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Exploring effects of light intensity on sustainability indicators in finishing pig production

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ABSTRACT

With an ongoing transition towards the use of Light Emitting Diodes, more knowledge is needed on which light settings optimise sustainability parameters in pig production. We studied the effects of four light intensities on social, environmental and economic sustainability indicators, including ammonia emissions, space use, pen fouling, weight gain, carcass quality, perception of the stockkeeper, costs of the light system, and use of drinking water, electricity and medicines. Light treatments included a low (45 lux), medium (198 lux) and high (968 lux) uniform intensity, and a spatial gradient treatment ranging from 71 lux in the front to 330 lux in the back of each pen. The latter treatment aimed to improve the space use of functional areas. A total of 448 growing-finishing pigs were studied on a commercial farm using two consecutive batches of four rooms containing eight pens with seven pigs. Light intensity influenced some aspects of space use and pen fouling. For example, the proportion of pigs lying in the resting area was higher in the high and medium light intensity treatment than in the low intensity and gradient treatment. Moreover, the high-intensity treatment resulted in more fouling with faeces in the feeding area compared with the low-intensity and the gradient treatment. Ammonia emissions were higher in the gradient than in the low intensity treatment (not measured in medium and high intensity treatment). Furthermore, light intensity did not affect weight gain, carcass quality, water use and medicine use. The stockkeeper was content to work in all light conditions, but slightly preferred the medium intensity due to optimal visibility. Concerning economic performance, the costs of the light system and electricity use increased in the following order: low intensity, gradient, medium intensity, and high intensity. In conclusion, contrary to expectation the spatial gradient did not notably improve space use or reduce pen fouling, but rather increased ammonia emissions in comparison with uniform light. This is likely because the gradient could not be applied in an optimal way in the existing housing conditions. Among the other sustainability indicators, mainly electricity use and costs of the light system differed per treatment. These aspects can be improved by further optimising the number of light sources needed per pen to achieve the targeted intensities.

Implications

With an ongoing transition towards the use of Light Emitting Diodes, more knowledge is needed on which light settings (intensity, spectrum, photoperiod) optimise sustainability parameters such as pig welfare, electricity use, environmental impact and economic performance. This study provides an integrated overview of the effects of light intensity in pig production, by evaluating four light treatments on a commercial farm. Results can be used to explore trade-offs and synergies when evaluating optimal light settings. In our study, light intensity mainly influenced space use, pen fouling, ammonia emissions, electricity use and costs of the light system.

Introduction

Sustainable farming is characterised by producing under socially acceptable circumstances in an environmentally friendly

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way, while remaining economically viable (Lebacq et al., 2013). As the world population and demand for food are growing, the sustainability of food production is of increasing concern (Oosterveer and Sonnenfeld, 2012). Global consumption of meat proteins is expected to increase by 14% between 2020 and 2030 (FAO, 2021) and 35% of global meat production consists of pork (FAO and OECD, 2023). The pork sector, however, currently faces several sustainability challenges including societal concerns about animal welfare (Pedersen, 2018), environmental emissions (Philippe et al., 2011), resource use (Govoni et al., 2022) and financial instability for pork producers (Boone and Dolman, 2010). Efforts are being made to tackle these complex issues with a variety of complementary strategies, e.g. related with feed ingredient sourcing (DiGiacomo and Leury, 2019), manure management (De Vries et al., 2013) and pig housing conditions (Baxter et al., 2011).

An aspect of pig housing that has received relatively little attention so far is lighting, although several studies have reported effects of light on sustainability parameters, such as feed conversion ratio (Martelli et al., 2015), meat quality (Sardi et al., 2012) and pig welfare (Van Putten, 1984). Most previous work, however, mainly focussed on differences in photoperiod and/or light source (Andersson et al., 1998; Cook et al., 1998; Glatz, 2001; Fredriksen et al., 2006; Knecht et al., 2013; Savić and Petrović, 2015; Barnabé et al., 2020). In these studies, the separate effects of the various characteristics of light, such as light intensity, generally could not be distinguished.

Altering light intensity may, however, play a promising role in improving sustainability of pig farming. Within the social domain of sustainability, pig welfare may benefit from light intensities higher than the EU legal minimum of 40 lux (Council Directive 2008/120/EC, 2009), with e.g. less aggression and more non-agonistic social interactions under 80 lux (Martelli et al., 2010). Higher light intensities may also improve welfare via pathways similar to light therapy used for depressive disorders in humans (Penders et al., 2016). Detailed evaluations of the effects of light intensity on pig welfare are, however, scarce (Davis et al., 2019; Scaillierez et al., 2024), and other aspects of social sustainability, such as effects on product quality for the consumer and working conditions of the farmer, have also received relatively little attention (Martelli et al., 2010; O'Connor et al., 2010; Sardi et al., 2012). Within the environmental domain of sustainability, providing a clear contrast in light intensity between lying and dunging areas may stimulate pigs to properly use functional areas within the pen (Taylor et al., 2006; Opderbeck et al., 2020), thereby possibly reducing pen fouling and ammonia emissions. Moreover, differences in eating and drinking behaviour suggest that light intensity can affect pigs' production performance (Christison, 1996; Martelli et al., 2010), although limited differences in feed intake, weight gain and feed conversion ratio may be expected based on studies so far (Van Putten, 1984; Martelli et al., 2010; Sardi et al., 2012). Lastly, economic parameters of sustainability may be affected, but an evaluation that integrates the effects of light intensity on costs and returns is lacking.

A transition towards using more energy-efficient light sources such as Light Emitting Diodes (**LED**) is currently ongoing (Verma et al., 2016). Such light sources provide opportunities to fine-tune light characteristics such as spectrum and intensity in a more dynamic way in comparison with traditional incandescent or fluorescent light sources. Despite the large potential of dynamic LED systems to better fit the needs of both pigs and farmers, optimal light settings remain unclear. Given the lack of integrated knowledge on various sustainability aspects and a limited range of light intensities tested, this study aims to provide more insight into optimal light intensity as a first step. Within the context of using a dynamic LED system, the objective of this study was therefore to explore the effects of various light intensity settings on a diversity of sustainability indicators, such as ammonia emissions, pig behaviour related to space use and pen fouling, resource use, economic performance and stockkeeper experiences.

Material and methods

Animal housing and management

This study was conducted between September 2021 and April 2022 on a commercial farm in The Netherlands. As the study did not include invasive procedures, the Animal Care and Use committee of Wageningen University & Research did not consider the study an animal experiment and formal ethical approval was not required. The study ran concurrently with the study of Scaillierez et al. (2024), in which the same animals were investigated. A total of 448 TN70 × Tempo pigs (Topigs Norsvin, the Netherlands) were studied from entry in the finishing room at 9–10 weeks of age until slaughter around 22 weeks of age, using two consecutive batches. Per batch, 224 pigs were equally divided over four rooms, each containing eight pens with seven pigs. Each room had four pens with gilts and four pens with boars. Each pen measured 3.6 × 1.8 m and consisted of a dunging area with metal slats in the back (~30%), a lying area with a convex solid concrete floor in the middle (~40%) and a feeding area with concrete slats in the front of the pen (~30%, Fig. 1). The feeding area contained a feeder with one eating place and a built-in water nipple. Feeders were filled automatically once per day, providing pigs semi−*ad libitum* access to dry feed. A starter feed was given during the first 5–7 weeks (10.0 MJ NE / kg and 149 g/kg DM CP) and a finisher feed was given during the remainder of the finishing phase (9.9 MJ NE / kg and 140 g/kg DM CP). Pigs had access to a metal chain attached to the pen partition above the dunging area, and two strands of cotton rope attached to the pen partition above the resting area. Ropes were replaced in case a rope was lost, and all ropes were renewed halfway through each batch for all pens. In addition, a handful of alfalfa was provided usually daily on the solid floor. The climate was controlled by automatic mechanical ventilation.

Before starting the experiment, pigs were housed and managed according to the standard procedures of the commercial farm. Pigs were born in a farrowing crate system, received an RFID ear tag after birth, and were tail−docked but not castrated. Piglets were weaned around 5 weeks of age and litters were mixed to form new groups, sorted by sex and BW. Pre-experimental light conditions consisted of manually controlled tube lights (**TL**, also called luminescent tubes or fluorescent tubes) combined with daylight exposure through windows. This resulted in a variable photoperiod, light intensity and light spectrum experienced during rearing.

