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CARACTERIZACIÓN DEL ESTRÉS CALÓRICO Y SU EFECTO SOBRE LA PRODUCCIÓN DE LECHE EN GANADO HOLSTEIN EN HATOS DE PRODUCCIÓN INTENSIVA EN CONDICIONES ÁRIDAS DEL NORTE DE MÉXICO

Tesis

Que presenta RAFAEL RODRÍGUEZ VENEGAS

como requisito parcial para obtener el Grado de
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Tesis

Elaborada por RAFAEL RODRÍGUEZ VENEGAS como requisito parcial para obtener el grado de Doctor en Ciencias en Producción Agropecuaria con la supervisión y aprobación del Comité de Asesoría

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Caracterización del estrés calórico y su efecto sobre la producción de leche en ganado Holstein en hatos de producción intensiva en condiciones áridas del norte de México

Rafael Rodríguez Venegas

Doctor en Ciencias en Producción Agropecuaria

Universidad Autónoma Agraria Antonio Narro

Dr. Oscar Ángel García

Director de tesis

Caracterizamos el Estrés Calorico (EC) mediante el Índice Temperatura y Humedad (ITH) y evaluamos las variables de producción de leche con estrés calórico, en la región norte de México, donde el ganado lechero está sujeto a las condiciones de clima extremo que la caracteriza. Para el primer artículo se utilizó (ITH) como biomarcador de EC, para lo cual se utilizaron los datos climáticos (temperatura ambiente (ºC) y humedad relativa (%) de cinco establos ubicados en esta región y de cinco años (2015 a 2020), El segundo artículo analiza el efecto del EC sobre la producción y características de la leche y sobre el bienestar animal. Se utilizaron los datos de ITH, producción y características de la leche, así como de confort animal (tiempo de reposo). Las variables de respuesta consideradas fueron Producción de leche por hato (totPL) y por vaca (vacaPL), consumo de materia seca (kg), cantidad de componentes de leche y tiempo de reposo (h). Los resultados observados apoyaron nuestra hipótesis, confirmando en promedio anual más de 300 d con EC. Tanto totPL como vacaPL difieren ($p < 0,05$) a medida que aumentaba el ITH; los valores más grandes (77,886 L y 35.9 L) ocurrieron en ITH más bajos, mientras que la producción de leche cayó (66,584 L y 31,7 L) con los ITH más altos. Como resultados de este estudio resaltan la importancia de cuantificar los impactos negativos que el EC puede generar a nivel productivo y reproductivo para delinear estrategias de mitigación que disminuyan el impacto ambiental.

Palabras claves: Estrés calórico, Indice temperatura y humedad, Producción de lechen Composición de la leche, Norte de México.

ABSTRACT

Characterization of heat stress and it's effect on milk production in Holstein cattle in dairy farm production under arid conditions in northern of Mexico

Rafael Rodríguez Venegas

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We characterize Heat Stress (HS) through the Index Temperature and Humidity (THI) and evaluate the variables of milk production with HS, in the northern region of Mexico, where dairy cattle are subject to the extreme climatic conditions that characterize it . For the first article (THI) was obtained as a biomarker of HS, for which climatic data (ambient temperature (ºC) and relative humidity (%) of five stables located in this region and five years (2015 to 2020) were used. The second article analyzes the effect of HS on the production and characteristics of milk and on animal welfare. The data of THI, production and characteristics of milk, as well as animal comfort (rest time) were used. The variables The responses considered were milk production per herd (totMP) and per cow (cowMP), dry matter intake (kg), quantity of milk components, and annual rest time (h) for more than 300 d with HS. Both totMP as a different cow MP ($p < 0.05$) as ITH increased; the largest values (77,886 L and 35.9 L) occurred at lower THI, while milk production fell (66,584 L and 31.7 L) with the highest THI. The results of this study highlight the importance of quantifying the negative impacts that the EC can generate at a productive and reproductive level to outline mitigation strategies that reduce the environmental impact.

Keywords: Heat stress, Temperature and humidity index, Milk production Milk composition, North of México.

INTRODUCCIÓN

Uno de los factores externos más importantes que afectan negativamente el rendimiento de las vacas lecheras es el ambiente térmico en el que viven(Nardone *et al*., 2010). De hecho, los animales de alto rendimiento con alto valor genético son particularmente susceptibles al estrés por calor (EC) debido a su mayor actividad metabólica que aumenta la termogénesis (Bernabucci *et al*., 2014; St-Pierre *et al*., 2003). El límite de temperatura del EC se puede reducir en 5 °C cuando la producción de leche de vaca aumenta de 35 kg/día a 45 kg/día, lo que significa que las vacas experimentan estrés por calor más rápidamente (Becker & Stone, 2020).

El EC tiene la capacidad de afectar la termorregulación de los animales, aumentando la termogénesis y disminuyendo el consumo de alimento, la fertilidad y la producción de leche (Armstrong, 1994; Gantner *et al*., 2012). Sin embargo, debido a lo antes mencionado, no solo se podrá observar una pérdida en la producción de leche, también observaremos cambios en sus componentes, incluidos los contenidos de proteína (Mbuthia *et al*., 2022), grasa, sólidos no grasos, caseína, lactosa y urea y en el número de células somáticas (Dikmen *et al*., 2022).

El EC no solo afecta las cuestiones productivas y reproductivas del animal, sino también se ha descrito que puede llegar a alterar el bienestar animal, como el tiempo de reposo, el cual se describe como una característica conductual muy importante debido a que es un marcador fundamental del estado fisiológico y de salud de las vacas lecheras (Tolkamp *et al*., 2010). Ciertamente, este marcador ayuda a tomar decisiones para reducir las enfermedades de las pezuñas, la cojera y aumentar tanto el consumo de alimento como la actividad ruminal (Herbut & Angrecka, 2018a). Por lo tanto, el tiempo de reposo de la vaca podría ser utilizado como un indicador más de su bienestar (Vasseur *et al*., 2012), observándose que cuando el EC disminuye se produce un mayor tiempo de descanso en el animal (Herbut & Angrecka, 2018b).

En 1940 se empezaron a investigar los índices bioclimáticos como predictores del estrés calórico, sin embargo, hasta los principios de la década de 1960 se desarrolló un índice específico para el ganado lechero (Wijffels *et al*., 2021): el índice de temperatura y humedad (ITH), herramienta útil para medir la respuesta productiva en función del clima (Ravagnolo *et al*., 2000; Dikmen & Hansen, 2009). El ITH está basado en la temperatura y la humedad del aire y sirve como una medida de la suma de estos elementos en el animal, que actúan para desplazar la temperatura del animal de su punto homeostático (Dikmen & Hansen, 2009).

La Comarca Lagunera registra el 21% del inventario nacional de vacas lecheras. Esta región se encuentra ubicada en el Centro Norte de México (24º 01´ a 26º 48’ LN y 101º 52´ a 104º 40´ LO) y se caracteriza por una precipitación promedio anual de alrededor de 200 mm, concentrada de junio a octubre, con 6 a 7 meses de sequía, siendo la precipitación mensual inferior a 7 mm. La temperatura media mensual del aire oscila entre 12,7 ºC en enero y 28,5 ºC en junio, con extremos de -5 ºC a 41,5 ºC, y también se registra alta radiación solar (Mazcorro, *et al*., 1991). Estas condiciones de clima crean un entorno adverso para el ganado lechero y representan un desafio para la aclimatación de las vacas.

Hipótesis generales.

La Comarca Lagunera presenta durante la mayor parte de los días del año condiciones de EC intenso, el cual afecta el rendimiento lechero, la composición de la leche y, el bienestar en las vacas Holstein.

Objetivo general:

Caracterizar el ITH de la Comarca Laguera y cuantificar cuanto afecta el estrés calórico la producción y composición de la leche y el confort de vacas lecheras en el norte árido de México.

Objetivos específicos:

Cuantificar los días en que los niveles de ITH representan un riesgo de estrés calórico para el ganado lechero en la Comarca Lagunera.

Identificar los días de EC en relación a las horas de exposición del ganado lechero en la Comarca Lagunera.

Identificar cuáles son las estaciones que representan un mayor riesgo de estrés calórico para el área de la Comarca Lagunera.

Determinar los efectos negativos del EC sobre la producción y composición de la leche y el bienestar animal.

Revisión de literatura

Producción de leche a nivel mundial, latinoamericano y nacional

En el mundo existen alrededor de más de 6 mil millones de consumidores de productos derivados de lácteos o de la misma leche, encontrándose principalmente en los países en vías de desarrollo, en los cuales la producción de leche es a través de productores pequeños y de traspatio, contribuyendo así al bienestar del hogar, medios de vida, seguridad alimentaria y nutrición.Para perseguir el ritmo del crecimiento de la demanda del consumno de leche se necesita un crecimiento de la oferta de cerca del 2% anual.

En los últimos 3 años a aumentado la demanda de leche en más del 50%, pasando de 500 a 769 millones de T en 2013 (FAO, 2016). Gran parte de los países en vía de desarrollo se uncuentran en el Mediterráneo y el Cercano Oriente, India, África occidental, las tierras altas de África oriental y partes de América del Sur y Central. Los países sin tradición en la producción de lácteos se ubican en el sudeste de Asia, en regiones del trópico, con alta temperatura y/o humedad.

Reciebntemenbte los países en desarrollo están incrementando su papel a nivel mundial como productores de lácteos. Esto es debido más a un aumento en el número de animales productores que a un aumento en la productividad por animal (Kapaj & Deci, 2017), por otra parte, en la mayoría de los países que se en desarrollo, la producción de leche se restringe por una baja calidad en la alimentación, enfermedades, escasez de acceso a mercados y servicios, y sobre todo, por una mala condición genética del ganado lechero, amén de la desventaja de la calidad climática, ya que cuentan con climas cálidos y/o húmedos considerados como inadecuados para el ganado lechero.

