

# Precision Livestock Farming: The Opportunities in Poultry Sector

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**Abstract:** Precision management of animals using technology is one innovation in agriculture that has the potential to revolutionize whole livestock industries including the poultry sector. Limited research in precision livestock farming (PLF) in the poultry production has been so far conducted and most of them are conducted within the past 5-10 years. The PLF collects real-time data from individual or group of animals or birds using sensor technology, and involves the multidisciplinary team approach to give it a reality. Poultry scientists play a central role in executing poultry PLF with collaboration from agri-engineers and computer scientists for the type of measurements to be made on biological or environmental variables. A real-time collection of environmental, behavioral and health data from bird grow-out facilities can be a strong tool for developing daily action plans for poultry management. Unlike other livestock farming, the attributes of poultry rearing such as a closed housing system and vertically integrated industry provides a greater opportunity for poultry sector to adopt technology-based farming for enhanced production output.

**Key words:** Precision farming, poultry, sensors, data, management tool.

## 1. Introduction

“Precision”, a focal word in livestock farming including the poultry sector, refers to the precise control and optimization of production processes in order to improve animal welfare, productivity and profitability [1]. Precision management of animals using technology is one innovation in agriculture that has the potential to revolutionize whole livestock industries. Precision livestock farming (PLF) of commercial poultry has both challenges and opportunities because of the large size of the flock as PLF, in principle, involves monitoring farm animals at an individual level [2]. An important dimension of PLF that requires an initial consideration would be evaluating spatial distribution suitability of farm geography so that there is minimal environmental impact and greater prospect on economic viability of farm construction in a specific area [3]. Siting of a farm could be evaluated for slope gradient, land type, ecology conservation, cultural

relics, soil fertility demand, distance to transport route, distance to surface water, distance to residential area, and distance to existing large-scale livestock and poultry farms [3].

There is an ongoing discussion on whether the PLF technology in poultry precision management at individual bird level would be feasible or would still need considerable research and development before its acceptance to the poultry sector [4, 5]. Nonetheless, tremendous opportunity lies in the poultry sector for PLF technology [6]. Because of the fast growth rate, modern broilers are vulnerable to problems such as lameness, contact dermatitis, and metabolic diseases [7]. Using proper sensors and artificial intelligence technology such as ultra-wideband (UWB) tracking, computer vision (CV), accelerometers, or radio frequency identification (RFID), the potential remains to monitor the flock at an individual bird level [8-11]. The RFID is a form of wearable sensor technology whereas CV is the remote sensor technology. The RFID can be utilized in bird behavior study [8]. It

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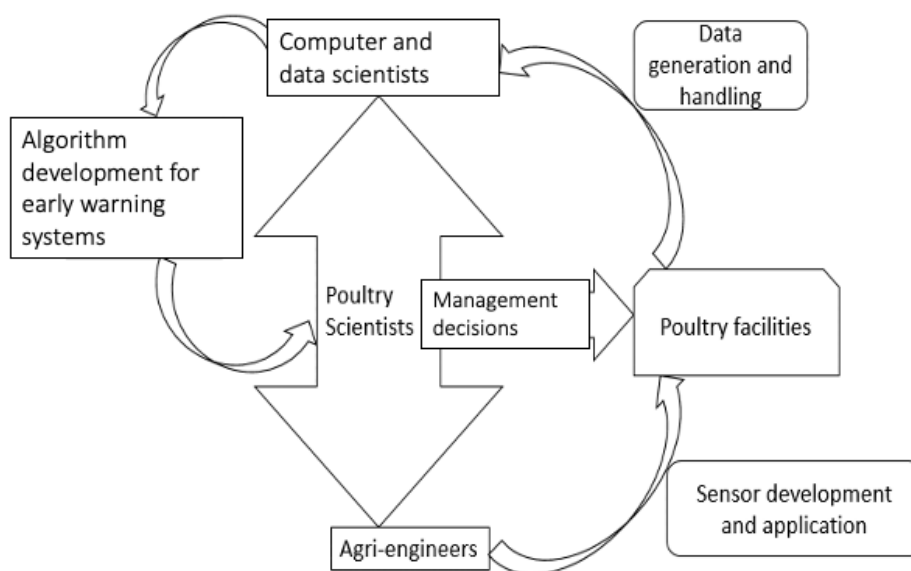
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becomes even more meaningful for poultry sector if PLF technology can be fully adopted as compared to its application in other livestock species as thousands of birds in the flock can be saved from early detection of one sick bird that needs to be culled from the flock before the situation transforms to endemic. The strength of PLF technology lies in its ability of distinguishing abnormal behavior or activities in early stage and real-time as a consequence of disease, injury or any type of stressors, and thus, applying corrective action to the affected flock that sick animal or bird represents. The poultry farming, like any other livestock farming, is faced with many challenges as more concerns are raised in animal welfare, antibiotic-free (ABF) production, and environmental impacts while producing the food animals [12-14]. Poultry producers and growers are optimizing their profit margin handling larger flocks with limited labor access and availability. A survey with poultry growers in one of the states in US showed the average number of employees per farm was 1.42 [15]. This necessitates an application of new technologies in grow-out facilities. The data outputs of PLF aid in enhanced monitoring of flock at the individual level