Experimental design

Four treatments differing in light intensity and light distribution were investigated (Table 1) using an incomplete block design. Treatments consisted of three treatments with a homogeneous light distribution within each pen, i.e. a low intensity (45 ± 7 lux), a medium intensity (198 ± 29 lux) and a high intensity treatment (968 ± 139 lux), and the fourth treatment had a heterogeneous light distribution with a spatial gradient ranging from 71 ± 7 lux in the feeding area to 330 ± 27 lux in the dunging area of each pen. Each treatment was applied at room level to guarantee the intended contrast in light intensity between each treatment. Windows were blinded for the experiment to avoid interference of daylight. Light was provided by LED sources (ONCE ND-Domes from Signify, the Netherlands), which were controlled by one gateway per room (NatureDynamics Zigbee Gateway, Signify, the Netherlands). The light settings were communicated to the gate-

Fig. 1. Top view of two adjacent pig pens. Each pen had functional areas for eating and drinking (1.12 × 1.84 m concrete slats), resting (1.40 × 1.84 m solid concrete) and elimination (1.05 × 1.84 m metal slats).

Table 1
Experimental setup with pigs exposed to four treatments differing in light intensity and distribution (mean ± SD). Intensity was measured before the start and at the end of the experiment in three pens per room.

Treatment	Low intensity	Medium intensity	High intensity	Gradient
Light intensity (lux)	45 ± 7	198 ± 29	968 ± 139	From 71 ± 7 in feeding area to 330 ± 27 in dunging area (average: 198 ± 108)
Light distribution across pen	Uniform	Uniform	Uniform	Spatial gradient
Uniformity coefficient[1]	0.77 ± 0.08	0.83 ± 0.03	0.83 ± 0.03	0.33 ± 0.03

[1] Minimum light intensity divided by the average light intensity per pen.

way using the Interact Agriculture application (version 3.1.0–0, Signify, the Netherlands). An automated photoperiod of 11L:13D was provided with lights on between 0700–1800 h. In the morning, lights went on gradually during a 5-min transition phase, and also in the evening lights went off gradually with a 5-min transition time. The number of light sources per pen was 2 for the low intensity, 10 for the medium intensity, 15 for the high intensity and 3 for the gradient (Fig. 2). The exact number of ND-Domes needed per pen was uncertain beforehand and a surplus of light sources was installed to (i) guarantee achievement of the targeted light intensities, (ii) attain a homogeneous light distribution in the low, medium and high intensity, to ensure the contrast with the spatial gradient, and (iii) remain flexible in the setup for future experiments using the dynamic potential of the system. Lights were mounted on the ceiling at approximately 2.5 m above floor level. The low intensity was targeted at 40 lux, i.e. the legal minimum intensity in the EU (Council Directive 2008/120/EC, 2009). The medium and high intensity were targeted at 200 and 1 000 lux respectively, resulting in two times a fivefold difference among the three uniform intensity treatments, respectively. In the gradient treatment, the intensity gradually decreased from the back towards the front of the pen. The dunging area in the back was brightest to stimulate the proper use of functional areas, e.g. defecating and urinating over the metal slats and resting in the other parts of the pen. The lower and upper ranges of the gradient were determined by the maximum achievable contrast using three domes per pen above the dunging area. Light intensity was measured at the start and end of each batch (Supplementary Material S1). During the scotophase, light intensity was 0 lux. The light spectrum generated by the LED light was equal for all treatments (Supplementary Material S2).

Between batches, allocation of treatments to rooms was alternated (Table 2). Due to a 1-week batch farrowing system used on farm, a maximum of two finishing rooms could be filled with pigs of the same age group per week. Therefore, there was an interval between the start of the low intensity and gradient treatment on the one hand, compared with the medium and high intensity treatment on the other hand (Table 2). Per entry moment, allocation of animals to treatments was balanced for average BW at pen level on the day of pig entry. As the group of pigs available for selection slightly differed per interval, the average starting weight per pig (derived from pen-based weighing) was 28.2 ± 6.2 kg (low intensity), 24.2 ± 2.8 kg (medium intensity), 24.5 ± 2.0 kg (high intensity) and 28.1 ± 5.9 kg (gradient). In addition, weaning pen

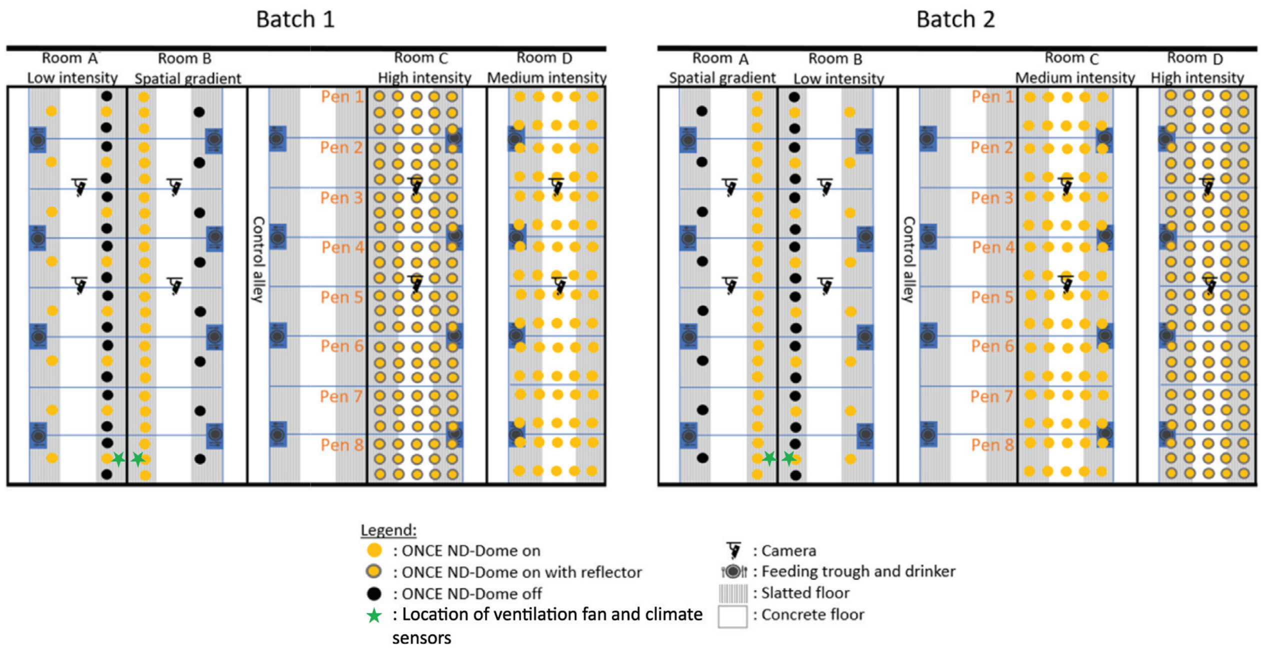

Fig. 2. Layout of light source placement per room and pen. Luminaires in the high intensity treatment were provided with a reflector at their base to guide the light beam further downwards for more security that the high light intensity would be achieved at pig level. To be able to alternate light treatments between batches, spare domes were installed in room A and room B, which were switched on or off according to the applied treatment. In room C and room D, treatments were swapped by relocating five domes per pen and all of the reflectors.

Table 2
Allocation of rooms to treatments per batch, and timing of pig entry per treatment per batch.

Batch	Room A	Room B	Room C	Room D
Batch 1	Low intensity	Gradient	High intensity	Medium intensity
Timing of pig entry			2 weeks after room A+B	2 weeks after room A+B
Batch 2	Gradient	Low intensity	Medium intensity	High intensity
Timing of pig entry			1 week after room A+B	1 week after room A+B

Table 3
Sustainability indicators used in the investigation of light intensity effects on pigs.