La ganadería lechera en la Comarca Lagunera, características climáticas.

En México sólo se produce 2% de la producción mundial a nivel mundial y el 8% de la leche que se consume en América del Norte, además de ser de los paises que más importan de leche en polvo descremada, pero a pesar de lo anterior, se considera que la producción de leche muestra una tendencia al crecimiento, empero, se considera que de acuerdo con los consumos mínimos determinados por FAO, el país tiene un déficit del 40% en el consumo de este producto (Aguilar & Luévano González, 2001).

La Comarca Lagunera esta ubicada al Centro Norte de México (24º 01´ a 26º 48' LN y 101º 52´ a 104º 40´ LO), tiene una precipitación anual de alrededor de 200 mm, donde la mayoria de la precipitación es de junio a octubre, donde podemos observar sequías de 6 a 8 meses, la temperatura media mensual del aire oscila entre 12,7 ºC en enero y 28,5 ºC en junio, con extremos de -5 ºC a 41,5 ºC, donde también se registra alta radiación solar (Mazcorro, *et al*., 1991).

El estrés calórico, la productividad y fertlidad en la ganadería lechera.

El EC se define como la suma de las fuerzas ambientales externas que actúan sobre un animal, lo que resulta en un aumento de la temperatura corporal y, dispara ajustes fisiológicos y conductuales (Kadzere *et al*., 2002a). En las vacas, estos ajustes representan la activación de mecanismos adaptativos en un intento por mantener el equilibrio homeostático (Herbut *et al*., 2018). A medida que el calentamiento global continúa aumentando, la incidencia, la duración y la gravedad del EC en el ganado lechero también aumentarán (Min *et al*., 2017; Theusme *et al*., 2021). Por lo tanto, disminuir los efectos negativos del EC en la productividad y confort del hato lechero se ha convertido en un desafío para la industria láctea mundial (Bouraoui *et al*., 2002).

El balance térmico o termorregulación es un mecanismo de adaptación que mantiene el equilibrio entre el calor que recibe el animal y el calor interno generado, el calor acumulado en el organismo y el calor disipado en el ambiente para mantener la temperatura corporal constante. El equilibrio se mantiene cuando el calor recibido y el generado por el organismo es el mismo que el calor disipado. Tiene dos componentes interactuando: a) **La Temperatura corporal**, que en los bovinos fluctúa entre 37.8 °C y 39.3 °C, temperatura en la cual todas las funciones metabólicas se desarrollan con mayor eficiencia y; b) **La Temperatura ambiental**, que es la cantidad de calor presente en el ambiente y el aire de una zona determinada; la “Zona de Confort” o “Zona Termoneutral” es la temperatura ambiental en la que el animal mantiene su temperatura corporal constante sin necesidad de ajustes fisiológicos o de manejo y en la cual el ganado se siente confortable y produce de manera óptima (Pérez, 2020).

La baja en la leche producida se debe a efectos directos e indirectos del EC, siendo los primeros debidos a la regulación metabolica de la energía y las proteínas, determinando la prioridad de la disponibilidad de nutrientes durante la termorregulación de las vacas lecheras, en lugar de dirigirlos a las glándulas mamarias para la producción láctea.

La Comunidad Europea ha advertido también de una mayor presencia de estrés oxidativo, que cambia la actividad metabólica y las funciones moleculares de las células del tejido mamario y disminuyen la eficiencia de diversos componentes que se sintetizan en la leche (Gao *et al*., 2019). Por otra parte, el EC afecta negativamente al transcriptoma realacionado con el metabolismo general y con la síntesis de proteína láctea, en el tejido mamario de las vacas lecheras. De manear indirecta, este mecanismo se correlaciona con una disminución en el consumo de materia seca debido a una mayor demanda de energía para mantenimiento por la activación de los mecanismos fisiológicos termorreguladores en un ambiente con nutrientes corporales reducidos debido al bajo consumo de alimento (National Research Council, 1981; Min *et al*., 2017b;), lo que provoca una disminución del 30% al 50% en la eficiencia energética en vacas en climas cálidos (Kadzere *et al*., 2002b).

La temperatura puede afectar significativamente la reproducción de las vacas lecheras reduciendo la eficiencia reproductiva del hato desde un 10% a un 75%. La mayor reducción en la tasa reproductiva se debe a la falla en la implantación del embrión, ya que para disipar el calor, las vacas estresadas por el calor experimentan vasodilatación periférica, lo que reduce el suministro de sangre a órganos como el útero. Por otra parte, el estrés causa la liberación de prostaglandinas, como la PgF2, la cual posee un efecto luteolítico, exacerbando la baja en la fertilidad y aumentando la mortalidad embrionaria (Salvador, 2007).

Efectos del estrés calórico sobre el eje HHA, daños fisiológicos y productivos

En la hembra bovina los principales indicadores de la repruccion son el comportamiento sexual y la tasa de fertilidad, los cuales se afectan negativamente por el EC. Debido a este estrés, los programas para la aumentar la fertilidad en las hembras bovinas se ven afectados teniendo menor éxito en las épocas calurosas (Chemineau, 1993).

El EC afecta negativamente la duración del estro y en su intensidad, debido a que puede disminuir el tiempo del estro hasta cinco horas, el cual, en algunas regiones templadas tienen como promedio de 11 a 9 horas. Asimismo, se ve afectada la secreción de la Hormona Leutilizante (LH) y el desarrollo folicular, lo cual retarda o inhibe la ovulación (Góngora & Hernández, 2010). También, durante los primeros ocho días del ciclo estral, afecta el desarrollo folicular y la dominancia. Si este efecto persiste durante mucho tiempo, disminuye la actividad de la aromatasa y la concentración de estradiol en el líquido folicular. Posterior a la ovulación, la producción de progesterona se ve afectada por cambios en el cuerpo lúteo, y en el microambiente del oviducto y del útero, afectando la supervivencia embrionaria (Góngora & Hernández, 2010).

Estado endocrino

Las vacas criadas en temperaturas altas suelen tener los niveles de estradiol bajos. Esto podría influir en el celo, la ovulación y el cuerpo lúteo. El EC altera la secreción de gonadotrofina, inhibina y PGF2α. Asimismo, las vacas con EC suelen tener una duración de la fase lútea más larga que las hembras sin EC. Al parecer el útero tiene una secreción PGF2α menor debido a que las células endometriales pueden interferir en la liberación de PGF2α y así tener una reducción en la síntesis de estradiol.

El endometrio uterino necesita estar preparado con estradiol para una producción suficiente de prostaglandina, desencadenando así la luteólisis. Las concentraciones de FSH e inhibina y la función del cuerpo lúteo también se alteran por el EC, disminuyendo el contenido de líquido de los folículos. Las células tecales que secretan androstenediona se ven afectadas por las altas temperaturas y se reduce el número de las células de la granulosa y la actividad de la aromatasa. (Wolfenson *et al*., 1993).

Selección y desarrollo folicular:

Uno de los principales desafíos reproductivos del EC en las vacas es el desarrollo folicular alterado. La ingesta reducida de alimento en vacas estresadas por calor reduce la frecuencia del pulso de la hormona luteinizante (LH), lo que resulta en ondas foliculares más largas. El alargamiento de esta ola de folículos conduce a la selección y ovulación de varios folículos menos dominantes (Sartori *et al*., 2002). El estrógeno es el responsable que las vacas muestren los signos de celo y los responsables de producir el estrógeno son los folículos. El tamaño de los folículos determina la cantidad de estrógeno, es decir; los folículos pequeños producirán menor estrógeno que los folículos más grandes, y a su vez los más pequeños tienen una menor actividad estral. El estradiol es sintetizado por las células somáticas y por los ovocitos que se encuentran en los folículos y se encarga de la inducción del estro y el aumento de la hormona luteinizante entre otras acciones. La selección folicular y el aumento de la longitud de onda folicular es afectada por el EC y esto produce que la calidad de los ovocitos sea menor, a la vez que origina que se desarrollen folículos más dominantes (Góngora & Hernández, 2010).

La disminución del consumo de alimento causada por EC causa en las vacas una baja pulsatilidad de la hormona luteinizante (LH) y ondas pulsátiles más largas. Este suceso conduce a la ovulación y selección de los folículos más pequeños dominantes (Sartori *et al*., 2002). Los folículos más pequeños producirán menos estrógeno que los más grandes resultando en menos actividad estral. Los folículos ováricos contienen ovocitos, así como células somáticas que sintetizan estradiol. El estradiol tiene una variedad de acciones que incluyen causar el estro y el pico de LH. El estrés calórico causa un daño en las células somáticas dentro de los folículos (células de la teca y de la granulosa) (Sartori *et al*., 2002).

Cuerpo lúteo

El EC no solo afecta a los folículos, sino también al cuerpo lúteo. La progesterona, que proviene del cuerpo lúteo, es necesaria para el embarazo y existe una relación entre los niveles bajos de progesterona y la infertilidad. El estradiol folicular induce la luteólisis en el ganado. Las células lúteas son diferentes de las células foliculares. Por lo tanto, si el EC reduce la progesterona en la sangre, entonces esta reducción puede deberse al efecto del EC en los folículos que eventualmente ingresan al cuerpo lúteo. Alternativamente, los cambios metabólicos asociados con el EC pueden alterar el metabolismo de la progesterona (Samal & Samal, 2014b, 2014a).

Desarrollo del embrión

La calidad y el crecimiento del embrión a menudo se reducen durante el EC. El cual también altera la capacidad de los embriones para convertirse en blastocistos, aumentando el riesgo de muertes embrionarias prematuras y disminución del crecimiento fetal. El período de mayor susceptibilidad es inmediatamente después del inicio del estro temprano, durante el período posterior a la monta. Una alta temperatura en el útero de la vaca con EC puede originar una mala implantación del embrión y un aumento de la muerte embrionaria (Sartori *et al*., 2002).

