749–4762. **(70 pkt., IF 2,695)**.
6. Puppel, K., Gołębiewski, M., Slósarz, J., Kunowska-Slósarz, M., Solarczyk, P., **Grodkowski, G**., Kostusiak, P., Grodkowska, K., Madras-Majewska, B., & Sakowski, T. (2023). The Influence of Cold-Pressed Linseed Cake Supplementation on Fatty Acid Profile and Fat-Soluble Vitamins of Cows' Milk in an Organic Production System. Animals, 13, 1–12. **(100 pkt., IF 3,231)**.
7. **Grodkowski, G.**, Szwaczkowski, T., Koszela, K., Mueller, W., Tomaszyk, K., Baars, T., & Sakowski, T. (2022). Early detection of mastitis in cows using the system based on 3D motions detectors. Scientific Reports, 1–11 **(140 pkt., IF 4,997)**.
8. Puppel, K., Slósarz, J., **Grodkowski, G.**, Solarczyk, P., Kostusiak, P., Kunowska-Slósarz, M., Grodkowska, K., Zalewska, A., Kuczyńska, B., & Gołębiewski, M. (2022). Comparison of Enzyme Activity in Order to Describe the Metabolic Profile of Dairy Cows during Early Lactation. International Journal of Molecular Sciences, 23, 1–11 **(140 pkt., IF 5,600)**.
9. Sakowski, T., **Grodkowski, G.**, Gołębiewski, M., Slósarz, J., Kostusiak, P., Solarczyk, P., & Puppel, K. (2022). Genetic and Environmental Determinants of Beef Quality - A Review. Frontiers in Veterinary Science, 9, 1–8 **(70 pkt., IF 3,200)**.

10. Puppel, K., Gołębiewski, M., Slósarz, J., **Grodkowski, G.**, Solarczyk, P., Kostusiak, P., Grodkowska, K., Balcerak, M., & Sakowski, T. (2021). Interaction between the level of immunoglobulins and number of somatic cells as a factor shaping the immunomodulating properties of colostrum. Scientific Reports, 11, 1–9 **(140 pkt., IF 4,997)**.
11. Puppel, K., Staniszewska, P., Gołębiewski, M., Slósarz, J., **Grodkowski, G.**, Solarczyk, P., Kunowska-Slósarz, M., Kostusiak, P., Kuczyńska, B., & Przysucha, T. (2021). Using the relationship between concentrations of selected whey proteins and BHBA to characterize the metabolism of dairy cows in early lactation. Animals, 11, 1–9 **(100 pkt., IF 3,231)**.
12. Puppel, K., Gołębiewski, M., Konopka, K., Kunowska-Slósarz, M., Slósarz, J., **Grodkowski, G.**, Przysucha, T., Balcerak, M., Madras-Majewska, B., & Sakowski, T. (2020). Relationship between the quality of colostrum and the formation of microflora in the digestive tract of calves. Animals, 10, 1–14 **(100 pkt., IF 2,752)**.
13. Puppel, K., Kalińska, A., Kot, M., Slósarz, J., Kunowska-Slósarz, M., **Grodkowski, G.**, Kuczyńska, B., Solarczyk, P., Przysucha, T., & Gołębiewski, M. (2020). The effect of *Staphylococcus* spp., *Streptococcus* spp. and *Enterobacteriaceae* on the development of whey protein levels and oxidative stress markers in cows with diagnosed mastitis. Animals, 10, 1–11 **(100 pkt., IF 2,752)**.
14. Puppel, K., Gołębiewski, M., **Grodkowski, G.**, Solarczyk, P., Kostusiak, P., Klopčič, M., & Sakowski, T. (2020). Use of somatic cell count as an indicator of colostrum quality. PLoS ONE, 15, 1–15 **(100 pkt., IF 3,240)**.
15. Puppel, K., Gołębiewski, M., **Grodkowski, G.**, Slósarz, J., Kunowska-Slósarz, M., Solarczyk, P., Łukasiewicz-Mierzejewska, M., Balcerak, M., & Przysucha, T. (2019). Composition and factors affecting quality of bovine colostrum: A review. Animals, 9, 1–14 **(100 pkt., IF 2,240)**.
16. Puppel, K., Gołębiewski, M., Solarczyk, P., **Grodkowski, G.**, Slósarz, J., Kunowska-Slósarz, M., Balcerak, M., Przysucha, T., Kalińska, A., & Kuczyńska, B. (2019). The relationship between plasma β-hydroxybutyric acid and conjugated linoleic acid in milk as a biomarker for early diagnosis of ketosis in postpartum Polish Holstein-Friesian cows. BMC Veterinary Research, 15, 1–11 **(140 pkt., IF 1,835)**.
17. Yin, T., Jaeger, M., Scheper, C., **Grodkowski, G.**, Sakowski, T., Klopcic, M., Bapst, B., & König, S. (2019). Multi-breed genome-wide association studies across countries for electronically recorded behavior traits in local dual-purpose cows. PLoS ONE, 14, 1–24 **(100 pkt., IF 2,740)**.
18. **Grodkowski, G.**, Sakowski, T., Puppel, K., & Baars, A. (2018). Comparison of different applications of automatic herd control systems on dairy farms – a review. Journal of the Science of Food and Agriculture, 98, 5181–5188 **(35 pkt., IF 2,422)**.
19. Puppel, K., Sakowski, T., Kuczyńska, B., **Grodkowski, G.**, Gołębiewski, M., Barszczewski, J., Wróbel, B., Budziński, A., Kapusta, A., & Balcerak, M. (2017). Degrees of antioxidant protection : a 2-year study of the bioactive properties of organic milk in Poland. Journal of Food Science, 82, 523–528 **(30 pkt., IF 2,018)**.