Sustainability domain and theme	Subtheme	Indicators
Environmental sustainability		
Emission of pollutants	Acidification / eutrophication	kg NH_3 / year per pig place[1]
Use of resources	Water use	L water / day per pig
	Electricity use	kWh / year per pig place[1]
Social sustainability		
Animal welfare	Behaviour	Occurrence of exploration, play, positive and negative social interactions, mounting and abnormal behaviours
	Health and physical condition	Pre- and *postmortem* scoring of abnormalities of eyes, skin, legs and organs, mortality %
Stockkeeper welfare	User experience	Average score of numeric rating scale questionnaire
Consumer preferences	Product quality	% lean meat, % of carcasses with boar taint
Human health risks	Antimicrobial resistance	Antimicrobial use in doses per pig place per year[1]
Economic sustainability	Net income change	€ per pig per day

[1] The number of pig places per room was 56 in the current study.

origin, physical condition (e.g. ear biting damage) and occurrence of mixing at relocation were kept equal among treatments as much as possible. Generally, pigs housed in the same pen in the weaning unit were split into smaller groups at entry in the finishing unit, and mixing was needed in only 3 out of 64 pens.

Space use (see later) was observed only in selected focal pens due to the time-consuming measurements. Per entry moment (Table 2), focal pens were balanced for pen weight and physical condition on the day of entry in the finishing room, selecting healthy pigs without lesions as much as possible. Pigs that were mixed with unfamiliar pigs at entry were placed in non-focal pens. These measures were taken to reduce possible bias, also in relation to the health assessment and behavioural observations carried out as part of the larger study (Scaillierez et al., 2024).

Measurements

A variety of sustainability indicators was used in this study, based on relevance and feasibility of measuring under commercial farm conditions (Table 3). In addition, the use of functional areas and the level of pen fouling were included in the study as supportive measurements related to ammonia emissions. Methodology and results related to animal welfare indicators have been reported by Scaillierez et al. (2024), and findings will be shortly repeated for integrative purposes only.

Space use of functional areas

In both batches, space use was observed in four focal pens per room during five 24-h periods in weeks 2, 4, 6, 8 and 10 after entry into the finishing rooms (16 pens with gilts and 16 pens with boars). Space use was observed by recording each pig's posture and location (more than half of the body on the concrete slats, on the solid floor or on the metal slats) using instantaneous scan sampling with 1 h-intervals (Table 4). If a pig's body covered 50% of two floor types, then the area where the head was located was registered.

Behaviour was observed from 1920 h of video material (recorded by eight Axis M3057-PLVE MkII cameras, with infrared LED) which was processed using BORIS software v. 7.12.2 (Friard and Gamba, 2016). Space use was scored by two observers using an observation schedule randomised for light treatment and observation week. Inter-observer reliability was assessed for one 24-h video of two pens, comparing the agreement in assigning one out of 12 possible posture-location combinations per pig. Averaged for the 12 different combinations and both pens, the mean weighted kappa was 0.91 ± 0.09 which indicates very strong agreement. As the cameras automatically corrected for the different light intensities, no notable difference in visibility was experienced. Recordings were made the day after conducting pen fouling observations.

Pen fouling

Pen fouling was assessed weekly in all eight pens per room by a single observer. Fouling with faeces and wetness was assessed separately on the metal slats, solid floor and concrete slats. Each score reflected the percentage of the respective floor area that was fouled with faeces (while also considering the quantity of faeces present) and wet spots. Wet spots mainly included stains caused by urine, but partly also by water or saliva. Pigs were made to stand up before scoring to ascertain a complete overview of the floor area. As a supportive measure, the soiled areas were drawn on a map of the pen. Fouling with wetness was scored for concrete floor elements only because of poorer visibility of wet spots on metal surfaces, i.e. the metal slats and the metal plate under the feeder. Observations were carried out in four time blocks per day, scoring two pens per treatment within each time block. The order of scoring treatments was randomised every week, and this observation order was repeated within each time block.

Table 4
Ethogram used for behaviour observations in pigs.

Posture	Description
Upright	The pig is in upright position and is supported by all four legs (e.g. standing or walking).
Sitting	The hindside of the pig is in contact with the floor and the upper body is supported by straightened front legs.
Lateral lying	The right side or left side of the pig is in full contact with the floor, with the underside of the belly fully exposed.
Ventral lying	The pig is lying fully or partly on its belly: the underside of the pig's belly is in contact with the floor.

Ammonia emissions

Only two sets of climate sensors were available, which were installed in the low−intensity and gradient rooms. These rooms were chosen to compare the control treatment with the minimum legal EU standards to the treatment which was expected to yield the most improvement in space use, pen fouling and emissions. Ammonia concentration in ppm (Dräger DOL 53 sensor, dol-sensors a/s, Denmark), ventilation rate in m^3/h (ATM45 measuring fan with the same size as the fan duct, Fancom, the Netherlands), temperature in °C, and relative humidity percentage (DOL 114 sensor, dol-sensors a/s, Denmark) were automatically logged at a 10-min interval. The DOL sensors were installed inside each room below the ventilation fan and measured the outgoing air just before leaving the room. The NH_3 concentration of the incoming air was determined every 2 weeks using gas detection tubes (ammonia 0.25/a Dräger Tube, 0.25–3 ppm range, Germany). Incoming air was measured outside the rooms, in the opening between the corridor and the attic (just before the air entered the room).

Using a density of 0.7 kg NH_3 / m^3, emission in g NH_3 per hour was calculated as follows: ((ppm NH_3 in outgoing air × 0.7 / 1 000) − (ppm NH_3 in incoming air × 0.7 / 1 000)) × ventilation rate (m^3/h). To calculate emission in g NH_3 per day per pig, the hourly emissions were averaged per day, multiplied by 24 h and divided by 56 pigs. The average ammonia concentration of the incoming air was determined per batch.

The measuring fans were calibrated on-site in March 2022 by technicians of Wageningen Livestock Research, the Netherlands. Ventilation rates were corrected using the calibration line obtained per room. The accuracy of the ammonia sensors was checked every 2 weeks using gas detection tubes (ammonia 2/a Dräger Tube, 2–30 ppm range, Germany) and a manual pump (Accuro gas detection pump, Dräger, Germany). The ammonia sensors deviated on average + 14.8% compared to the gas detection tubes (min −7.3%, max + 38.3%). This difference was within the range of deviation reported in the manuals, with a SD of the gas detection tubes of ± 10–15%, and an accuracy of the ammonia sensors of 1.5 ppm or ± 10% of the measured value.

BW, mortality, water use and medicine use

All pigs were weighed at pen level at the start and end of the finishing phase. The start weight was determined on the day of relocating pigs from the nursery unit to the finishing unit. In batch 1, the end weight was determined in week 11 of the finishing phase (8–17 days before delivery to the slaughterhouse) on a floor scale at the farm. The end weight of batch 2 was determined using a truck scale on the day of transportation to the slaughterhouse (i.e. week 11 of the finishing phase for the low intensity and gradient treatments and week 13 of the finishing phase for the medium and high intensity treatments). In case of mortality, the date and cause were recorded per individual. Water use was registered by reading the value of the water meter in each room once per week around 0900 h. These values included water used for drinking, but not for cleaning the rooms. In case of medicine use, treatment duration and type of medicine were registered. Antimicrobial use per pig place per year was calculated as the number of administered doses per animal / average stay in the finishing unit of 87 × 365 days.

Electricity use

ND-Domes had a power use of 12 W with a standby use of 0.5 W. The gateways had a maximum power consumption of 2.5 W. A surplus of ND-Domes was installed per pen to ensure the achievement of the targeted intensity per treatment, and after installation, the light sources were dimmed as needed to reach the desired intensity. This resulted in a dimming factor of 0.30 for the low intensity, 0.27 for the medium intensity, 0.80 for the high intensity and 1.0 for the gradient (where a dimming factor of 1 means that lights were on at full capacity). Taking into account the standby use, the remaining 11.5 W were linearly distributed to determine the power use. Consequently, electricity use in kWh per pig place per year was calculated as follows:

$$(P \times L \times W_P + S \times L \times W_S + G \times 24) / 56 \times 365 / 1000$$

P = photophase of 11 h/d, L = number of light sources per room, W_P = power use during photophase of 0.5+(12–0.5) W×dimming factor, S = scotophase of 13 h/d, W_S = power use during scotophase of 0.5 W, G = power use of gateway of 2.5 W, 24 = the number of functioning hours of the gateway per day, 56 = the number of pig places per room, 365 = the number of days per year, 1000 = conversion factor of Wh to kWh.