with minimal labor involved and promote in taking daily wholesome decision regarding flock management [16]. Unlike other livestock farming, poultry rearing is conducted in a closed housing system. Furthermore, the industry is vertically integrated, which allows more opportunity for the industry to adopt technology-based farming. This paper highlights the need of research and development of PLF in poultry sector, and traces the past and current research on the sensors and technology used in poultry facilities to collect and understand the barn environment, health and welfare, and feeding behavior.

## 2. PLF Is a Multi-disciplinary Approach with Poultry Scientists in a Key Role

The PLF is a multi-disciplinary team approach of mainly poultry scientists, agri-engineers, and computer scientists to make poultry PLF a success or a reality. The poultry scientists play a key role in precision poultry farming as understanding the fundamentals of bird biology and management cannot be overruled. Fig. 1 represents the schematics outlining the precision farming in poultry sector.



**Fig. 1 Outline of the application of precision livestock farming (PLF) approach in poultry sector.**  
An interdisciplinary team involvement in executing poultry PLF with poultry scientists playing the central role.

The PLF collects real-time data from individual animals or birds using sensor technology. The sensors can be installed in the barn unit or can be wearable by animal in the least intrusive way while allowing the animal to fully express its natural behavior. Poultry scientists will play a central role in collaborating with agri-engineers and computer scientists and articulating for the measurements to be made on biological or environmental variables. Agri-engineers can help design the PLF technology according to the need as expressed by poultry scientists. The concerted efforts produce an output, such as animal friendly sensors and/or data management systems, to generate information for decision making. In complex cases, handling the large pool of data (visual, categorical or numerical) will require aid of artificial intelligence to develop algorithms or patterns where computer engineers and data scientists come into picture. By comprehending these algorithms and patterns, it helps poultry scientists to take timely and real-time appropriate management decisions.

PLF system not only helps capture the animal-related data but also gives insights on the impacts of facility design on the performance of birds. By utilizing the data generated from animals/birds using PLF technology, it facilitates the considerations to be made to reengineer the whole facility design. PLF can be applied to several areas of poultry production.

### **3. PLF in Improving Management, Health and Welfare, and Feeding of Poultry**

Limited researches in PLF in the poultry sector have been so far conducted and most of them are conducted within the past 5-10 years (Table 1). The PLF researches in the poultry sector concentrated on taking data related to barn environment [17, 18], and health and behavior of bird to assess the welfare [19, 20]. Various automated sensors have been in use in poultry grow-out facilities to monitor air temperature, air velocity and humidity. Very few researches have

been conducted in precision feeding [21] or feeding behavior [22]. Combining the environmental data with bird behavior data measured from utilizing sensors, the algorithms can be developed [8, 23-26]. The pattern discovered from using algorithms can be a valuable tool to make decisions regarding daily bird management or improving welfare. A study utilized a prototype sensor to monitor volatile organic compounds (VOCs) in the air inside the barn, where it was shown to detect the presence of early coccidiosis infection [27]. Several wireless-based sensors and use of Internet of Things (IoT) tools to monitor environmental parameters have been proposed as a promising tool in PLF [28-33].