Ingesta de materia seca

La primera respuesta que muestran las vacas lecheras al EC es una menor ingesta de alimento, lo que proporciona menos energía y puede afectar su desempeño reproductivo. Debido a que las vacas lecheras se crían para producir grandes cantidades de leche, utilizan primero la energía disponible para el mantenimiento diario y la producción de leche, dejando menos nutrientes para la salud reproductiva (Samal & Samal, 2014b).

Efectos de arrastre

Incluso después de que haya terminado el calor del verano, los efectos persistentes del EC pueden retrasar la fertilidad, lo que puede reducir las tasas de concepción durante un período de tiempo más prolongado y provocar una detección de celo deficiente, más servicios por gestacióm y días abiertos más prolongados. Por todas estas razones, los abortos aumentan dramáticamente conforme aumenta el ITH. Como resultado, las tasas de concepción y embarazo disminuyen durante las estaciones más cálidas (Samal & Samal, 2014c).

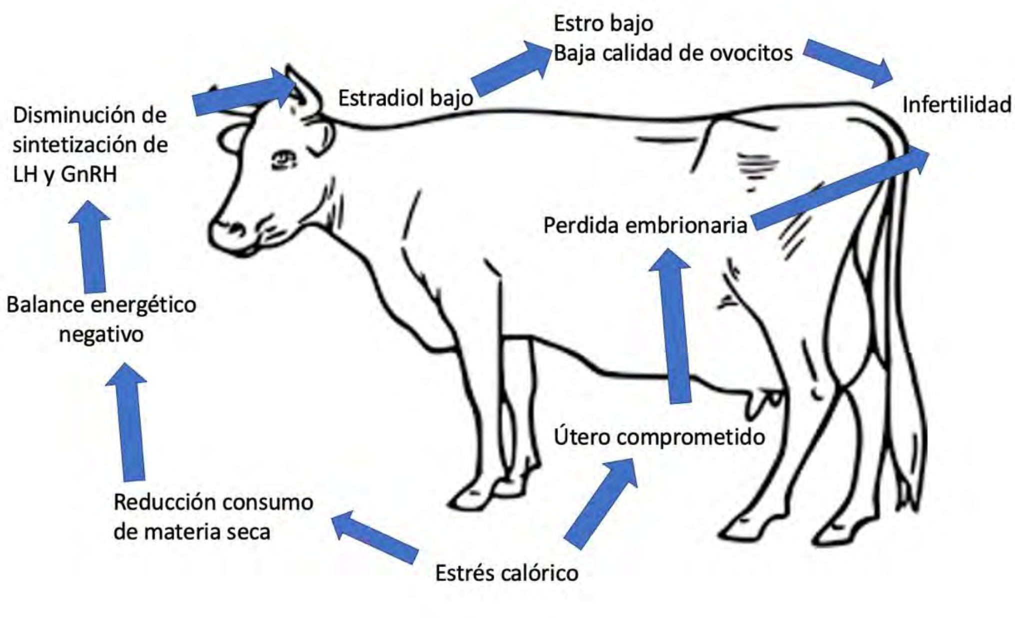

Figura 1 Descripción del estrés calórico en vacas

Regulación del estrés calorico (mecanismos fisiologicos).

Existen mecanismos en los animales para mitigar el EC, la mayoria de los cuales son de intercambio térmico. Los animales necesitan eliminar el exceso de calor causado por el EC por las situaciones de altas temperaturas.

Radiación. El mecanismo de pérdida de calor por este medio se basa en la pérdida del calor por sondas electromagnéticas que son en forma de los rayos infrarojos. Es el intercambio de energía electromagnética entre el animal y el ambiente o siemplente con objetos que se encuentran con temperaturas mas bajas y están situados a una mayor distancia debido al intercambio de energía electromagnética entre y el medio ambiente y el organismo o con los objetos menos calientes y ubicados a distancia. El volumen de radiación emitida varía con base en el gradiente existente entre el cuerpo y el ambiente. Este mecanismo es el más importante y disipa hasta el 60% del calor corporal (Perez *et al*., 2009).

Conducción: Se observa cuando el animal posee una temperatura corporal alta y entra en contacto directo con alguna superficie como el suelo o las paredes que contienen una temperatura más fría, perdiendo pequeñas cantidades de calor. Está basada en la pérdida de bajas cantidades de calor corporal. Este mecanismo de disipación de calor provoca a nivel corporal, una pérdida de calor hasta de un 30% (Perez *et al*., 2009).

Convección. El calor del cuerpo se transfiere a las partículas aereas o acuosas que están en contacto con ellas, las cuales se calientan por contacto con la superficie del cuerpo, y al dejar la superficie corporal, otras partículas calentadas, más frías, toman su lugar, y así sucesivamente. La cantidad de calor pérdida esta enb relación con el área expuesta pudiendo alcanzar hasta el 12%. Por esta razón, la convección forzada aumenta la liberación de calor cuando se utilizan ventiladores en edificios u otros sistemas de aire acondicionado (Perez *et al*., 2009).

Evaporación. Este es el calor que se pierde debido a la evaporación del agua. La única forma en que un organismo puede perder calor es a través de la evaporación, la cual representa algo más del 20% del calor corporal. Al evarporarse el agua de la superficie corporal se pierden 0,58 calorías por g de agua evaporada. En ausencia de sudor, la humedad se evapora imperceptiblemente por piel pulmones en cantidades específicas para cada especie, ocasionando una pérdida de calor constante de alrededor de 12 a 16 calorías por hora. Pero cuando se suda profusamente, dependiendo de la especie, se puede perder más de un L de agua por hora. La humedad del aire afecta la cantidad de calor perdido a través del sudor, cuanto mayor sea la humedad ambiental, menos calor se pierde a través de este mecanismo.

Los mecanismos para la pérdida de calor en en los animales llegan a incluir vias no perceptibles como la conducción, la radiación, evaporación a través de la piel, convección y eliminación de heces fecales y orina y mediante el sistema respiratorio.

Los bovinos controlan la temperatura corporal mediante un estrecho margen a mediante varios procesos fisiológicos (Bianca, 1968), el cual consiste en un proceso termoregulador de cuatro vías específicas, de las cuales tres se denominan “transferencias sensibles”: como son la conducción, la convección y la radiación, mientras que la cuarta vía se conoce como pérdida insensible de calor o pérdida latente.

Metodos de regulacion artificial

En el primer punto es posible la ventilación natural o la ventilación dinámica. Para que la ventilación natural sea la correcta, el edificio necesita unas condiciones de diseño y orientación. Su capacidad para aumentar la velocidad del aire no siempre es controlable porque también esta sujeta de las condiciones ambientales. Para aumentar la velocidad del aire se requieren dispositivos mecánicos que pueden funcionar en almacenes tipo túnel (que deben estar cerrados) o con ventiladores de circulación en almacenes abiertos. Si se desea aumentar la disipación de calor del animal, se tiene la opción de enfriar el aire circundante o humedecer directamente al animal. En ambos casos, el enfriamiento es evaporativo, ya que el agua se evapora absorbiendo calor del aire o del propio animal húmedo. Al elegir estos sistemas, no solo se debe considerar su diseño y tamaño, sino también la importancia de las decisiones de inversión y los costos operativos relacionados con el retorno estimado de la producción de leche y la salud animal.

El manejo general de la granja también puede reducir significativamente el estrés por calor. Por lo tanto, es necesario tratar de evitar el hacinamiento:

• reduciendo el tiempo de espera para el ordeño

• ordeñar en el clima más fresco posible

• proporcionar lugares de descanso adecuados

• control de insectos

• proporcionar agua de buena calidad sin restricciones de espacio o volumen.

Indicadores del estrés calórico.

Los indicadores usados para medir el EC en el ganado incluyen el índice de humedad del globo (Buffington *et al*., 1981), el índice de estrés por calor y el predictor de frecuencia respiratoria (Gomes da Silva *et al*., 2007) y el Índice de Temperatura y Humedad (ITH). Este último es una herramienta útil para medir las respuestas de producción en función del clima (Ravagnolo *et al*., 2000; Gomes da Silva *et al*., 2007; Dikmen & Hansen, 2009; G. LeRoy Hahn *et al*., 2013). El ITH se basa en la temperatura del aire y la humedad relativa como una medida indicativa de la suma de las fuerzas externas aplicadas al animal para cambiar su temperatura corporal desde su punto de estado estacionario(Dikmen & Hansen, 2009). Algunas variaciones de la fórmula para el ITH incluyen términos de velocidad de aire para tener en cuenta el efecto de enfriamiento de los movimientos del aire (Tao & Xin, 2003), o términos para la velocidad del viento y la radiación solar (Mader *et al*., 2006).

Para poder obtener el índice temperatúra humedad existen varias propuestas: Kliber (1964) utiliza la ecuación ITH= 1.8×Ta–(1–RH) ×(Ta–14.3) +32, mientras que Kelly y Bond, (1971) utilizan las siguientes: ITH = 0.4 (DB + WB) = 15; ITH = 0,55 dB + 0,2 DP + 17,5; ó ITH = dB-(0,55-0,55 RH) {dB-58), donde el significado de los términos son DB= temperatúra de bulbo seco del aire; WB = temperatura de bulbo húmedo del aire; DP = tempratura del punto de rocío del aire y; RH = Humedad relativa del aire.

Los umbrales para la medición del ITH varían según las características específicas de la especie y su estado fisiológico, la tasa metabólica está incluida y, revisando sus efectos sobre el ganado, se ha modificado con el paso del tiempo. Para el ganado lechero, las pérdidas en la producción de leche tienen una relación muy clara con los cambios por el ITH. Al nivel de 70 unidades los animales muestran poca molestia, y en nivel de 75 ITH el rendimiento de la leche y la ingesta del alimento se ven deprimidos. A partir de un ITH de 78 o superior a este, se muestran grados de incomodidad en los bovinos de todas las edades (Kelly y Bond, 1971).