As a reference, electricity use under the standard light conditions on the farm (i.e. four TL tubes per room, Philips Master TL-D Super 80, 36 W / 840) was calculated using 0 W power use in the scotophase and a dimming factor of 1.0.

Experience of the stockkeeper

The experience of the stockkeeper with working in the different light conditions was assessed by conducting an interview at the start, middle and end of the experiment (n = 3 repetitions). Only one person was interviewed because this stockperson was responsible for caretaking activities in the experimental rooms, and only this person was exposed regularly to the tested light treatments. Per repetition, the stockkeeper was asked to reflect on the preceding period, and at the end, the stockkeeper was asked to additionally assess the experiment as a whole. The semi-structured interview included questions related to climate, animal performance and light perception using a numeric rating scale, in combination with open questions (Supplementary Material S3). The aim was to monitor user experience with the various light settings and make a descriptive inventory of the advantages and disadvantages of the four light intensities. A comparison was also made with finishing rooms with existing conventional TL lighting so that possible opportunities and obstacles for practical implementation of the LED system could be identified.

Meat quality

Pigs were slaughtered in a commercial slaughterhouse (Westfort, IJsselstein, the Netherlands), which provided the researchers with commonly collected performance results. Muscle thickness and fat thickness were measured between the third and fourth rib on the left side of each pig using a Capteur Gras Maigre device (Fives Syleps, France). Based on these values, the lean meat percentage was calculated. Muscularity was visually assessed using the following classification: AA: exceptionally good muscularity, A: (very) good muscularity, B: moderate muscularity, C: thin muscularity (Rijksdienst voor Ondernemend Nederland, 2019). Net carcass weight was registered per individual. The presence of boar taint was detected using a hot iron smell test. All carcass measurements were performed by an independent inspection organisation (BV Kwaliteitskeuring Dierlijke Sector, working for the Netherlands Food and Consumer Product Safety Authority).

Economic performance

Economic performance was assessed by evaluating costs that were expected to change as a result of the different light treatments, i.e. expenses for the light system and electricity. This assessment was included despite the installation of a surplus of light sources, to evaluate possible trade-offs with other sustainability parameters and to explore possibilities to make material use more cost-effective, while retaining the dynamic potential of the light system. For the light system, the number of light sources and fixtures needed per treatment was considered in the calculations, plus the costs of one gateway per treatment for the LED−based system. ND-Domes that were present but not turned on in a specific batch (Fig. 2) were not considered in the calculations. Daily costs were based on the (minimum) lifespan reported in the manuals, i.e. 50 000 h for the LED system and 15 000 h for the TL tubes. Labour costs for installation were not considered. Electricity costs were calculated with a 5-year average price of €0.14 per kWh for consumers with a variable contract between 2018 and 2022 (CBS, 2023). All prices are excluding Value Added Tax. The net change in income per pig per day was calculated by summing the costs and comparing them to the standard TL light conditions on the farm.

Statistical analysis

Data were analysed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA), and results were reported as raw data means ± SE. Model assumptions were checked, and *P*-values below 0.05 were considered statistically significant. Significant effects were further investigated with posthoc tests, using a Tukey-Kramer adjustment for multiple pairwise comparisons. An autoregressive structure was specified for all repeated measurements. See Supplementary Material S4 for the code of the models used.

Pen fouling and space use were analysed using generalised linear mixed models with a beta distribution and logit link function. As zero values cannot be processed with the logit link function, a minor value was added to zero values to avoid the exclusion of important data in the analysis. The minor value corresponded to 0.01% fouled floor area for pen fouling and 0.1% of pigs present per floor area for space use. Models included fixed effects of light intensity in interaction with week and a random effect of room nested in batch. Repeated measurements were accounted for by including a random effect of observation week at the pen level. Observations of one pen with pig mortality were partly excluded from analysis due to expected effects of deviating stocking densities on pen fouling and space use (i.e. premortality data remained included). Space use data were averaged per pen and per observation day before analysis, and the model contained an extra fixed effect of batch because batch 1 was scored by a different observer than batch 2. Lateral and ventral lying were summed to analyse the total proportion of lying.

Ammonia emission was analysed at room level using mixed models including effects of light intensity in interaction with week, ambient temperature as a covariate, and batch as a fixed effect. Room was included as a random effect and repeated observations within the same room were accounted for by including a repeated statement of room within batch. The volume of drinking water used per pig was analysed at room level using mixed models including effects of light intensity in interaction with week, and a fixed effect of batch. Weekly repeated observations in the same room were accounted for by including a repeated statement of room within batch. User experience scores, economic performance, mortality, medicine use and electricity use were processed using only descriptive statistics.

Daily weight gain was calculated for the average pig, using the pen weights at the start and end of the finishing phase. Average daily gain was analysed using mixed models with fixed effects of light intensity and sex, average starting weight as a covariate, and a random effect of room nested in batch. Meat quality per individual carcass was analysed using mixed models with fixed effects of light intensity and sex, age at slaughter as a covariate, a random effect of room nested in batch, and a random effect of pen nested in room and batch. The dataset for meat quality contained some missing values due to lost ear tags, resulting in a sample size of 112 for the low intensity, 105 for the medium intensity, 106 for the high intensity and 110 for the gradient treatment. The effect of light intensity on muscularity type per individual carcass was analysed for more descriptive purposes, using a basic chi-square test. The occurrence of type B and type C was too low to be included in the test; therefore, the analysed dataset included only carcasses with a type AA or type A classification.

Results

Space use

Space use results are described per functional area, i.e. first for the dunging area with metal slats, then for the solid-floored resting area, and lastly for the feeding area with concrete slats. For correct space use, lying behaviour was expected mainly in the resting and feeding area but not in the dunging area. Upright postures could, however, be expected in all three functional areas (e.g. eating in the feeding area, engaging with the rope above the resting area, eliminating in the dunging area), and therefore the total proportion of lying is shown as a main indicator of correct space use. For more detail, the occurrence of lateral and ventral lying is specified in Supplementary Material S5.

The proportion of pigs lying on the metal slats was affected by an interaction between light intensity and time (P < 0.0001, Fig. 3a). In week 2, fewer pigs lay on the metal slats in the medium intensity compared with the low intensity and gradient (330 lux above metal slats and 71 lux above concrete slats). Thereafter, an increase over time was seen in the medium and high intensity treatment, whereas the proportion of pigs lying on the metal slats in the gradient and low intensity treatment did not differ per week. More specifically, in the medium intensity treatment, a lower proportion of pigs lay on the metal slats in week 2 than in weeks 4, 6, 8 and 10, and additionally, week 4 differed from week 10. In the high intensity treatment, a lower proportion of pigs lay on the metal slats in week 2 than in week 8 and week 10.

The proportion of pigs lying on the solid floor was higher in the high and medium light intensity than in the low intensity and gradient treatment (P < 0.0001, Fig. 3b) and generally did not differ per week (P = 0.06). Furthermore, light intensity did not affect the occurrence of lying on the concrete slats (P = 0.83, Fig. 3c). The average proportion of pigs per pen per day lying on the concrete slats decreased between week 2 and week 4, and between week 4 and week 10 (time effect P < 0.0001). Lastly, light intensity also did not affect the occurrence of standing (P = 0.87) and sitting (P = 0.68), which was observed in 11% and 2% of all scan samples, respectively. Standing gradually decreased between week 2 and week 8 (time effect P < 0.0001), whereas sitting increased between week 2 and week 6, thereafter stabilising (time effect P = 0.03). Occurrence of these postures was too low for proper statistical analysis per functional area.

Pen fouling

The percentage of faeces on the metal slats was affected by an interaction between light intensity and time (P < 0.0001, Fig. 4a, also see Supplementary Material S5). In general, the amount of faeces on the metal slats decreased over time. The medium and high intensity, however, showed an increase in week 2 compared with week 1, whereas the gradient showed a decrease in this period. Correspondingly, light treatments did not differ from one another within each time point, except in week 2, in which more faeces were present on the metal slats in the high and medium intensity than in the gradient, and the medium intensity tended to have more faeces present than the low intensity.