Footpad dermatitis is one major welfare concern in broiler production that is linked to poor grow-out environmental conditions. Broilers affected with footpad dermatitis develop ulcers in footpads affecting their gait, and eventual inability to reach to feed or water. Welfare assessment in broilers using the manual scoring resource is time-demanding and can risk farm from biosecurity measure. Strong co-relation was predicted ( $p < 0.001$ ) for footpad incidence in broilers with thermal temperature and humidity index [23]. Several other studies proposed the fully automated monitoring system for early detection of lameness [34-36].

Sensors have also been utilized for the early detection of viral disease states. Avian influenza can sometimes be epidemic and pose a potential health threat to both birds and humans. A research team developed an avian influenza monitoring system utilizing sensor network by a simulation of the spread of highly pathogenic avian influenza viruses in chickens, and the results showed the capability of sensors detecting the avian influenza virus two days earlier than conventional detection of disease outbreak [37]. Other respiratory diseases can be timely detected using appropriate sound technologies [26, 38].

Sensing devices such as video cameras have been utilized to identify and differentiate broiler and breeder

**Table 1 Research highlights in precision livestock farming (PLF) technology in poultry sector.**

Variables measured	Sensor technology	Assessment	Technology provider	Data processing and analysis	References
Environmental: humidity and air temperature	RHM.2-RHO/2 Sensor and air temperature (SF.7 Temp Sensor) sensors	Foot pad dermatitis	Fancom BV, Panningen, the Netherlands	Manual with WQ protocol; a mixed-effects logistic regression model, mean scatter plot; SAS Inst. Inc.	[23]
Sound: vocalizations	Recorder, microphone	Growth rate	Marantz PMD 661 MK II, Marantz Professional, USA	Adobe® Audition™ CS6; the Fast Fourier Transform (FFT); SAS 9.3 version, <i>t</i> -test	[24]
Environmental: air temperature, humidity, light, air speed, and air quality (CO <sub>2</sub> and NH <sub>3</sub> concentrations)	EL-USB-2 (temperature and humidity); TGS 826 Ammonia Gas Sensor; TGE-0011; Tinytag CO <sub>2</sub>	Bird performance and energy consumption	-	Excel spreadsheet	[25]
Behavior: feather pecking in laying hens	Ultra-wideband (UWB), radio frequency identification (RFID), and computer vision (CV)	Behavior	-	-	[8]
Environmental: humidity, CO <sub>2</sub>	TGS4161 CO <sub>2</sub> ; SHT75 humidity	Barn environment	ZigBee, USA	Trans-receiver nodes	[32]
Sound: sneezing	Microphone	Respiratory health	SoundTalks NV, Belgium	Manual annotation of sneezing sound; Audacity (version 2. 1.1); Specs sub command in Matlab	[26]
Gait score	Camera/imager	Lameness	Allied Vision Technologies GmbH, Taschenweg 2a D-07646 Stadtroda, Germany	Image processing software that involved calibration, subtraction, and shape parameters; Friedman and Dunn tests	[34, 35]
Activity/broiler behavior	eYeNamic™ camera system	Activity & occupation indices	Fancom BV, the Netherlands	Regression correlations between locomotory behavior (activity and occupation patterns) and welfare scores (for footpad lesions and hock burn)	[20]
Sound: individual pecking	Microphone and video images	Feed intake	Monacor ECM 3005, Germany	Sound signal filtering, extraction, adapting threshold, and sound recognition; analysis of variance (ANOVA)	[39]
Body positions to behavior	Video images	Broiler breeder behavior		Image processor and CV	[40]
Feeding and drinking events	Controlled chambers with electronic weighing balance	Feeding and drinking behavior	Feeder: Model CT1200, Ohaus Corporation, Florham Park, NJ, USA; Waterer: Cole Parmer Co., Vernon Hills, IL, USA	Custom built 485 master modules interfaced with PC; Excel	[41]