B. Monografie, publikacje naukowe w czasopismach międzynarodowych lub krajowych innych niż znajdujące się w bazie, o której mowa w pkt. I A

1. Balcerak, M., Batorska, M.,, Damaziak, K., Głogowski, R., Gołębiewski, M., **Grodkowski, G.**, Kamaszewski, M., Kostusiak, P., Kuczyńska, B., Kunowska-Slósarz, M.: (red.) Kuczyńska, B.: Analiza Jakości Surowca Mięsnego, 2022, Szkoła Główna Gospodarstwa Wiejskiego w Warszawie (SGGW), ISBN 978-83-8237-085-0, 324, **(20 pkt)**.
2. Solarczyk, P., **Grodkowski, G.**, Kostusiak, P., & Puppel, K. (2020). Lokalne rasy bydła w Polsce. Przeglad Mleczarski: miesięcznik przeznaczony dla pracowników przemysłu mleczarskiego, 40–46 **(5 pkt.)**.
3. Solarczyk, P., **Grodkowski, G.**, Kostusiak, P., & Puppel, K. (2020). Pogłowie i rasy bydła mlecznego znane na całym świecie a użytkowane w Polsce. Przegląd Mleczarski: miesięcznik przeznaczony dla pracowników przemysłu mleczarskiego, 39–45 **(5 pkt.)**.
4. Kostusiak, P., Puppel, K., Kunowska-Slósarz, M., Slósarz, J., Gołębiewski, M., **Grodkowski, G.**, Solarczyk, P., Wiśniewski, K., & Przysucha, T. (2019). Beef cattle breeds in Poland. Annals of Warsaw University of Life Sciences- SGGW Animal Science, *58*, 261–277 **(5 pkt.)**.
5. Puppel, K., Łukasiewicz, M., Sakowski, T., Kuczyńska, B., **Grodkowski, G.**, Solarczyk, P., & Matuszewski, A. (2018). Rolnictwo ekologiczne w Polsce na tle krajów członkowskich Unii Europejskiej i świata. Przegląd Hodowlany, 1–5 **(6 pkt.)**.
6. Sakowski, T., Puppel, K., Gołębiewski, M., Kuczyńska, B., Metera, E., & **Grodkowski, G.** (2015). Influence of lactation stage on selected blood parameters and biological value of cow milk during pasture season in organic system of production. Annals of Warsaw University of Life Sciences- SGGW Animal Science, 95–104 **(12 pkt.)**.