Fouling of the solid floor with faeces and wetness was not influenced by light intensity (P = 0.54 and P = 0.94, respectively), but increased over time (P < 0.0001, Fig. 4b and d), with the exception of a temporary decrease in wet spots in week 10.

Light intensity affected fouling with faeces on the concrete slats (P = 0.001, Fig. 4c), with the high intensity resulting in more fouling (4.9 ± 0.3%) than the low intensity (3.2 ± 0.3%) and the gradient (3.6 ± 0.3%). In addition, fouling with faeces increased over time on the concrete slats (P < 0.0001). The level of wetness on the concrete slats depended on an interaction between light intensity and observation week (P = 0.002, Fig. 4e). The increase over time differed per light treatment, but when comparing within time points no significant treatment differences emerged.

Ammonia emissions

Ammonia emissions (as calculated in g NH_3 per day per pig) were affected by an interaction between light intensity and week (P < 0.0001, Fig. 5). The gradient treatment resulted in higher ammonia emissions than the low intensity treatment in weeks 6, 7, 10 and 11. Both treatments showed quite stable ammonia emissions in the first four weeks, thereafter showing an increase over time. This increase, however, started sooner in the gradient treatment (week 5) than in the low intensity treatment (week 6). Note especially here that all results are presented with raw data, rather than fitted values of statistical models. See Supplementary Material S6 for the graph based on least squares means of the model output. Supporting climate measurements are presented in Supplementary Material S7.

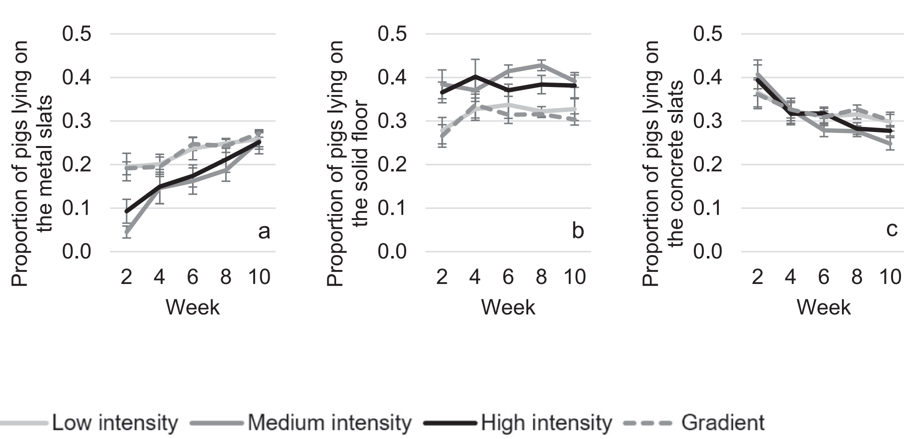

Fig. 3. The average proportion of pigs per pen lying on the metal slats (a), solid floor (b) and concrete slats (c) per light−intensity treatment over time (raw means ± SE).

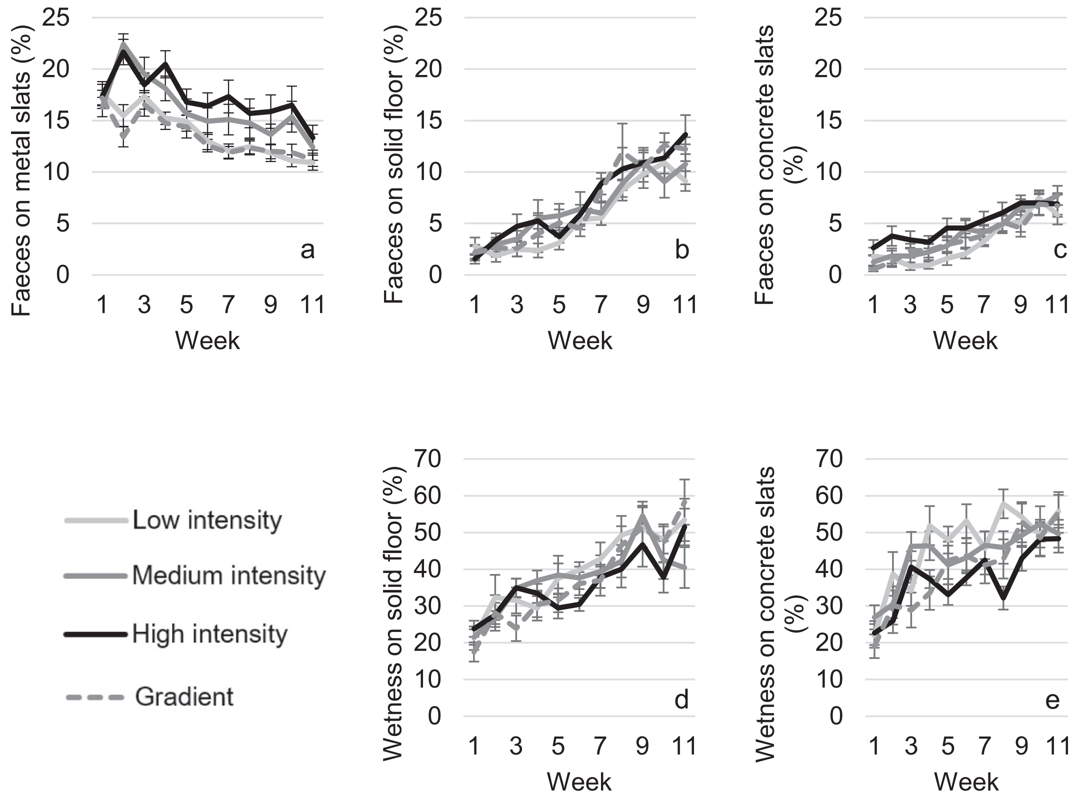

Fig. 4. The percentage of fouled floor area per light intensity treatment over time in pig pens (raw means ± SE). Fouling with faeces is presented for the metal slats (a), the solid floor (b) and the concrete slats (c). Fouling with wetness is presented for the solid floor (d) and the concrete slats (e).

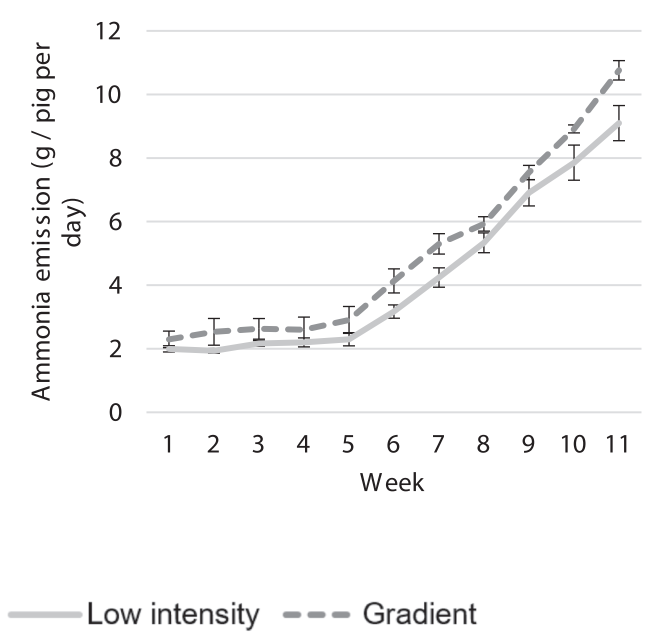

Fig. 5. Ammonia emission per pig for the low intensity and gradient treatment over time (raw means ± SE).

User experience

User experience -related to climate, animal performance and perception of the light- was consistently scored as (very) positive in all three repetitions of the questionnaire (Table 5). The level of dust formed an exception due to cessation of an unrelated trial with dust reduction that occurred on the farm. The perception of most aspects did not differ per light intensity treatment. The smell in the experimental rooms temporarily improved at the beginning of the study, in comparison with the reference TL rooms. The underlying reason remained unclear, but it may have been related to a different smell of the newly installed materials, as the different smell was not noted anymore later on. Furthermore, pen fouling was scored slightly worse towards the end of batch 2 for the low intensity, gradient and reference TL rooms. Pig health and behaviour were perceived slightly worse in the high intensity treatment due to euthanasia of two pigs in the same pen in batch 2 (one due to lameness and one due to tail biting injury). In addition, behaviour in the reference TL rooms was perceived slightly worse around halfway batch 1 due to tail–biting issues. Lastly, the ease of performing daily animal caretaking activities was scored slightly lower for the low intensity and gradient treatment. Checking the pigs and the feeders was slightly more difficult at the beginning of the experiment, but after getting more used to the light conditions, this was not an issue anymore.