Existen varios artículos que señalan que la producción de leche y el consumo de materia seca tienen diferentes umbrales. Du Preez *et al*. (1990 a, b), determinan que es a partir de los valores de ITH mayores a 72, Bouraoui *et al*. (2002) lo colocan en 69, mientras que Bernabucci *et al*. (2010) y Collier *et al*. (2012) pusieron que el umbral es de 68 ITH. Los animales que están expuestos a un ITH de 80 y más, corren el riesgo de muerte (Vitali *et al*., 2009).

Si bien el ITH es importante para identificar períodos críticos para la salud, el bienestar, e incluso la producción, y dado que las condiciones climáticas de la Comarca Lagunera son propicias para inducir el estrés calórico, no existen estudios que señalen si existen áreas de la Comarca Lagunera con un mayor riesgo por los niveles de ITH que no han sido identificados, ni qué momentos del año o día se requieren tomar medidas para mitigar los efectos negativos del EC Tampoco se sabe si la cantidad de días cada año en los que las condiciones de ITH superan el umbral establecido para las vacas ha aumentado históricamente debido al cambio climático.

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Estudio 1

Articulo 1: Heat Stress Characterization in a Dairy Cattle Intensive Production Cluster under Arid Land Conditions: An Annual, Seasonal, Daily, and Minute-To-Minute, Big Data Approach.

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Article

Heat Stress Characterization in a Dairy Cattle Intensive Production Cluster under Arid Land Conditions: An Annual, Seasonal, Daily, and Minute-To-Minute, Big Data Approach

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Abstract: This study characterized the environmental–climatic trends occurring in the largest dairy cattle intensive production cluster under arid land conditions in northern Mexico. The study was based on the Temperature Humidity Index (THI); it aimed to identify the number of days with THI values $\geq$68 as a bio-marker of heat stress (HS) and evaluate the possible HS effect upon the milk production of dairy cows. Climate data were obtained every 10 min in five farms across years (i.e., 2015–2020). THI was divided into four HS subclasses, 68–71, 72–76, 77–79, and $\geq$80, according to the circadian HS occurrence (i.e., 1, 4, 8, 12, 16, 20, 24 h), and analyzed across seasons–years. Thus, a total of 1,475,319 THI across different time-scale subclasses was analyzed. The observed results supported our working hypothesis in that yearling-average periods with more than 300 d, HS was confirmed. A yearly average of 31.2 d with THI $\geq$ 80 with similar ($p > 0.05$) trends across dairy farms and a slight annual variation ($p < 0.05$) were also witnessed. Moreover, the highest days with THI levels $\geq$68 occurred in summer and autumn ($p < 0.05$), while the in the subclasses 68–71, 72–76, and 77–79, THI occurred in any hour-scale subclass (i.e., 1, 4, 8, and 12 h). Furthermore, a trend to observe THI-HS increases either among years or within an hour-scale basis were also observed. On average, HS engendered a reduction of up to 11.8% in milk production. These research outcomes highlight the need to identify and quantify the negative impacts that HS may generate at a productive and reproductive level in order to delineate mitigation strategies that may lessen the environmental impact upon the dairy cattle industry.

Keywords: arid climate; dairy cattle; warm environment; temperature–humidity index; heat load; milk production

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1. Introduction

Heat stress (HS) affects the ability of animals to thermoregulate, causing an increase in body temperature with significant while adverse implications for livestock productivity [1] with reductions in feed intake, fertility and milk production [2–8]. Moreover, impairments on well-being have also been described, such as resting time, which is a behavioral characteristic that indicates the physiological and health status of cows [9]. Certainly, when avoiding such adverse scenarios, not only hoof diseases but lameness are reduced, observing an enhanced feed intake while an augmented ruminal activity [10]. Thus, the resting time of cows is an important marker of their well-being [11]; a longer nightly resting time is observed once the HS decreases [12]. Additionally, in dairy cows, an increased HS upon commensal microbes of the normal gut microbiota may trigger pathogenic events leading to mastitis [13]. Similarly, the biological adaptation of dairy cows to high temperatures is associated with reductions in milk production and body skin temperature increases [14], mainly in the middle and at the end of the lactation [15]. The use of bioclimatic indices as a measure or predictor of HS was first investigated in the 1940s; however, it was not until the early 1960s that a specific dairy cow HS-marker was developed [16]. Since then, the Temperature Humidity Index (THI) has been a useful tool to measure the productive and reproductive response as a function of climate differences [14,17–20], based on air temperature and relative humidity. The THI as served as a bioclimatic marker of the sum of external forces on animals that act to displace body temperature from its homeostatic point [20]. Although it was common to place the THI threshold at 72 as the point where milk synthesis begins to decline, later on, it was proposed that high-yielding dairy cows reduce their milk production with a THI around 68 [21]; at such value, dairy cattle become more sensitive to HS as milk production declines [3].

The Comarca Lagunera located in northern arid Mexico concentrates 21% of the national dairy cow inventory. This region is characterized by an annual average rainfall of 200 mm and monthly average temperatures that fluctuate between 12.7 °C in January and 28.5 °C in June, with extremes of −5 °C and 41.5 °C, as well as high sun radiation. These conditions have been shown to create an adverse environment for dairy cattle while representing a challenge for dairy cows for their acclimatization; such HS conditions lessen the maximum expression of their productive potential. Certainly, while decreases in milk production and fertility occur, an increased rate of mastitis alongside reductions in feed intake and resting time are also generated by HS. Reiczigel et al. [22] reported an increase in the number of HS days per year (THI $\geq$ 68) from 5 to 17 days during the last 30 years, while Dunn et al. [23] suggest that by the year 2100, the number of days exceeding the THI threshold may increase from a yearly average of 1–2 to more than 20. Hempel et al. [24] posit that the impacts of future increases in heat stress risk will depict different severities among diverse locations, and there is expected to be an overall increasing trend in the number and duration of heat stress events. Centered in such evidence, we hypothesize an increase in the number of days reaching THI values $\geq$ 68 in the Comarca Lagunera, Mexico. We aimed to characterize the thermic scenario across years in five representative dairy farms based on the THI to quantify the magnitude of such climatic insult upon milk yield. Thus, an annual, seasonal, daily, and minute-to-minute, THI-big data approach was considered.

2. Materials and Methods

2.1. Location of the Area of Study and Selected Representative Dairy Farms

The Comarca Lagunera (CLAG; 102° 22′, 104° 47′ WL; 24° 22′, 26° 23′ NL, at 1139 m) is located in a semi-arid ecotype, with an average temperature of 22 °C, lows of 0 °C (winter) and highs of 40 °C (summer). While the rainy season extends from June to October, the mean annual rainfall and temperature are 225 mm and 24 °C, correspondingly. Relative humidity ranges from 26.1% to 60.6%, while the photoperiod ranges from 13 h, 41 min (summer solstice, Jun) to 10 h, 19 min (winter solstice, Dec). In Mexico, the CLAG is a major agrifood region; while it has the largest national dairy cow cluster with more than 420,000 Holstein dairy cows, it also owns large agricultural areas devoted to forage production (i.e., alfalfa, sorghum forage, corn forage). A total of five representative intensive dairy farms were selected; they were distributed in five geographical points in the CLAG: Campanario, 25°50′, 103°15′ WL; Gilio, 25°61′ NL, 103°55′ WL; Lucero, 25°90′ NL, 103°39′ WL; Madero, 25°51′ NL, 103°60′ WL, and Noacan, 25°40′ NL, 103°31′ WL. The polygon formed by these farms corresponds to the area where most of the dairy farms are placed.

2.2. Climate Data and THI

The climatic data considered ambient temperature (T; °C) and relative humidity (RH; %) and were obtained in each dairy farm using the DiGiTH™ application (DiGiTH

Technologies, Torreón, Coauila, Mexico). This application allows obtaining climate data in any place worldwide because of its satellite connectivity. With such information, the THI was calculated as (1.8·T + 32) − [(0.55 − (0.0055 × RH) ((1.8 × T) − 26)] [25]. THI values were obtained daily at 10 min frequency intervals, along 2015–2020 in each dairy farm; the Noacan farm has no available data in 2015. Thus, a total of 1,475,319 THI data were obtained to accomplish our research targets.

2.3. Days with Heat Stress Based on THI

The time of the day at which THI ≥ 68 units occurred, considered as those in which dairy cattle experienced HS, were registered. The observed THI values were divided into 4 heat stress subclasses: 68–71 THI (light); 72–76 THI (moderate); 77–79 THI (intense), and THI ≥ 80 (extreme). Based on this information, 29 images of THI levels were generated along with farms and years. From each of the 29 images, a total of 5 images per dairy farm was generated across years, except for Noacan, due to the lack of data in 2015. Although such images are not all presented, the chromatic THI diagram of the representative dairy farm in the CLAG, based on the number of HS days in relation to the observed THI values, were generated. Figures 1 and 2 considering the THI level causing HS across month, days, and minutes of exposure to heat stress (i.e., Time of Exposure to HS; TOE-HS: 1, 4, 8, 12, 16, 20 and 24 h) were generated. Furthermore, the average, maximum, and minimum values for THI, temperature air, and relative humidity within season were also considered.