C. Sumaryczny Impact factor według listy *Journal Citation Reports* (JCR), zgodnie z rokiem opublikowania

IF=61,326

D. Liczba cytowań publikacji według bazy *Web of Science* (WoS)

117

E. Indeks Hirscha według bazy Web of Science (WoS)

H-Index=5

F. Kierowanie międzynarodowymi i krajowymi projektami badawczymi oraz udział w takich projektach

1. Pozyskiwanie najwyższej jakości biodynamicznego mleka siennego A2. (Grupa Operacyjna JUCHOWOMILK). ARiMR 00020.DDD.6509.00338.2022.16, okres realizacji 01.01.2023-31.12.2024, budżet 1 614 058,00 zł - **wykonawca.**
2. „Wsparcie dla projektów demonstracyjnych i działań informacyjnych" w ramach działania „Transfer wiedzy i działalność informacyjna", objętego Programem Rozwoju Obszarów Wiejskich na lata 2014-2020, pt. Wsparcie dla projektów demonstracyjnych i działań informacyjnych" objętego PROW na lata 2014-2020 w zakresie Nowoczesnych technologii chowu i hodowli bydła ras mięsnych – na terenie Polski", ARiMR, nr SIWZ DDD.65141.2.2021, okres realizacji od 30.03.2023 do 30.06.2025, budżet 3 428 017,72 zł - **wykonawca.**
3. Poprawa dobrostanu zwierząt z wykorzystaniem szybkich przesiewowych badań pod kątem detekcji podwyższonej temperatury zwierząt oraz procesów termicznych w rolnictwie za pomocą uniwersalnego nieinwazyjnego oraz mobilnego detektora TherMobEye (Grupa Operacyjna Hodowla Przyszłości). ARiMR 00056.DDD.6509.00281.2022.03, okres realizacji 01.01.2023-31.12.2024, budżet 553 824,00 zł - **wykonawca.**
4. Kompleksowa usługa realizacji części merytorycznych prac dotyczących „Inteligentny system wykrywania porodu u krów „CalfCam". Szybka ścieżka – Agrotech PIOR.01.01.01-00-2235/20, okres realizacji 01.10.2021-30.09.2023, budżet 559 988,24 zł - **zastępca kierownika.**
5. Stworzenie narzędzia do monitorowania ilości i dostępności dla krów paszy na stole paszowym, przy użyciu kamer wideo. Inkubator Innowacyjności 4.0. MNISW/2020/358/DIR, okres realizacji 1.03.2022-30.04.2023, budżet 41 700 zł – **kierownik.**
6. „CoolCalf"- Opracowanie oraz przetestowanie w warunkach produkcyjnych zautomatyzowanego systemu sterowania mikroklimatem w budynkach inwentarskich, poprawiającego dobrostan cieląt, realizacja w ramach Bonu na Innowacje Polskiej Agencji Rozwoju Przedsiębiorczości, okres realizacji 01.09.2021-28.02.2023, budżet 482 754,11 zł - **kierownik.**
7. Kompleksowa usługa realizacji części merytorycznych prac dotyczących „Opracowania na bazie technik sztucznej inteligencji nowatorskiego systemu wykrywania zafałszowań mleka. Milk Fraud Analyzer (MFA)". Szybka ścieżka – Agrotech POIR.01.01.01-00-2162/20, okres realizacji 01.08.2021-31.10.2022, budżet 783 940,50 zł. - **kierownik zadania.**
8. Zwiększenie wydajności, efektywności wykorzystania zasobów i jakości produktów w celu poprawy konkurencyjności systemów produkcyjnych opartych o wypas bydła i produkcję pasz na użytkach zielonych, Program międzynarodowy ERA-Net SUSAN/I/SusCatt/01/2017, okres realizacji 01.09.2017- 31.08.2020, budżet 811 849,50 zł - **wykonawca.**

9. Profilaktyka zdrowotna w stadach rodzimego bydła dwustronnie użytkowego przystosowanego do ekologicznego systemu produkcji opartego na wykorzystaniu użytków zielonych oraz innowacyjnym podejściu do realizowanej strategii hodowlanej i zapisu ocenianych cech. Core Organic, CoreOrganicPlus/2-ORG-COWS/125/IGHZ/2015, okres realizacji 01.04.2015-31.08.2018, budżet 262 112,50 zł - **wykonawca PhD Student.**