Although small differences between light treatments were noted, the stockkeeper was generally content with working under all light conditions. Considering all aspects together, light treatments were ranked as follows: (1) Medium intensity, (2) High intensity, (3) Standard TL, (4) Low intensity, (5) Gradient. The gradient was least preferred due to the heterogeneous light distribution in the room. The darkest areas included the control alley and the feeding area in the pen and the stockkeeper mentioned that checking e.g. the feed and water supply took somewhat more effort. A high light intensity was preferred at the start of the experiment, with more light in the room providing a good overview and enjoyable working conditions. Later on, however, a preference for the medium intensity emerged, with the high intensity being

Table 5
User experience scores per light intensity treatment applied on a pig farm, averaged over the three repetitions of the questionnaire. Scores range from 1 (very poor experience) to 10 (very good experience).

Item	Low intensity	Medium intensity	High intensity	Gradient	Standard TL[1]
Dust	5.5	5.5	5.5	5.5	5.5
Smell	9.3	9.3	9.3	9.3	9.0
Airways	10.0	10.0	10.0	10.0	10.0
Fouling	9.0	9.7	9.7	9.0	9.0
Growth	10.0	10.0	10.0	10.0	10.0
Uniformity	10.0	10.0	10.0	10.0	10.0
Feed intake	10.0	10.0	10.0	10.0	10.0
Health	10.0	10.0	9.3	10.0	10.0
Behaviour	10.0	10.0	8.7	10.0	9.7
Restless	10.0	10.0	10.0	10.0	10.0
Daily check	9.7	10.0	10.0	9.7	10.0
Vision	10.0	10.0	10.0	10.0	10.0
Labour	10.0	10.0	10.0	10.0	10.0
Satisfaction	10.0	10.0	10.0	10.0	10.0

[1] Tube lights, also called luminescent tubes or fluorescent tubes.

described as too intense. This preference persisted throughout the rest of the experiment and, in conclusion, the stockkeeper speculated that the medium intensity might provide an intermediate optimum which balances the pigs' and stockkeeper's needs.

In terms of practical limitations and opportunities for implementation of the light system, the stockkeeper indicated that a balance between (expected) benefits and costs of installing the system is important. Using light to stimulate desirable pig behaviour was repeatedly mentioned as an opportunity that could motivate farmers to change their light system. This was seen as relevant in the context of ongoing changes in the pig sector, such as banning tail docking, reducing emissions, providing more freedom of movement and in general thinking more from the animal's point of view. Moreover, automated regulation of the lights was generally seen as positive by the stockkeeper, but an overriding control option was important to turn on lights outside of the programmed photoperiod in case of e.g. calamities or pig delivery. Anecdotally, the researchers observed once that the standard TL lights were switched on during cleaning in the low intensity and gradient room while the LED lights were also on, most likely for better visibility.

Water use, electricity use, medicine use, mortality, meat quality and economic performance

Water use was not affected by light intensity (P = 0.88), but increased over time between week 1 and week 9 (time effect P < 0.0001, Fig. 6). Calculated electricity use and electricity costs increased with increasing light intensity, and the LED-based system seemed more efficient than the TL light (Table 6). Costs of the light system were mainly determined by the number of light sources and fixtures used. For example, the medium intensity and gradient treatment both averaged 198 lux, but system costs were threefold higher in the medium intensity treatment because of the higher number of domes used.

As part of the standard management routine, a singular dose of an anthelminthic was administered in the feed 2–3 weeks after entry in the finishing rooms (Dopharma Flubendazole 5% topdressing powder). No antibiotics against bacterial infections were used. In total, three pigs died during the experiment. In the medium intensity treatment, one pig with breathing difficulties died several hours after the weighing procedure. In the high intensity treatment, one pig was euthanised due to tail biting wounds and one pig was euthanised due to lameness. Live weight gain, carcass weight and carcass quality were not affected by light intensity treatment (Table 7). Boar taint was not detected in any sample.

Overview of sustainability indicators

Aforementioned results have been summarised in Table 8 to integrate the various sustainability indicators together and provide some context using reference values. Reference values were based either on literature or on measurements done under the standard light conditions on farm, i.e. fluorescent TL. Most of the welfare indicators are not repeated in Table 8 because of difficulty comparing those results to reference values from literature due to differences in observation methods between studies.

Discussion

This study aimed to explore the effects of light intensity on sustainability indicators in finishing pig production. Light intensity had limited effects on the majority of used indicators, except for ammonia emissions, electricity use and costs associated with the light system.

Space use, pen fouling and ammonia emissions

In general, space use and pen cleanliness seemed to be somewhat better in the medium and high intensity treatment than in the low intensity and gradient treatment: More faeces were present in the dunging area and, especially at the start of the experiment, fewer pigs lay down in the dunging area. Furthermore, more pigs lay down in the resting area in the medium and high intensity, although the level of fouling in this area did not differ per treatment. On the other hand, fouling of the feeding area with faeces occurred more in the high intensity treatment than in the low intensity and gradient treatment, while intensity did not affect space use of this area. Improved space use under brighter illuminance may be related to better visibility of pen components, although light intensity seems to improve recognition of surroundings only quite marginally (Koba and Tanida, 2001; Zonderland et al., 2008). The total proportion of lying, lateral recumbency and sternal recumbency did not differ per light intensity treatment (data not shown). This is partly in contrast with earlier findings that pigs exposed to 80 lux rested more frequently in sternal recumbency and less frequently in lateral recumbency than pigs exposed to 40 lux (Martelli et al., 2010), but the authors did not further elaborate on a possible reason for the effect of light intensity on specific lying postures.

Contrary to expectation, the spatial gradient did not notably improve space use or reduce pen fouling, but rather increased

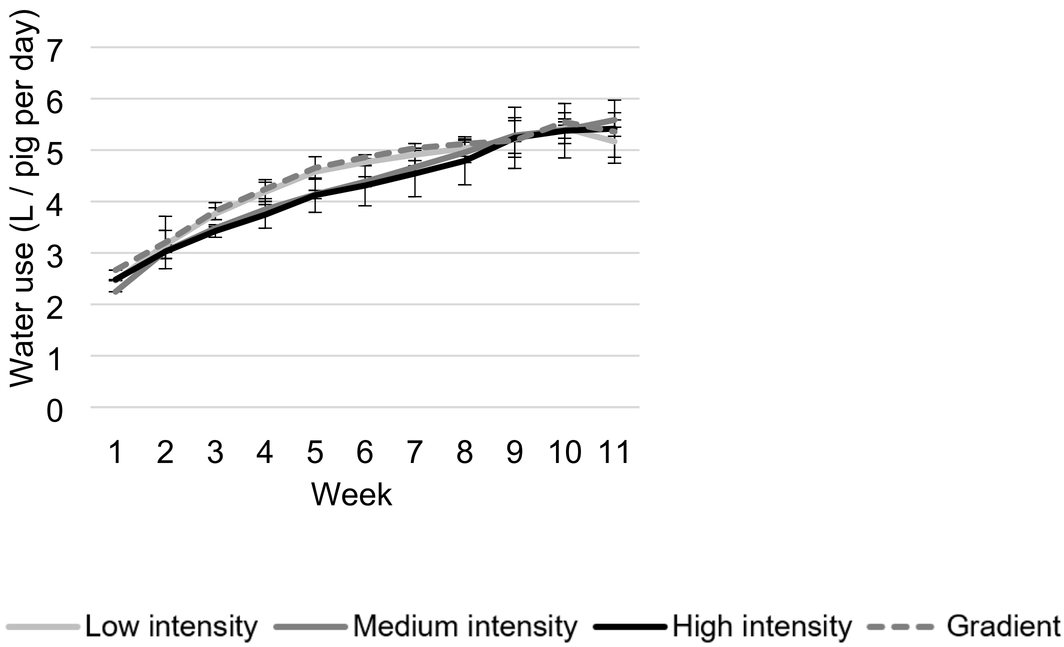

Fig. 6. Water use per pig per light intensity treatment over time (raw means ± SE).