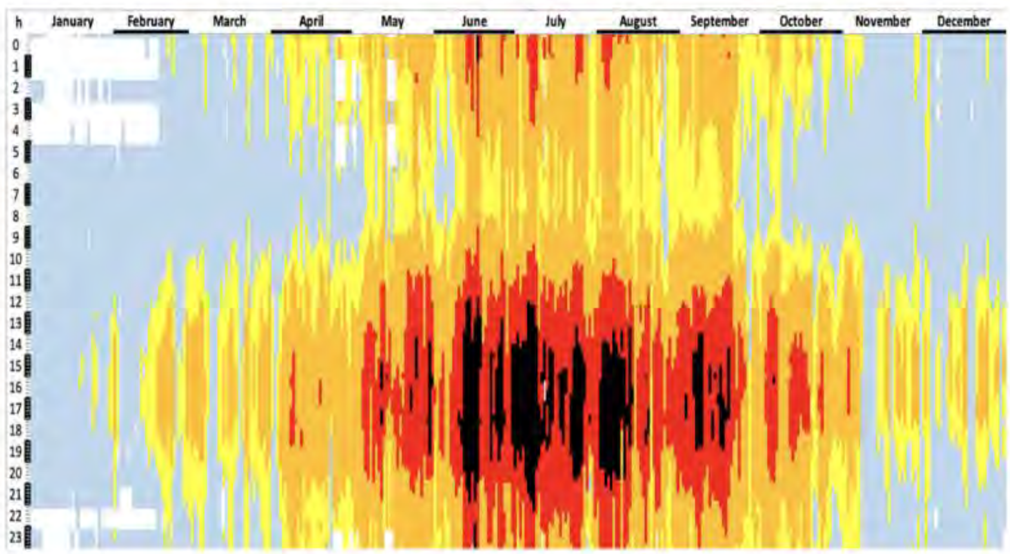

Figure 1. Chromatic THI diagram including the maximum THI values across hours, days and months in Lucero 2016, both dairy farm and year were selected as representative of the Comarca Lagunera, northern arid Mexico. Color code: ☐ = no data; ▪ = THI < 68; ▪ = THI 68–71; ▪ = THI 72–76; ▪ = THI 77–79; ▪ = THI ≥ 80. Note: Upper margin; each black and white line denotes one month. Left margin; each black and white line represent one hour.

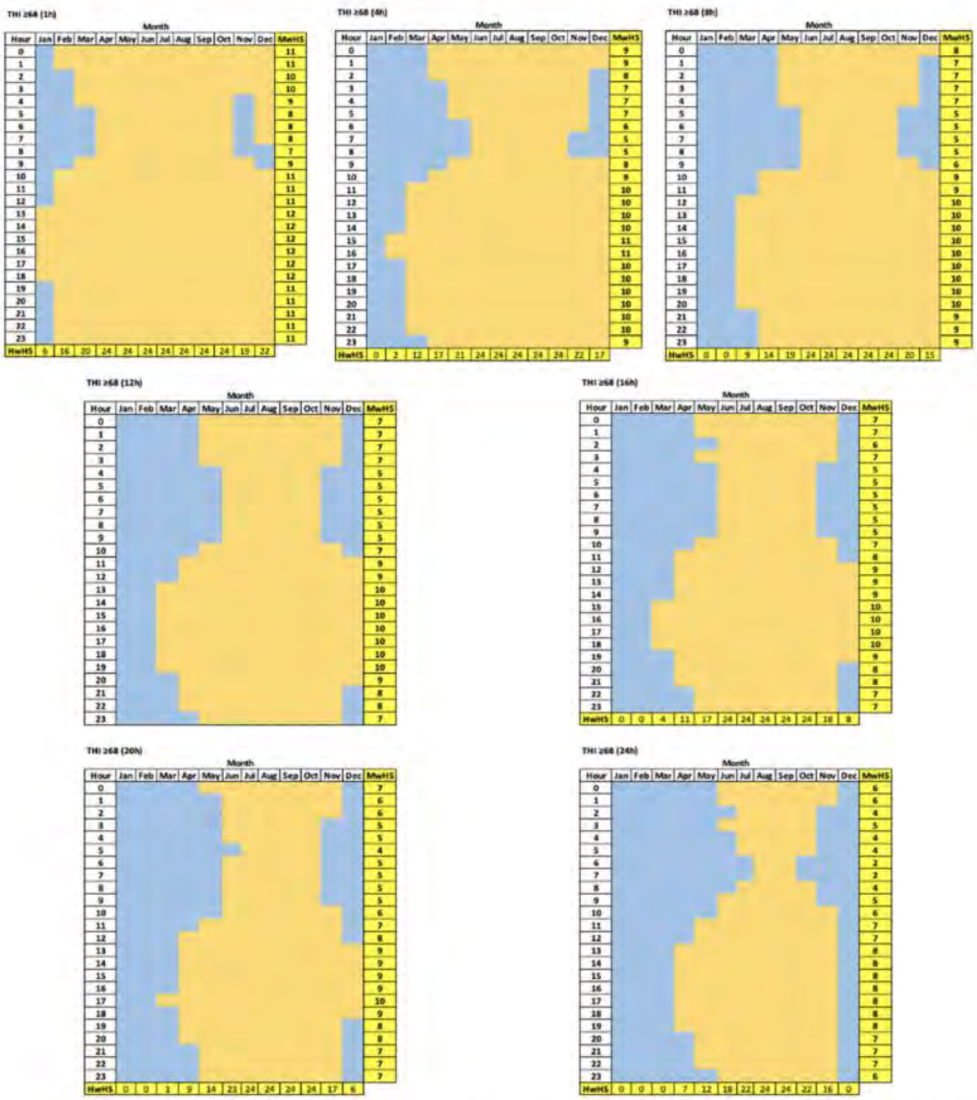

Figure 2. Average hour–month (HwHS) and month–year (MwHS) with HS (THI $\geq$ 68) in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico. Non-heat stress ; Heat stress .

2.4. *Dynamic of the THI $\geq$ 68 Units according to Geographic Site, Year and Season*

The effects of the geographical site (i.e., dairy farm), the year (i.e., 2016–2020), and the season of the year with respect to the number of THI days $\geq$ 68, divided according to the previously mentioned subclasses, were registered. The seasons included winter (January–March), spring (April–June), summer (July–September) and fall (October–December). Additionally, the number of days for each described THI level was subdivided based on the number TOE-HS level reached every day.

2.5. Relationship among the Daily Number of THI-Hours Causing Heat Stress across Years

Based on the above information, the average of HS days was generated considering a THI $\geq$ 68 as well as for each THI subclass. Subsequently, regressions analyses were performed among the HS days per THI subclass and across years to evaluate the THI dynamics across time.

2.6. Effect of THI Level on Milk Production

To identify the HS effect based on the different levels of THI, data from a typical dairy farm of the region, located at 25°89′ NL and 103°22′ WL, were used. The THI values according to the levels established in this study, except for the level $\geq$ 80, which were grouped with those of the THI level of 77–79, were also used to quantify the effect of HS on milk production on a monthly basis. The period of data analyzed was 2016–2018, and the cow's average population included during the evaluated period considered a total of 2467 dairy cows.

2.7. Statistical Analyses

Analyses considering the annual THI values across dairy farms, the estimation of the number of HS days based on the THI value, the regression analyses among the number of days with THI values $\geq$ 68, and those regarding each of the THI subclasses across years, were performed by means of the Excel software (Microsoft 2021, Jones Chicago, IL, USA). The effects of geographic site, year and season regarding the number of days with THI values $\geq$ 68 as well as regarding each THI subclass, and their possible effect upon milk production, considered the PROC GLM. The regression analysis between the number of days with THI $\geq$ 68 and each THI subclass within a year considered the PROC REG [26]. Statistical analyses were performed using the procedures of SAS (SAS Inst. Inc., Version 9.4, 2016, Cary, NC, USA). A statistical difference was considered when a value of $p < 0.05$ occurred.

3. Results

3.1. Days with Heat Stress Based on THI

The days with THI $\geq$ 68 and THI subclasses across farms years are shown in Table 1. Regarding the THI $\geq$ 68, the lowest record (291 d) occurred in Lucero 2018, while the highest values (327 d) occurred in 2017 in Gilio, Madero, and Noacan. At the levels that represent a greater risk to the health and productivity of cows (THI 77–79 and THI $\geq$ 80), the largest values occurred in Lucero 2016 (i.e., 156 d for THI 77–79, and 64 d for THI $\geq$ 80), while the lowest values for these THI levels were registered in 2020: Noacan (i.e., 96 d for the THI 77–79), as well as Noacan and Madero (i.e., 4 days for THI $\geq$ 80). Considering all farms and years, the average period with HS was 312 days. Because the farm and year with the nearest value to this average was Lucero in 2016, this farm year was used as the representative standard to graph the average THI of the CLAG (Figure 1). Even in winter, there were days with THI $\geq$ 68 values, although January had the most of the observed THI values around 68–71. In addition, in early November, a total of 3 h with THI 77–79 occurred. During June, July, and August, THI levels $\geq$ 68 were registered all day long yet with levels of 77–79 and $\geq$80 during most of the day.

Table 1. Number of days with THI ≥ 68 as well as at different THI subclasses with at least one hour of heat stress, collected from five dairy farms along with 2015–2020 in the Comarca Lagunera, northern arid Mexico.

Farm	Year					
	2015	**2016**	**2017**	**2018**	**2019**	**2020**
			Any THI value ≥ 68			
Campanario	303	325	325	297	321	317
Gilio	303	308	327	294	321	314
Lucero	303	309	325	291	317	309
Madero	302	308	327	297	323	315
Noacan	nd	308	327	294	323	323
			THI 68–71			
Campanario	272	302	302	289	298	294
Gilio	272	278	302	288	298	293
Lucero	272	279	302	288	295	291
Madero	272	278	302	289	298	335
Noacan	nd	278	302	288	298	292
			THI 72–76			
Campanario	186	220	220	201	211	219
Gilio	186	201	220	200	211	218
Lucero	186	202	221	201	196	213
Madero	185	200	213	204	211	212
Noacan	nd	200	213	204	208	210
			THI 77–79			
Campanario	146	140	140	123	154	130
Gilio	146	153	136	119	154	128
Lucero	146	156	141	118	129	131
Madero	143	149	134	124	140	105
Noacan	nd	149	134	115	133	96
			THI ≥ 80			
Campanario	51	44	44	15	32	20
Gilio	47	54	37	24	32	28
Lucero	49	64	46	25	6	25
Madero	40	47	31	22	7	4
Noacan	nd	45	30	20	13	4

nd = no data.