G. Wygłoszenie referatów na międzynarodowych i krajowych konferencjach tematycznych

1. Kulig, B., **Grodkowski, G.**, Redlin, R.J., & Sakowski, T. (2019): Validation of a locomotive detection system in cows with the help of direct behavioral observation. Book of abstracts of the 70th Annual Meeting of the European Federation of Animal Science (24), Ghent, Belgium, 26-30 August 2019
2. **Grodkowski, G.**, Puppel, K., Sakowski, T., & Krzyczkowska, A. (2018): Biodynamic agriculture as a production system predisposing to obtain milk characterized by a high antyoxidant capacity, XXVI Szkoła Zimowa Hodowców Bydła, Zakopane
3. **Grodkowski, G.**, Sakowski, T., Puppel, K., & Baars, T. (2017): Die Nutzung von Bewegungssensoren zur Verhaltens und Gesundheitskontrolle von Kühen auf Weideflächen", XVII Polsko-Niemiecka Konferencja Naukowa, Balice 26-27.06.2017.
4. **Grodkowski, G.**, Sakowski, T., Puppel, K., Van Meurs, K., & Baars, T. (2017): Validation of an electronic herd control system for grazing dairy cows. Book of Abstracts of the 68th Annual Meeting of the European Federation of Animal Science (23) 2017, Tallinn, Estonia, 28 August - 1 September 2017.
5. Solarczyk, P., **Grodkowski, G.**, Wójcik, W., Puppel, K., & Sakowski, T. (2017): „The breed of cows as a factor shaping the quality of colostrum". V ogólnopolska studencka konferencja teriologiczna w Poznaniu, Poznań 18-21.05.2017.
6. **Grodkowski, G.**, Sakowski, T., Puppel, K., & Baars, T. (2017): Growth and seasonal changes in the botanical composition of sward", XXV Szkoła Zimowa Hodowców Bydła, Zakopane, 27-30.03.2017.

II. Dorobek dydaktyczny i popularyzatorski oraz informacja o współpracy międzynarodowej doktoranta

A. Artykuły popularno-naukowe

1. Gołębiewski, M., Kalińska, A., Radzikowski, D., Kunowska-Slósarz, M., & **Grodkowski, G.** (2022). Indywidualne i grupowe utrzymanie cieląt. Farmer, 118–121.

B. Udział w komitetach organizacyjnych międzynarodowych i krajowych konferencji naukowych

1. I Sympozjum Naukowe „Nauki o Zwierzętach w Praktyce Hodowlanej i Badaniach Biomedycznych"- 5.12.2019, Warszawa.

2. Udział w komitecie naukowym – sekretarz, w międzynarodowej konferencji „Studenci w Zootechnice i Akwakulturze – wyzwania i badania”

C. Otrzymane nagrody i wyróżnienia

1. Nagroda zespołowa III stopnia JM Rektora SGGW za osiągnięcia naukowe, 2022.
2. Nagroda zespołowa II stopnia JM Rektora SGGW za osiągnięcia naukowe, 2021.
3. Nagroda zespołowa III stopnia JM Rektora SGGW za osiągnięcia naukowe, 2020.
4. Nagroda zespołowa II stopnia JM Rektora SGGW za osiągnięcia naukowe, 2019.

D. Udział w komitetach redakcyjnych i radach naukowych czasopism

-

E. Członkostwo w międzynarodowych i krajowych organizacjach oraz towarzystwach naukowych

-

F. Osiągnięcia dydaktyczne w zakresie popularyzacji nauki lub sztuki

1. Koordynator ds. Monitorowania Losów Zawodowych Absolwentów Wydziału Hodowli, Bioinżynierii i Ochrony Zwierząt.
2. Członek Zespołu ds. Promocji i Współpracy z Otoczeniem Społeczno-Gospodarczym przy radzie Dyscypliny Zootechnika i Rybactwo.
3. Członek Zespołu Webmaster ds. Tworzenia i Projektowania Strony Internetowej Instytutu Nauk o Zwierzętach w ramach prac Komisji ds. Promocji i Współpracy z Otoczeniem Społeczno-Gospodarczym przy radzie Dyscypliny Zootechnika i Rybactwo.
4. Opiekun koła naukowego: Opiekun Sekcji Bydła- Koła naukowego hodowców Zwierząt Gospodarskich.
5. Opiekun laboratorium analiz mikroskopowych i laboratorium histologicznego Katedry Hodowli Zwierząt Instytutu Nauk o Zwierzętach SGGW.