Table 6
Lux level, electricity use, efficiency and costs per light intensity treatment in pig housing.

Variable	Low intensity	Medium intensity	High intensity	Gradient	Standard TL[1]
Intensity (lux)	45	198	968	198	71
Electricity use (kWh / year per pig place)	5.6	24.5	88.9	22.1	10.3
Efficiency (kWh / year per pig place per lux)	0.12	0.12	0.09	0.11	0.15
Light system costs[2] (€ per pig per day)	0.0024	0.0109	0.0162	0.0035	0.0030
Electricity costs (€ per pig per day)	0.0021	0.0094	0.0341	0.0085	0.0040

[1] Tube lights, also called luminescent tubes or fluorescent tubes.
[2] Including costs of light sources, fixtures and gateways. Excluding labour costs for installation.

Table 7
Pigs' live weight gain and carcass characteristics per light intensity treatment (raw means ± SE).

Variable	Low intensity (n = 112)	Medium intensity (n = 105)	High intensity (n = 106)	Gradient (n = 110)	Light intensity *P*-value
Average daily gain (kg/pig)[1]	1.17 ± 0.02	1.16 ± 0.02	1.16 ± 0.02	1.17 ± 0.01	0.98
Age at slaughter (days)	155.1 ± 0.3	152.3 ± 0.3	152.4 ± 0.3	155.1 ± 0.3	0.14
Net carcass weight (kg)	96.9 ± 0.8	95.1 ± 0.8	96.0 ± 0.8	96.5 ± 0.6	0.88
Lean meat (%)	59.0 ± 0.1	58.7 ± 0.2	58.7 ± 0.2	58.7 ± 0.2	0.86
Muscle thickness (mm)	70.7 ± 0.6	66.7 ± 0.7	67.4 ± 0.6	70.6 ± 0.5	0.41
Backfat thickness (mm)	13.6 ± 0.2	13.8 ± 0.3	14.0 ± 0.3	14.1 ± 0.3	0.91
Muscularity type (% of pigs)[2]					0.59
AA	10.7	6.7	6.6	6.4	
A	88.4	88.5	90.6	92.7	
B	0.9	4.8	2.8	0.9	
C	0	0	0	0	

[1] Average daily gain (based on pen weights) was calculated using n = 16 pens per treatment.
[2] Analysis could be performed for types AA and A only.

ammonia emissions in comparison with uniform light. A possible explanation could be that the spatial gradient could not be applied in an optimal way in the existing housing conditions. To better stimulate the use of functional areas, a bright dunging area and a dim resting area were preferred. The resting area was, however, located in the middle of each pen, creating a dim feeding area and an intermediately lit resting area. Moreover, the darkest part of the pen was still relatively bright at around 70 lux, while preference tests indicate that pigs prefer resting under intensities between 0 and 4 lux (Taylor et al., 2006; Götz et al., 2022), although note that in our study, pigs were provided with a fixed scotophase of 0 lux. With more clear-cut contrasts in intensity

Table 8
Summary of sustainability indicators per light intensity treatment and reference values.

Sustainability domain and theme	Subtheme	Indicator	Low intensity	Medium intensity	High intensity	Gradient	Reference values	Sources
Environmental sustainability								
Emission of pollutants	Acidification / eutrophication	kg NH_3 / year per pig place	1.59	NA[1]	NA[1]	1.87	1.5–4.3	Koerkamp et al., 1998; Van der Peet-Schwering et al., 1999; Hayes et al., 2006; Philippe et al., 2007
Use of resources	Water use	L water / day per pig	4.5	4.4	4.3	4.6	4.5–9.7	Rantanen et al., 1995; Li et al., 2005; Vermeer et al., 2009; Alvarez-Rodriguez et al., 2013
	Electricity use	kWh / year per pig place	5.6	24.5	88.9	22.1	10.3	Reference value based on standard light conditions on farm
Social sustainability								
Animal welfare[2]	Health and physical condition	Mortality %	0	0.9	1.8	0	2.3–4.7	Maes et al., 2004; Agostini et al., 2013; Agostini et al., 2014; AgroVision, 2022
Stockkeeper welfare	User experience	Average score of numeric rating scale questionnaire	9.54	9.61	9.46	9.54	9.51	Reference value based on standard light conditions on farm
Consumer preferences	Product quality	Lean meat %	59.0	58.7	58.7	58.7	51.8–65.8	Van der Wal et al., 1993; Vítek et al., 2008; Jiang et al., 2012; Bohrer et al., 2023
		% of carcasses with boar taint	0	0	0	0	1.8–5.6	Van Wagenberg et al., 2013; Aluwé et al., 2015; Heyrman et al., 2017; Heyrman et al., 2021
Human health risks	Antimicrobial resistance	Antimicrobial use in doses per pig place per year	4.2 (0)	4.2 (0)	4.2 (0)	4.2 (0)	2.2[3]	Agrimatie, 2022
Economic sustainability	Net income change	€ per pig per day	+0.0025	−0.0133	−0.0433	−0.0050	0.0000	Reference value based on standard light conditions on farm

[1] Not applicable: Ammonia emission was not measured in the medium and high intensity treatment.

[2] In previous work, effects of the tested light intensities on behavioural welfare indicators and physical condition were reported (Scaillierez et al., 2024). An interaction between light intensity and observation week affected the occurrence of exploration, positive and negative social interactions, abnormal behaviour, tear staining, conjunctivitis, eye staining, bursitis and lesions related to aggression and tail biting. However, none of the treatments consistently outperformed another treatment. Light intensity did not affect play behaviour, mounting behaviour, body condition, atrophic rhinitis, pumping, hernia, lameness, rectal prolapse and lesions related to ear biting and flank biting. Light intensity also did not affect the occurrence of postmortem abnormalities of the bowels, heart, liver, lungs, kidneys, tongue, skin and legs.

[3] This value applies to antibiotics used against bacteria only and does not consider anthelmintic use. Antibiotic use was zero in all treatment groups.

between different areas, other studies showed that light can in fact guide space use and defecating behaviour. Using a sheet-covered floodlight to direct a spotlight towards the dunging area, Opderbeck et al. (2020) found that more pigs lay in the designated lying area in comparison with pens without a spotlight. The level of pen fouling and pig fouling, however, did not differ between both treatments. Furthermore, in preference tests, pigs defecated more in the bright compartment (40 or 600 lux) than in the dark compartment (0, 2 or 4 lux) (Taylor et al., 2006; Götz et al., 2022). Aside from having more separated compartments, the contrast between dark and light areas was also higher in the latter two studies (a minimum difference of factor 10) than in our study (the brightest area had a four- to fivefold higher intensity than the dimmest area). Also in other circumstances with more clearly separated functional areas, effects of light intensity on space use were reported, e.g. when attracting piglets to use the creep area in the farrowing unit (Larsen and Pedersen, 2015; Morello et al., 2019). Nevertheless, also other factors can play a (possibly overruling) role in space use, such as tactile properties of the floor (Christison et al., 2000), temperature (Morello et al., 2019) and floor slope (Phillips et al., 1988). Furthermore, relocating some pigs shortly after entry into the finishing rooms may have disturbed space use and pen fouling (Nannoni et al., 2020), thereby interfering with a potential effect of light intensity. This was needed in the first batch only (12 out of 64 pens in total), to achieve a more balanced BW distribution per treatment. Similarly, carrying out health assessments as part of the larger study (Scaillierez et al., 2024) may have masked or altered potential effects of light intensity, as pen entry causes some disturbance. Nonetheless, the level of pen disturbance was similar among treatments and pen fouling was scored before carrying out the health assessment every week. In addition, space use was observed in a new batch of pigs that entered after finalising the experiment to check for a possible effect of human disturbance. These pigs experienced the same light conditions as in batch 2 of the experiment, but without disturbance of measurements on site. The average proportion of pigs observed per functional area was generally intermediate of batch 1 and batch 2, suggesting no major influence of human disturbance on space use in this case.