Table 1 to be continued

Variables measured	Sensor technology	Assessment	Technology provider	Data processing and analysis	References
Body weight (BW)	RFID transponder	Flock uniformity	RPGR30ATGA, Texas Instruments, Inc., Dallas, TX, USA	Mixed procedure of SAS; ANOVA	[42]
Ammonia, ventilation rates	Metal oxide semiconductor (MOS)	Barn environment	SGX, Switzerland		[43]
Production system variables, e.g., stocking density, beak trimming, husbandry type, etc.	Computer model, FOWEL	Welfare status of production system	-	Microsoft Access with tables, queries, forms and reports	[44]
Bird identification using barcodes in beaks and legs	Bar code scanner; images from camera	Bird identification/traceability	Domino Amjet Inc., Cambridge, United Kingdom	Manual, reading from sample using Cognex DataMan 7500; Chi-square and Pearson's tests (categorical data)	[45]
Posture analysis of birds (sick versus healthy)	Camera images generated by Logitech C922 CCD camera	Visual diagnosis of diseased state	-	CV; Support Vector Machine models	[36]
Air velocity, air temperature and relative humidity	Infrared thermometer; air velocity meter	Barn environment/tunnel ventilation system		Computational Fluid Dynamics model; Stepwise logistic regression (SPSS)	[46]
Vocal phrases and audio signals	Sound recorder	Bird health	-	Wiener entropy; Cepstral peak prominence	[38]
-	GPRS enabled held devices (e.g., cell phone, PDA)	Farm operation traceability system	-	Internet server and computer	[11]
Feeding events	Electronic weighing scale; digital communication ports; video recordings	Feeding statistics and pecking behavior	CT1200, Ohaus Corporation, Florham Park, NJ, USA	High-frequency time-series weigh scale recording	[47]
Temperature, humidity, light intensity and population density	Mobile phone and wireless sensor network (WSN)	Barn environment	-	Cloud services as database and computational offloading	[48]
Body temperature	Infrared thermography/portable thermographic camera	Sensible heat loss from body	Model b60, FLIR Systems, USA	FLIR ThermoCAM Researcher Pro 2.10; ANOVA using a general linear model	[49]

behavior pattern to predict their health condition in confined and non-confined conditions [40, 50-52]. Feed intake of birds can be measured utilizing the sound technology and by developing a correlation between numbers of pecking and feed intake of broiler chickens [39]. Precision feeding of broilers can be important to optimize the genetic growth potential of meat broiler strains and to maintain increased protein turnover that these birds are undergoing [53]. In breeder hens, the practice of precision feeding can help maintain target body weight (BW) of hens within a specified BW curve to retain their optimal reproductive state. Precision feeding showed the unprecedented flock BW uniformity ( $CV < 2\%$ ) versus the lowest reported in convention feeding of 6.2% CV in breeder hen rearing [42, 54]. Furthermore, the precision feeding breeder pullets showed relatively less expenditure of energy as heat, which was due to the reduced need to store and mobilize nutrients compared to pullets undergoing conventional restricted feeding [55].

PLF technology in the poultry sector will help enhance the overall poultry production and profitability improving the management decisions on bird health, nutrition and welfare [56]. However, adopting a new technology for taking daily management decision at farm level can be challenging. Technology adoption by growers needs data to be presented in the end-user format [57]. The companies pay incentives to growers based on how well the growers manage their flocks in terms of performance compared to flock performance of other farms in the region [15]. Educating growers on adoption of new technologies in production and management processes can enhance overall health and flock performance, and the overall economic return.