W trakcie mojej działalności dydaktycznej prowadzonej na Wydziałem Hodowli Bioinżynierii i Ochrony Zwierząt SGGW w Warszawie realizowałem zajęcia na następujących kierunkach:

WYDZIAŁ HODOWLI, BIOINŻYNIERII I OCHRONY ZWIERZĄT

- **Hodowla Bydła,** Kierunek Zootechnika, Studia stacjonarne oraz niestacjonarne I° (ćwiczenia).
- **Propedeutyka zootechniczna**, Kierunek Zootechnika, Studia stacjonarne oraz niestacjonarne I° (ćwiczenia).
- **Analiza instrumentalna**, Kierunek Zootechnika, Studia stacjonarne II° (ćwiczenia).
- **Analiza instrumentalna**, Kierunek Hodowla Zwierząt Dzikich i Towarzyszących, Studia stacjonarne II° (ćwiczenia).

- **Intensywne systemy produkcji zwierzęcej**, Kierunek Zootechnika, Studia stacjonarne II° (wykłady).
- **Towaroznawstwo produktów pochodzenia zwierzęcego,** Kierunek Zootechnika, Studia stacjonarne oraz niestacjonarne I° (ćwiczenia).
- **Techniki diagnostyczne**, Kierunek Bioinżynieria zwierząt, Studia stacjonarne I° (ćwiczenia).

WYDZIAŁ MEDYCYNY WETERYNARYJNEJ

- **Chów i hodowla zwierząt**, Kierunek Weterynaria, Studia stacjonarne I° (ćwiczenia).

WYDZIAŁ ROLNICTWA I BIOLOGII

- **Chów zwierząt**, Kierunek rolnictwo, Studia stacjonarne I° (ćwiczenia).

G. Staże w zagranicznych i krajowych ośrodkach naukowych lub akademickich

-

H. Recenzowanie publikacji w czasopismach międzynarodowych i krajowych

-

I. Patenty i wdrożenia

-

J. Uzyskanie uprawnień zawodowych

- Uprawnienia inspektora rolnictwa ekologicznego: w rejestrze GIJHARS 0743 w zakresie:
  - → nieprzetworzone rośliny i produkty roślinne, w tym nasiona i inny materiał przeznaczony do reprodukcji roślin;
  - → zwierzęta gospodarskie i nieprzetworzone produkty pochodzenia zwierzęcego;
  - → przetworzone produkty rolne, w tym produkty akwakultury, do wykorzystania jako żywność;
  - → pasza;
  - → wino;
  - → wprowadzanie na rynek produktów ekologicznych, w tym importowanych z państw trzecich.
- Rzeczoznawca wpisany do rejestru WIJHARS pod nr 1619.
- Specjalista do spraw zarządzania projektem - Studium Prawa Europejskiego.
- Polskie Towarzystwo Nauk o Zwierzętach Laboratoryjnych PolLasa:
  - → szkolenie dla osób odpowiedzialnych za planowanie procedur i doświadczeń oraz za ich przeprowadzanie;
  - → szkolenie dla osób wykonujących procedury;
  - → szkolenie dla osób uśmiercających zwierzęta wykorzystywane w procedurach.

Sumaryczne zestawienie dorobku publikacyjnego

Tabela 1. Sumaryczne zestawienie **całkowitego dorobku** publikacyjnego

Lp.	Rodzaj Publikacji	Liczba prac	Zgodnie z datą publikacji	
			Punty MNiSW/MEiN	IF
1	Publikacje naukowe w czasopismach znajdujących się w bazie Journal Citation Reports (JCR)	19	1905	61,326
2	Monografie i publikacje naukowe w czasopismach międzynarodowych lub krajowych innych niż znajdujące się w bazie, o której mowa w punkcie I.A. (JCR)	6	53	Nie dotyczy
3	Doniesienia i abstrakty	6	Nie dotyczy	
4	Publikacje popularno-naukowe w czasopismach nie znajdujących się na liście MNiSW/MEiN	1	Nie dotyczy	
5	Łącznie	32	1958	

Warszawa, …………………………….