When analyzing data with HS ≥ 68 according to month and day at the 1 h TOE-HS (Figure 2), from April to October, this level of THI occurred on a daily basis. In contrast, January and February registered the lowest TOE-HS, with 12 h and 8 h, respectively. Figure 3 shows the dynamics of the different THI levels causing HS; the number of day–hours with HS decreased as the THI level increased. Interestingly, at levels 77–79 and ≥80, the period from April to October was especially risky for dairy cattle based on such THI values.

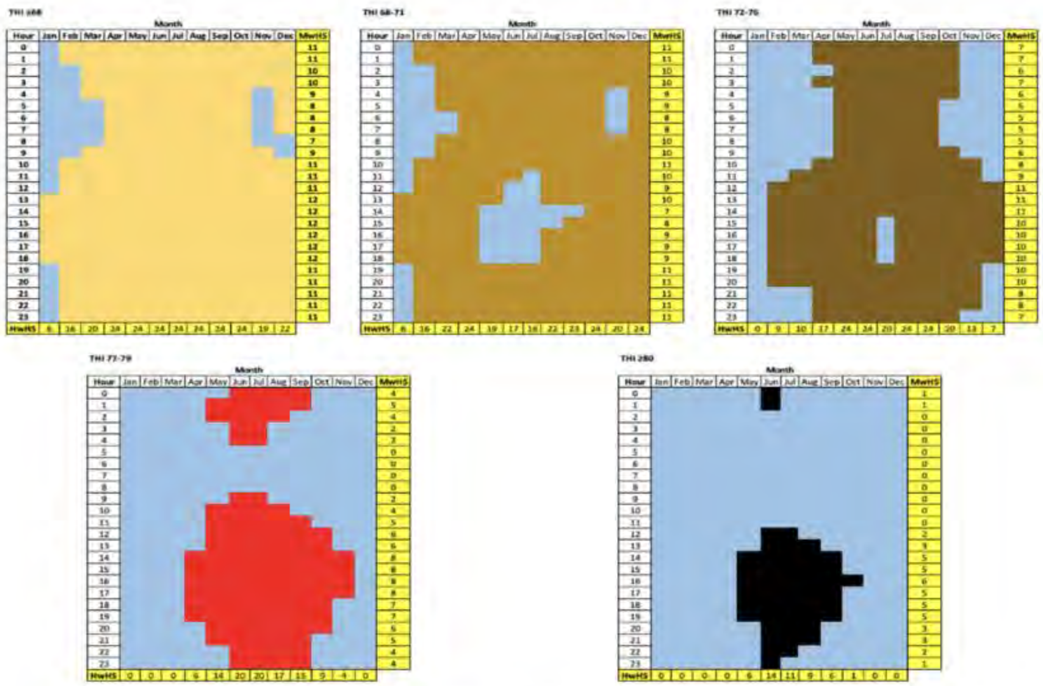

Figure 3. Average hours of the month and average month of the year with HS at different THI levels ≥ 68) in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico. Hours without HS ; h THI ≥ 68 ; h THI 68–71 ; h THI 72–76 ; h THI 77–79 and h THI ≥ 80.

Table 2 shows the average day–month and average month–year collected in five farms across years in which a THI ≥ 68 was reached, as well in which the different levels of THI were recorded.

Table 2. Average day–month and month–year with THI ≥ 68 (time exposure, hours) and THI levels in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico.

Time Exposure (h)	Days	Months
1	21	10.5
6	17	8.4
12	15	7.7
18	14	7.1
24	12	6.0
THI level		
≥ 68	21	10.5
68–71	19	9.7
72–76	16	8.0
77–79	9	4.4
≥ 80	4	2.0

3.2. *Difference in THI ≥ 68 by Geographical Site, Year and Season*

The analysis of the differences by geographical sites, year and season on the levels of THI ≥ 68, and their subdivisions are presented based on the different levels of exposure.

3.2.1. Differences according to Geographical Site (Farm)

The different sites showed a great similarity in relation to the THI (Figure 4), observing differences ($p < 0.05$) only for the 4 h time of exposure and only for the THI level $\geq$ 80, with Campanario, Gilio and Lucero showing the largest number of days.

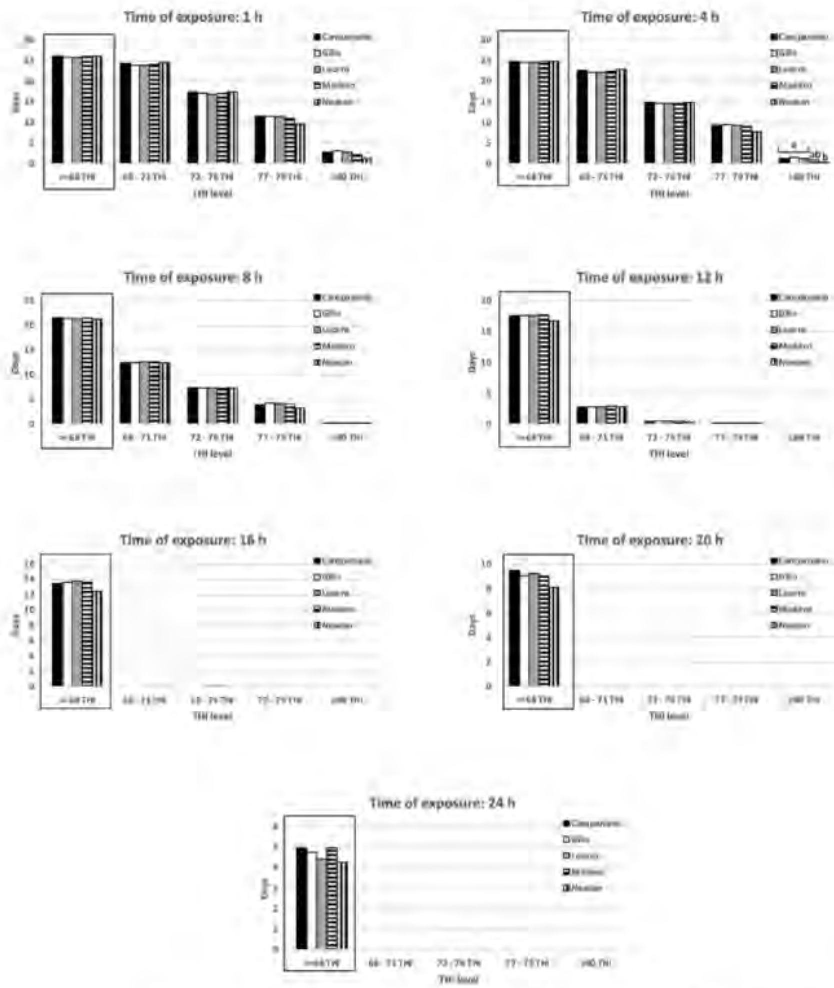

Figure 4. Days with THI $\geq$ 68 and across THI subclasses: 68–71 THI (light stress); 72–76 THI (moderate stress); 77–79 THI (intense stress); and $\geq$80 THI (extreme stress) in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico. Note: Subclasses with different literals, differ ($p < 0.05$); absence of literals shows no differences ($p > 0.05$). Bars with different superscript differs ($p < 0.05$).

3.2.2. Differences across Years

The THI values differed ($p < 0.05$) across years (Figure 5), especially for the TOE-HS1h, 8 h, 20 h and 24 h during 2017 and a THI $\geq$ 68. In addition, the TOE-HS24h in 2016 and 2017 had the largest number of days ($p < 0.05$), with a risk of HS.

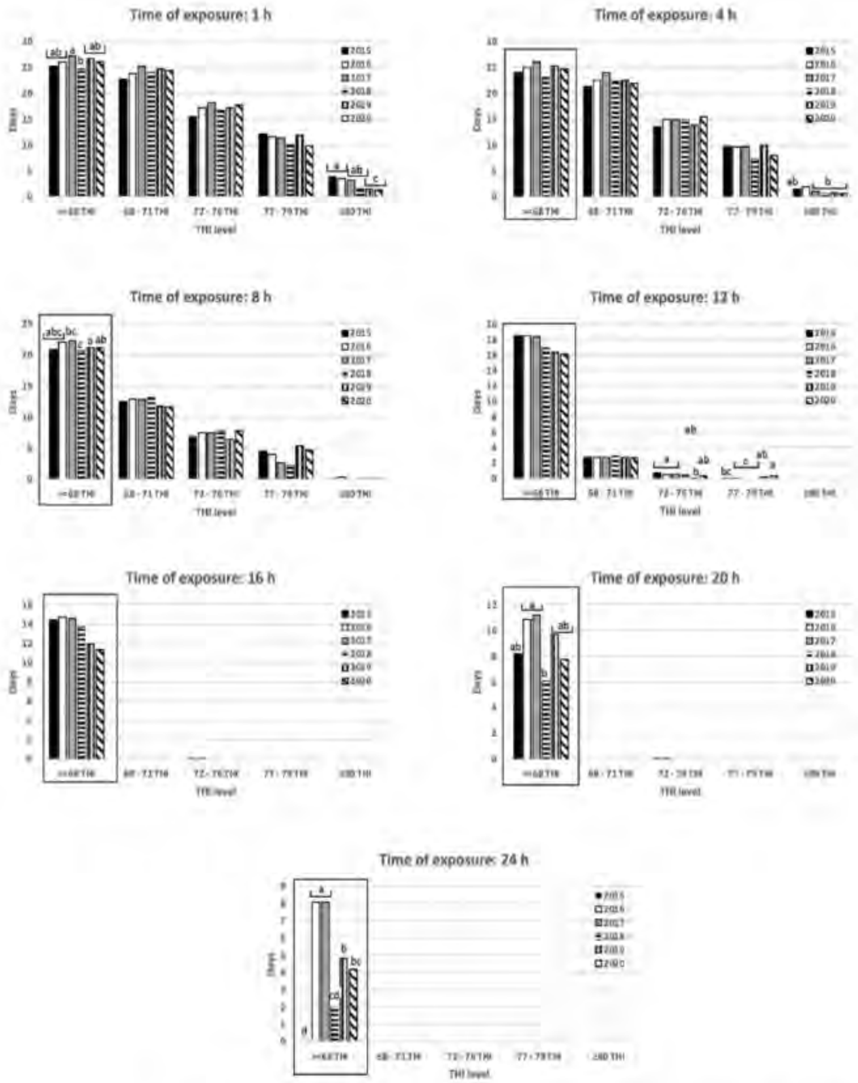

Figure 5. Days with THI $\geq$ 68 by season and across THI subclasses: 68–71 (light stress); 72–76 (moderate stress); 77–79 (intense stress) and $\geq$80 (extreme stress) in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico. Note: Subclasses with different literals, differ ($p < 0.05$); absence of literals indicates no differences ($p > 0.05$). Bars with different superscript differs ($p < 0.05$).