#### 4. Summary

PLF of commercial poultry can be a promising approach to enhance productivity and profitability. The PLF technologies in poultry sector are still in

primitive stage. Poultry scientists, agri-engineers and computer scientists play key roles in bringing poultry PLF into a reality. However, it is equally important that all sectors involved in the poultry production chain including but not limited to, start-up companies working on sensor development, feed suppliers, farm equipment providers, farm facility designer, veterinarians and environmental scientists, should put concerted effort in making PLF a reality in poultry sector. An automatic and systematic collection of environmental and health data from bird grow-out facilities can be a strong tool for developing action plans for poultry management. Unlike other livestock farming, the attributes of poultry rearing such as a closed housing system and vertically integrated industry set-up provide a greater opportunity for poultry sector to adopt technology-based farming. The PLF research in all dimensions of poultry management, health, welfare and feeding is the current need in the poultry sector, as many areas remained unexplored. Hi-tech farms and economically viable poultry production can be created by transitioning to PLF technology that will assure future food security issues.

#### References

- [1] Banhazi, T. M., and Black, J. L. 2009. "Precision Livestock Farming: A Suite of Electronic Systems to Ensure the Application of Best Practice Management on Livestock Farms." *Aust. J. Multi-Discip. Eng.* 7: 1-14.
- [2] Halachmi, I., and Guarino, M. 2016. "Precision Livestock Farming: A 'Per Animal' Approach Using Advanced Monitoring Technologies." *Animal* 10 (9): 1482-3.
- [3] Peng, L., Chen, W., Li, M., Bai, Y., and Pan, Y. 2014. "GIS-Based Study of the Spatial Distribution Suitability of Livestock and Poultry Farming: The Case of Putian, Fujian, China." *Computers and Electronics in Agriculture* 108: 183-90.
- [4] Wathes, C. M., Kristensen, H. H., Aerts, J. M., and Berckmans, D. 2008. "Is Precision Livestock Farming an Engineer's Daydream or Nightmare, an Animal's Friend or Foe, and a Farmer's Panacea or Pitfall?" *Computers and Electronics in Agriculture* 64 (1): 2-10.
- [5] Johnson, R. 2018. "Is Precision Poultry Production Possible?" The Poultry Site. <https://thepoultrysite.com/news/2018/07/is-precision-poultry-production-possible>.