The general trend over time was that pigs lay more on the metal slats, while the use of the solid floor remained quite constant and lying on the concrete slats decreased. Concurrently, pen fouling in the resting and feeding area increased, pigs defecated less in the dunging area and ammonia emissions increased, which is in line with literature (Aarnink et al., 1995; Larsen et al., 2019). Ammonia emissions were in the lower range compared to the reference values from other studies (Table 8). A contributing factor may be the presence of an automated daily manure removal system on farm, which regularly flushed the manure gutter under the metal slats (Ivanova-Peneva et al., 2008). Increased pen fouling may be caused by altered space use due to pigs preferring the possibly cooler microclimate of the metal floor to lie down on, as the thermoneutral zone changes with age, and due to crowding over time (Larsen et al., 2018). Generally, appropriate space use was hindered from weeks 5–6 of the finishing phase onwards, as pigs grew too large to simultaneously use the same functional area. Later in the finishing phase, the size of functional areas may have been suboptimal even for use by single pigs. An illustrating example is that pigs were seen positioning their anterior side in the dunging area and carrying out pre-elimination behaviour such as sniffing the floor (Andersen et al., 2020), but due to the limited size of the dunging area, the excreta still landed on the solid floor. Therefore, using growing-finishing units that house larger groups in more spacious pens may be more suitable for applying a clearer distinction between functional areas, even at equal stocking density. In such a setting, the added value of varying light intensity per functional area to guide pig behaviour may be more pronounced than in the current setup.

Growth performance, medicine use and product quality

Weight gain did not differ between light intensity treatments and was substantially higher in comparison with reference values between 0.6 and 0.9 kg / day per pig (Knauer and Hostetler, 2013; Rocadembosch et al., 2016; AgroVision, 2022). While fast growth may be favourable from an environmental and economic point of view, the associated high physiological demands can have a trade-off with animal welfare (Prunier et al., 2010). Anecdotally, this was supported by observations of pigs having increasing difficulty to get up and occurrences of pigs urinating and defecating while sitting or lying down, which deviates from the normal elimination posture (Whatson, 1985). During the questionnaire, the stockkeeper mentioned that the high growth performance was characteristic for the farm in general and that antibiotics were also generally not used. Therefore, the potential of light intensity to influence these parameters may also have been limited in the studied context. Furthermore, light intensity did not affect carcass characteristics, which is in line with previous findings. In finishing pigs, the dressing out percentage and lean meat yield did not differ between groups kept under 40 or 80 lux (Martelli et al., 2010; Sardi et al., 2012). In addition, when comparing 40 lux to 80 or ~162 lux, there was no effect of light intensity on backfat thickness (Martelli et al., 2010; O'Connor et al., 2010) and measurements related to Italian ham production (Sardi et al., 2012). The latter included carcass weight; percentages of loin, thigh, lean cuts and fat cuts; lean:fat cut ratio; pH; meat and fat colour; percentages of drip and cooking loss; fatty acid composition and iodine number of uncured thighs; ham weights and losses during the curing process; and chemical composition and colour of cured hams. The percentage of polyunsaturated fatty acids in the subcutaneous fat of cured hams was, however, higher in the 80 lux group than the 40 lux group, i.e. more linoleic acid and less stearic acid (Sardi et al., 2012).

Despite raising intact boars, no occurrence of boar taint was detected. This seems to be in line with low occurrences of mounting behaviour observed by Scaillierez et al. (2024). It is known that seasonal changes, including shifting photoperiods, can affect boar reproduction performance (Kunavongkrit et al., 2005), but the role of light intensity in this process is less clear. With the photoperiod and light intensity kept constant over time within each treatment in our study, no clear contribution was observed. A detailed examination of light intensity on boar reproduction performance was, however, beyond the scope of the study as measurements were incorporated in the context of product quality and animal welfare (e.g. restlessness created by mounting).

Resource use, animal welfare and economic performance

Water use did not differ among treatments and was in the lower range in comparison with reference values, indicating that further reduction may not be feasible or desirable. The relationship between light intensity and water intake has been scarcely studied. In a preference test, the occurrence of drinking behaviour did not differ in compartments with 2, 4, 40 or 400 lux (Taylor et al., 2006), while a lower occurrence of drinking behaviour was observed in finishing pigs kept under 80 vs 40 lux (Martelli et al., 2010). The quantity of water consumed was however not reported in either study.

Calculated electricity use was reduced by 48% for the low intensity treatment in comparison with the standard light conditions on farm, whereas the other treatments resulted in a twofold (medium and gradient) up to almost ninefold (high intensity) increase in electricity use. As the high intensity did not seem to yield substantial benefits for the pigs and the stockkeeper, an illuminance between 40 and 200 lux may be preferable. The EU legal minimum of 40 lux would favour reduced electricity use, but from other studies it appears that this intensity is suboptimal for pig welfare. In comparison with 40 lux, an intensity between 80 and 200 lux ameliorated the effect of increased ammonia levels on salivary cortisol (O'Connor et al., 2010), reduced aggression (Martelli et al., 2010; Parker et al., 2010) and increased social discrimination between pigs (Parker et al., 2010). In our own study, light intensity did not seem to have major effects on pig welfare (Scaillierez et al., 2024). There were minor benefits of the medium intensity in specific weeks with fewer negative social interactions in week 4, relatively low tear stain scores in week 8 and higher exploration in week 10, but this intensity also resulted in more abnormal behaviour in week 8. The contrast in relation to the other three treatment groups was however not consistent for these measurements. Lastly, it is not clear how the low uniformity coefficient of the gradient treatment (0.33) affects aspects such as visual fatigue and discomfort in pigs. For humans, indoor work spaces are generally required to have a uniformity coefficient of 0.5 or higher, but exact specifications also depend on the visual nature of the work (Reinhold and Tint, 2009). Therefore, it is not certain how these requirements relate to the visual environment of the pigs, and it is also not known how pigs experience differences in light distribution in general.

Concerning the stockkeeper, the good vision in the medium intensity contributed to the slight preference for this treatment. Yet, the stockkeeper indicated that costs of the system would also play a decisive role. The net income change was, however, less favourable in the medium and high intensity than in the low intensity and gradient treatment. More specifically, the combined material and electricity costs of the current installation were about threefold higher for the medium intensity compared with the standard TL light of around 70 lux, and four- to fivefold higher compared with the low intensity treatment of 45 lux. As material use was a main determinant of economic performance, costs could be reduced by optimising the number of light sources needed per room to achieve the desired range in intensity. To remain flexible in the light setup for future research, a surplus of light sources was installed and dimmed as needed in our study. In general, the number of light sources installed per pen was based on ensuring that the correct intensity was achieved in each treatment, rather than having the most economically efficient use of material. In practice, also the gateways could be used more efficiently by connecting multiple rooms that require equal light settings to the same gateway. Considering more cost-effective use of materials, e.g. one light source per pen used at full capacity, it is estimated that an intensity of 60–70 lux would be reached. This is similar to the intensity reached by the standard TL, however, the costs of material and electricity would be reduced by around 39% with the more energy-efficient LED system. It is unclear if such an intensity level is appropriate in relation to pig behaviour and welfare, but basic performance parameters such as feed intake, weight gain and feed conversion ratio at least do not seem to be affected at 80 lux (Martelli et al., 2010). Other alternative light sources that are more energy efficient than standard TL while being more cost−effective than the currently used system do exist, such as tubular light emitting diode lighting which fits traditional TL fixtures. These light sources are, however, less dynamic than the currently used ND-Dome system in terms of colour tuning for example.

To conclude, light intensity influenced some aspects of space use and pen fouling, and ammonia emissions were higher in the gradient than in the low intensity treatment. Light intensity did not affect weight gain, carcass quality, water use and medicine use. The stockkeeper was content to work in all light conditions, but slightly preferred the medium intensity. Electricity use and costs of the light system increased with the number of light sources used, but these aspects could be improved by more efficient use of material. In general, more finetuned balancing in the range of 40–200 lux between system costs, electricity use, pig welfare and proper visibility seems needed. To ease this optimisation and to make use of the dynamic potential of the system, separate settings could be developed for the pigs (e.g. a daily light schedule that supports the expression of natural behaviours) and the stockkeeper (e.g. temporary change in light to monitor the pigs or relocate them). These settings could also include differences in light spectrum and photoperiod over time. In such a dynamic system, the effects of (gradual) transitions in light should also be investigated, as these may affect animal performance and behaviour (Kluivers-Poodt et al., 2018).

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101283.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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