3.2.3. Differences across Seasons

The THI values across seasons differed ($p < 0.05$) at any TOE-HS (Figure 6), especially at THI $\geq$ 68. While spring and summer had the largest HS period (i.e., days), both fall and winter had fewer HS days. Interestingly, all the THI subclasses exerted HS when considering the TOE-HS1h; spring and summer are highlighted because of the recorded day number.

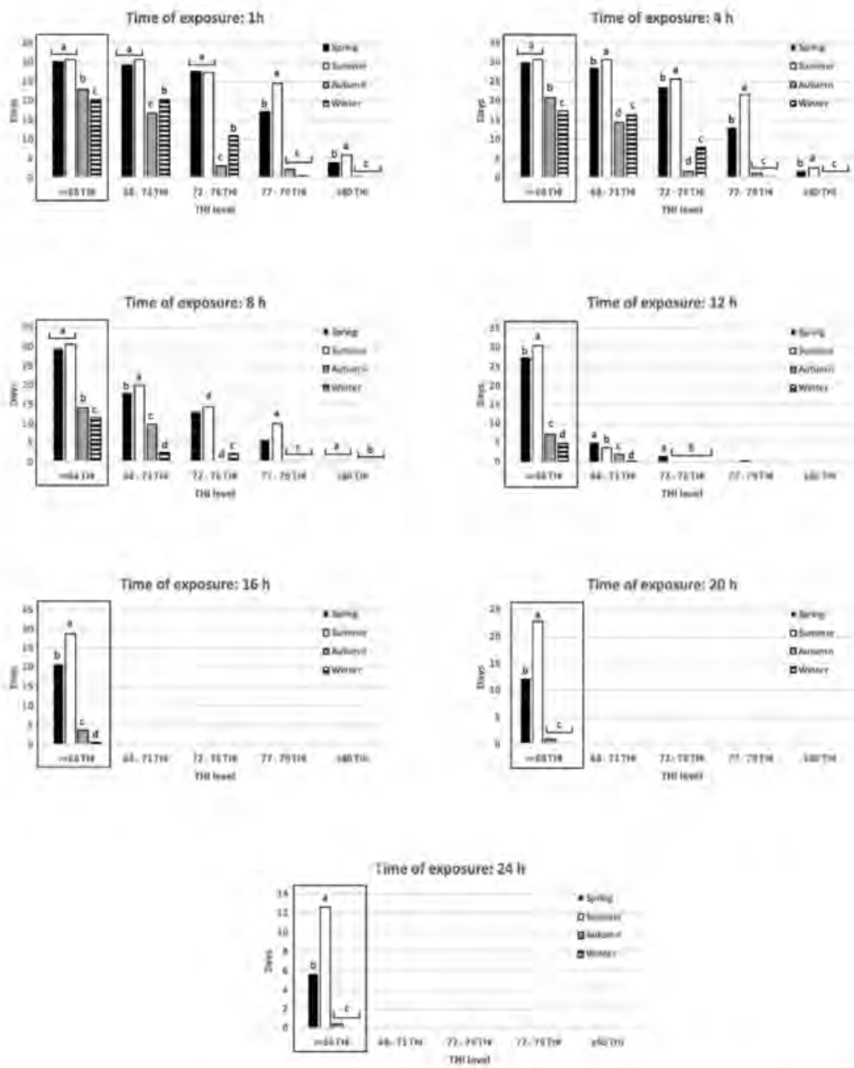

Figure 6. THI $\geq$ 68 across day-season and across THI subclasses: 68–71 (light stress); 72–76 (moderate stress); 77–79 (intense stress); and $\geq$80 (extreme stress) in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico. Note: Subclasses with different literals, differ ($p < 0.05$); absence of literals indicates no differences ($p > 0.05$). Bars with different superscript differs ($p < 0.05$).

3.2.4. Representative Farm–Year Environmental Values in the Comarca Lagunera

Lucero 2016 showed the more representative environmental values as per site and year for the region along the study period. The average, maximum and minimum values of THI (units), air temperature (°C) and relative humidity (%) are shown by season (Table 3).

Table 3. THI average (Avg), maximum (Max) and minimum (Min), temperature air, and relative humidity, across seasons, in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico.

Season	Temperature (°C)			Relative Humidity (%)			THI (Units)		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Winter	19.18	34.10	1.10	34.91	99.00	2.00	61.88	75	35
Autumn	21.39	34.20	6.10	49.77	96.00	0.00	66.00	80	43
Spring	27.97	38.90	11.70	34.96	91.00	0.00	72.53	82	54
Summer	27.97	38.1	18.3	52.59	100.00	15.00	74.77	82	64

The percentages of annual hours with HS, showing their highest value at TOE-HS1h (84.1%), a middle value at TOE-HS12h (64.2%), and the lowest one at TOE-HS 24h (50.3%) are presented in Table 4. In turn, the percentages of annual hours with HS, with their highest value at THI $\geq$ 68 (84.1%) and the lowest one at THI $\geq$ 80 (16.3%), are concentrated in Table 5. Interestingly, the percentages of annual days with dangerous levels of HS 72–79 and $\geq$80 are respectively, 36.5% and 16.3%.

Table 4. Percentage of annual hours with heat stress (THI $\geq$ 68) at different time of exposure (TOE-HS, h) in one representative dairy farm (2015–2020) in the Comarca Lagunera, northern arid Mexico.

TOE-HS (h)	Percentage
1	84.1
4	73.3
8	68.4
12	64.2
16	61.8
20	57.6
24	50.3

Table 5. Percentage of annual hours with heat stress at different THI levels in five dairy farms (2015–2020) in the Comarca Lagunera, northern arid Mexico.

THI Level	Percentage
$\geq$68	84.1
69–71	80.9
72–76	66.7
77–79	36.5
$\geq$80	16.3

3.3. *Effect of THI Level on Milk Production*

Milk production was affected by HS (Figure 7). The highest ($p < 0.05$) milk production was registered at THI < 68, and 68–71, with resultant milk values of 35.96 l and 35.90 l. In contrast, THI values of 72–76 and $\geq$77 decreased ($p < 0.05$) milk production, with respective values of 33.55 l and 31.72 l. Considering that the maximum milk production threshold (100%) occurs at THI < 68 points, we quantified that at 72–76 THI and $\geq$77 THI, the milk production sloped 6.7% and 11.80%, respectively (i.e., 2.4 l and 4.2 l).

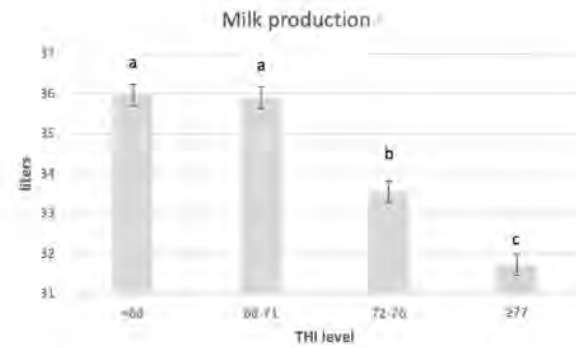

Figure 7. Average milk production (liters) according to the THI level in one representative dairy farm (2015–2020) in the Comarca Lagunera, northern arid Mexico. Note: Values are mean ± s.e; Bars with different superscript differs ($p < 0.05$).

3.4. Relationship of Days with THI Levels with Heat Stress and the Year

3.4.1. Relationship among Years and the THI—TOE-HS1h Subclass

When considering the subclass TOE-HS1h (Figure 8), at THI ≥ 68, we observed a trend ($p > 0.05$) of increases in the HS days (i.e., 10.05 d per year; $R^2 = 0.37$). The same was true when considering the different THI subclasses. However, THI ≥ 80 generated an annual decrease of 5.66 d regarding the number of HS days.

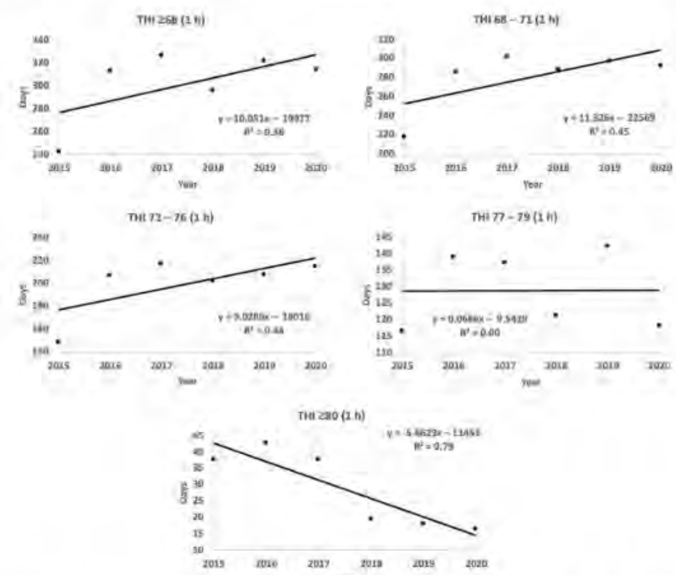

Figure 8. Regression analysis among year-days (THI ≥ 68) in at least 1 h–TOE d^{-1} by THI level.