- [6] Zuidhof, M. J., Schneider, B. L., Carney, V. L., Korver, D. R., and Robinson, F. E. 2014. "Growth, Efficiency, and Yield of Commercial Broilers from 1957, 1978, and 2005." *Poult. Sci.* 93: 2970-82.
- [7] Knowles, T. G., Kestin, S. C., Haslam, S. M., Brown, S. N., Green, L. E., Butterworth, A., Pope, S. J., Pfeiffer, D., and Nicol, C. J. 2008. "Leg Disorders in Broiler Chickens: Prevalence, Risk Factors and Prevention." *PLoS ONE* 3: e1545.
- [8] Ellen, E. D., Van Der Sluis, M., Siegford, J., Guzhva, O., Toscano, M. J., Bennewitz, J., and Piette, D. 2019. "Review of Sensor Technologies in Animal Breeding: Phenotyping Behaviors of Laying Hens to Select against Feather Pecking." *Animals* 9 (3): 108.
- [9] Ren, G., Lin, T., Ying, Y., Chowdhary, G., and Ting, K. C. 2020. "Agricultural Robotics Research Applicable to Poultry Production: A Review." *Computers and Electronics in Agriculture* 169: 105216.
- [10] Morales, I. R., Cebrián, D. R., Blanco, E. F., and Sierra, A. P. 2016. "Early Warning in Egg Production Curves from Commercial Hens: A SVM Approach." *Computers and Electronics in Agriculture* 121: 169-79.
- [11] Sallabi, F., Fadel, M., Hussein, A., Jaffar, A., and El Khatib, H. 2011. "Design and Implementation of an Electronic Mobile Poultry Production Documentation System." *Computers and Electronics in Agriculture* 76 (1): 28-37.
- [12] Cervantes, H. M. 2015. "Antibiotic-Free Poultry Production: Is It Sustainable?" *Journal of Applied Poultry Research* 24 (1): 91-7.
- [13] Appleby, M. C., Hughes, B. O., and Elson, H. A. 1992. *Poultry Production Systems: Behaviour, Management and Welfare*. Wallingford: CAB International.
- [14] Boggia, A., Paolotti, L., and Castellini, C. 2010. "Environmental Impact Evaluation of Conventional, Organic and Organic-Plus Poultry Production Systems Using Life Cycle Assessment." *World's Poultry Science Journal* 66 (1): 95-114.
- [15] Bukari, F. 2014. "Profile of Broiler Producers in Tennessee and Vertical Integration in Broiler Production." Ph.D. thesis, Tennessee State University.
- [16] Ribeiro, R., Casanova, D., Teixeira, M., Wirth, A., Gomes, H. M., Borges, A. P., and Enembreck, F. 2019. "Generating Action Plans for Poultry Management Using Artificial Neural Networks." *Computers and Electronics in Agriculture* 161: 131-40.
- [17] Curi, T. M. R. C., Conti, D., Vercellino, R. A., Massari, J. M., de Moura, D. J., de Souza, Z. M., and Montanari, R. 2017. "Positioning of Sensors for Control of Ventilation Systems in Broiler Houses: A Case Study." *Sci. Agric.* 74: 101-9.
- [18] Ji, B., Zheng, W., Gates, R. S., and Green, A. R. 2016. "Design and Performance Evaluation of the Upgraded Portable Monitoring Unit for Air Quality in Animal Housing." *Comput. Electron. Agric.* 124: 132-40.
- [19] De Montis, A., Pinna, A., Barra, M., and Vranken, E. 2013. "Analysis of Poultry Eating and Drinking Behavior by Software eYeNamic." *J. Agric. Eng.* 44: 166-72.
- [20] Fernandez, A. P., Norton, T., Tullo, E., van Hertem, T., Youssef, A., Exadaktylos, V., Vranken, E., Guarino, M., and Berckmans, D. 2018. "Real-Time Monitoring of Broiler Flock's Welfare Status Using Camera-Based Technology." *Biosyst. Eng.* 173: 103-14.
- [21] Aerts, J.-M., Van Buggenhout, S., Lippens, M., Buyse, J., Decuypere, E., Vranken, E., and Berckmans, D. 2003. "Active Control of the Growth Trajectory of Broiler Chickens Based on On-Line Animal Responses." *Poult. Sci.* 82: 1853-62.
- [22] Aydin, A., and Berckmans, D. 2016. "Using Sound Technology to Automatically Detect the Short-Term Feeding Behaviours of Broiler Chickens." *Comput. Electron. Agric.* 121: 25-31.
- [23] Tullo, E., Fontana, I., Peña Fernandez, A., Vranken, E., Norton, T., Berckmans, D., and Guarino, M. 2017. "Association between Environmental Predisposing Risk Factors and Leg Disorders in Broiler Chickens." *Journal of Animal Science* 94 (4): 1512-20.
- [24] Fontana, I., Tullo, E., Butterworth, A., and Guarino, M. 2015. "An Innovative Approach to Predict the Growth in Intensive Poultry Farming." *Computers and Electronics in Agriculture* 119: 178-83.
- [25] Corkery, G., Ward, S., Kenny, C., and Hemmingway, P. 2013. "Monitoring Environmental Parameters in Poultry Production Facilities." In *Computer Aided Process Engineering-CAPE Forum 2013*, Institute for Process and Particle Engineering, Graz University of Technology, Austria.
- [26] Carpentier, L., Vranken, E., Berckmans, D., Paeshuysse, J., and Norton, T. 2019. "Development of Sound-Based Poultry Health Monitoring Tool for Automated Sneeze Detection." *Computers and Electronics in Agriculture* 162: 573-81.
- [27] Grilli, G., Borgonovo, F., Tullo, E., Fontana, I., Guarino, M., and Ferrante, V. 2018. "A Pilot Study to Detect Coccidiosis in Poultry Farms at Early Stage from Air Analysis." *Biosystems Engineering* 173: 64-70.
- [28] Fauzi, O. M., and Shazali, K. 2012. "Wireless Sensor Network Applications: A Study in Environment Monitoring System." *Procedia Engineering* 41: 1204-10.
- [29] Mahale, R. B., and Sonavane, S. S. 2016. "Smart Poultry Farm Monitoring Using IoT and Wireless Sensor Networks." *International Journal of Advanced Research in Computer Science* 7 (3): 187-90.

- [30] Murad, M., Yahya, K. M., and Hassan, G. M. 2009. "Web Based Poultry Farm Monitoring System Using Wireless Sensor Network." In *Proceedings of the 7th International Conference on Frontiers of Information Technology*, 1-5.
- [31] Ammad-Uddin, M., Ayaz, M., Aggoune, E. H., and Sajjad, M. 2014. "Wireless Sensor Network: A Complete Solution for Poultry Farming." In *2014 IEEE 2nd International Symposium on Telecommunication Technologies*, 321-5.
- [32] Dong, F., and Zhang, N. 2009. "Wireless Sensor Networks Applied on Environmental Monitoring in Fowl Farm." In *International Conference on Computer and Computing Technologies in Agriculture*, Berlin, Heidelberg: Springer, 479-86.
- [33] Goud, K. S., and Sudharson, A. 2015. "Internet Based Smart Poultry Farm." *Indian Journal of Science and Technology* 8 (19): 1.
- [34] Aydin, A. 2017a. "Development of an Early Detection System for Lameness of Broilers Using Computer Vision." *Computers and Electronics in Agriculture* 136: 140-6.
- [35] Aydin, A. 2017b. "Using 3D Vision Camera System to Automatically Assess the Level of Inactivity in Broiler Chickens." *Computers and Electronics in Agriculture* 135: 4-10.
- [36] Zhuang, X., Bi, M., Guo, J., Wu, S., and Zhang, T. 2018. "Development of an Early Warning Algorithm to Detect Sick Broilers." *Computers and Electronics in Agriculture* 144: 102-13.
- [37] Okada, H., Itoh, T., Suzuki, K., and Tatsuya, T. 2010. "Simulation Study on the Wireless Sensor-Based Monitoring System for Rapid Identification of Avian Influenza Outbreaks at Chicken Farms." In *Proceedings of the SENSORS, 2010 IEEE*, November 1-4, 2010, Kona, HI, USA, 660-3.
- [38] Mahdavian, A., Minaei, S., Yang, C., Almasganj, F., Rahimi, S., and Marchetto, P. M. 2020. "Ability Evaluation of a Voice Activity Detection Algorithm in Bioacoustics: A Case Study on Poultry Calls." *Computers and Electronics in Agriculture* 168: 105100.
- [39] Aydin, A., Bahr, C., Viazzi, S., Exadaktylos, V., Buyse, J., and Berckmans, D. 2014. "A Novel Method to Automatically Measure the Feed Intake of Broiler Chickens by Sound Technology." *Computers and Electronics in Agriculture* 101: 17-23.
- [40] Pereira, D. F., Miyamoto, B. C., Maia, G. D., Sales, G. T., Magalhães, M. M., and Gates, R. S. 2013. "Machine Vision to Identify Broiler Breeder Behavior." *Computers and Electronics in Agriculture* 99: 194-9.
- [41] Puma, M. C., Xin, H., Gates, R. S., and Burnham, D. J. 2001. "An Instrumentation System for Studying Feeding and Drinking Behavior of Individual Poultry." *Applied Engineering in Agriculture* 17 (3): 365.
- [42] Zuidhof, M. J., Fedorak, M. V., Ouellette, C. A., and Wenger, I. I. 2017. "Precision Feeding: Innovative Management of Broiler Breeder Feed Intake and Flock Uniformity." *Poultry Science* 96 (7): 2254-63.
- [43] Lin, X., Zhang, R., Jiang, S., El-Mashad, H., and Xin, H. 2017. "Emissions of Ammonia, Carbon Dioxide and Particulate Matter from Cage-Free Layer Houses in California." *Atmospheric Environment* 152: 246-55.
- [44] De Mol, R. M., Schouten, W. G. P., Evers, E., Drost, H., Houwers, H. W. J., and Smits, A. C. 2006. "A Computer Model for Welfare Assessment of Poultry Production Systems for Laying Hens." *NJAS-Wageningen Journal of Life Sciences* 54 (2): 157-68.
- [45] Fröschle, H. K., Gonzales-Barron, U., McDonnell, K., and Ward, S. 2009. "Investigation of the Potential Use of E-Tracking and Tracing of Poultry Using Linear and 2D Barcodes." *Computers and Electronics in Agriculture* 66 (2): 126-32.
- [46] Du, L., Yang, C., Dominy, R., Yang, L., Hu, C., Du, H., and Jiang, X. 2019. "Computational Fluid Dynamics Aided Investigation and Optimization of a Tunnel-Ventilated Poultry House in China." *Computers and Electronics in Agriculture* 159: 1-15.
- [47] Gates, R. S., and Xin, H. 2008. "Extracting Poultry Behaviour from Time-Series Weigh Scale Records." *Computers and Electronics in Agriculture* 62 (1): 8-14.
- [48] So-In, C., Poolsanguan, S., and Rujirakul, K. 2014. "A Hybrid Mobile Environmental and Population Density Management System for Smart Poultry Farms." *Computers and Electronics in Agriculture* 109: 287-301.
- [49] Souza-Junior, J. B. F., El-Sabrou, K., de Arruda, A. M. V., and de Macedo Costa, L. L. 2019. "Estimating Sensible Heat Loss in Laying Hens through Thermal Imaging." *Computers and Electronics in Agriculture* 166: 105038.
- [50] Xiao, L., Ding, K., Gao, Y., and Rao, X. 2019. "Behavior-Induced Health Condition Monitoring of Caged Chickens Using Binocular Vision." *Computers and Electronics in Agriculture* 156: 254-62.
- [51] Lao, F., Du, X. D., and Teng, G. H. 2017. "Automatic Recognition Method of Laying Hen Behaviors Based on Depth Image Processing." *Transactions of the CSAM* 48 (1): 155-62.
- [52] Mehdizadeh, S. A., Neves, D. P., Tschärke, M., Nääs, I. A., and Banhazi, T. M. 2015. "Image Analysis Method to Evaluate Beak and Head Motion of Broiler Chickens during Feeding." *Computers and Electronics in Agriculture* 114: 88-95.
- [53] Maharjan, P., Mullenix, G., Hilton, K., Beitia, A., Weil, J., Suesuttajit, N., Martinez, D., Umberson, C., England, J.,



- Caldas, J., Naranjo Haro, V. D., and Coon, C. 2020. "Effects of Dietary Amino Acid Levels and Ambient Temperature on Mixed Muscle Protein Turnover in Pectoralis Major during Finisher Feeding Period in Two Broiler Lines." *J. Ani. Physiol. Ani. Nutr.* (in press)
- [54] Zuidhof, M. J., Holm, D. E., Renema, R. A., Jalal, M. A., and Robinson, F. E. 2015. "Effects of Broiler Breeder Management on Pullet Body Weight and Carcass Uniformity." *Poultry Science* 94 (6): 1389-97.
- [55] Hadinia, S. H., Carneiro, P. R. O., Ouellette, C. A., and Zuidhof, M. J. 2018. "Energy Partitioning by Broiler Breeder Pullets in Skip-a-Day and Precision Feeding Systems." *Poultry Science* 97 (12): 4279-89.
- [56] Rowe, E., Dawkins, M. S., and Gebhardt-Henrich, S. G. 2019. "A Systematic Review of Precision Livestock Farming in the Poultry Sector: Is Technology Focused on Improving Bird Welfare?" *Animals* 9 (9): 614.
- [57] Van Hertem, T., Rooijackers, L., Berckmans, D., Fernández, A. P., Norton, T., and Vranken, E. 2017. "Appropriate Data Visualisation Is Key to Precision Livestock Farming Acceptance." *Computers and Electronics in Agriculture* 138: 1-10.