3.4.2. Relationship among Years and the THI—TOE-HS4h Subclass

A similar relationship as in TOE-HS1h was observed in TOE-HS4h (Figure 9) yet with a decreased number of days per year and a decreased R^2. In fact, this new THI ≥ 68 analysis generated an annual increase of 8.75 d ($R^2 = 0.29$). In the THI subclasses, the number of days with HS were 7.85 d per year ($R^2 = 0.26$; THI 68–71) and 6.7 d ($R^2 = 0.38$; THI 72–76). As the THI enlarged up to ≥ 80, an inverse relationship occurred (-2.29 d year^{-1}; $R^2 = 0.52$).

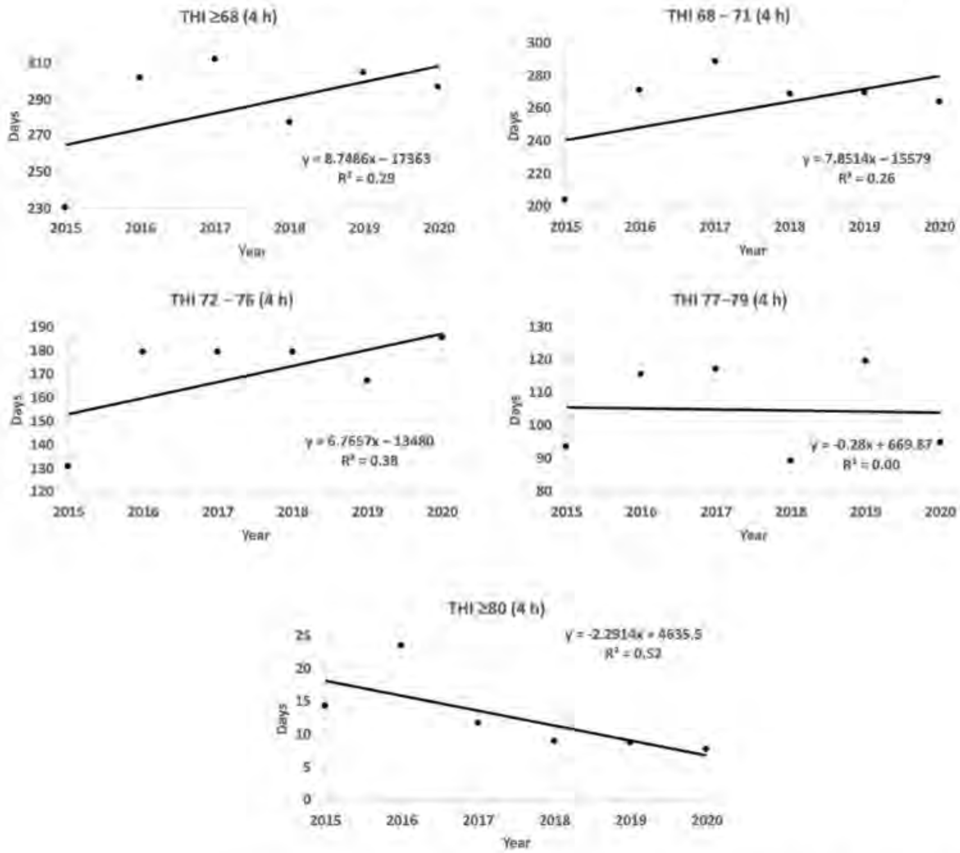

Figure 9. Regression analysis among year–day (THI ≥ 68) in at least 4 h TOE d^{-1} by THI level.

3.4.3. Relationship among Years and the THI—TOE-HS8h Subclass

As for the subclass TOE-HS8h, there was quantified an annual increase of 6.3 HS-d ($R^2 = 0.23$) when considering THI ≥ 68 (Figure 10). Once evaluated along with other subclasses, the observed values were 1.8 d for THI 68–71 with $R^2 = 0.05$; 3.1 d for 72–76 with $R^2 = 0.27$; and 2.9 d for 77–79 with R^2 0.16. Nonetheless, such a trend did not occur with respect to THI ≥ 80, which generated the values -0.13 d ($R^2 = 0.02$).

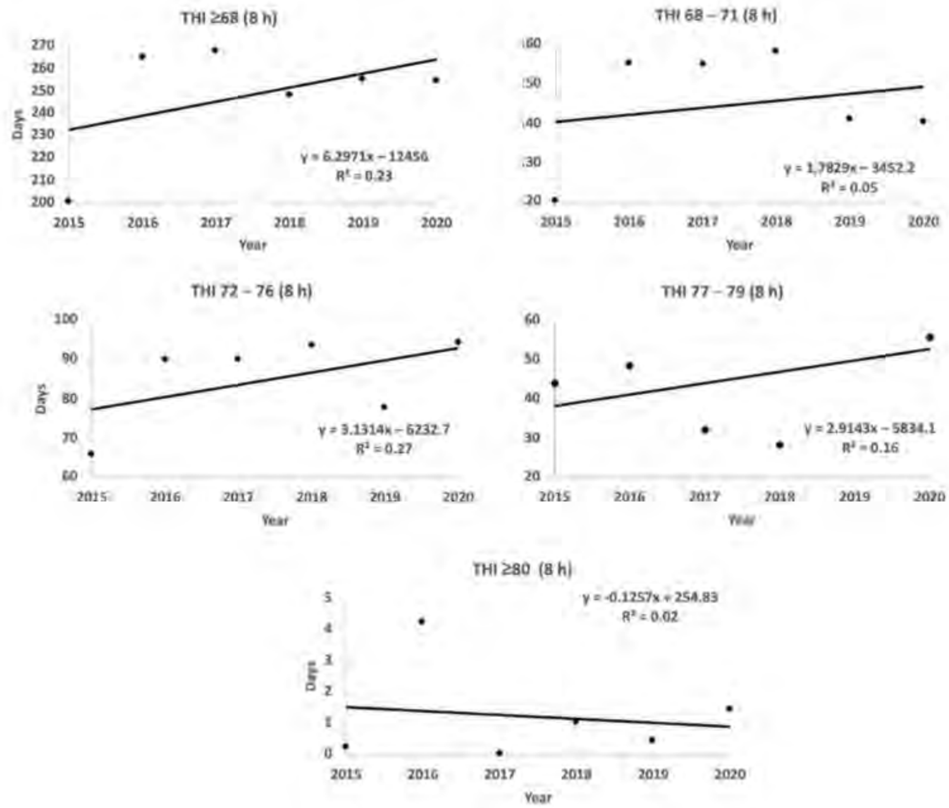

Figure 10. Regression analysis among year–day (THI ≥ 68) in at least 8 h TOE d^{-1} by THI levels.

3.4.4. Relationship among Year–THI value at TOE-HS8h and TOE-HS 16h Subclass

Figure 11 shows the remaining significant ($p < 0.05$) regressions for the TOE. THI levels of 69–71 and 77–79 show an increase in the number of days (0.78 d with $R^2 = 0.24$, and 0.67 d with $R^2 = 0.58$ respectively), while at 72–76 THI, a decrease was observed (−1.02 d with $R^2 = 0.57$). Finally, at 16 h of exposure, at level ≥ 68, there is also a decrease (−3.45 d with $R^2 = 0.12$).

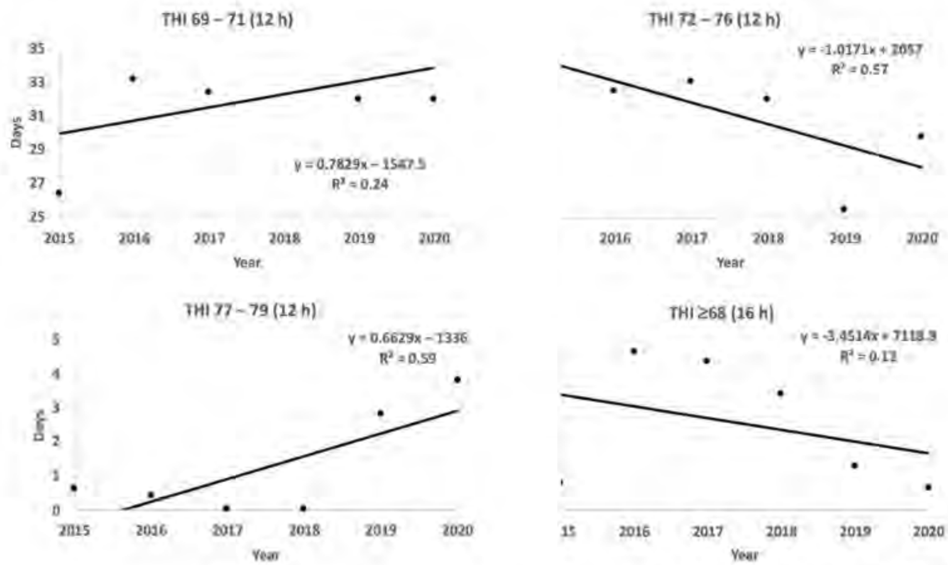

Figure 11. Regression analysis among year–day when THI ≥68 occurred daily at least 12 h and 16 h.

4. Discussion

Our working hypothesis stated an increase, across years, in the annual number of days with THI levels above the normal THI threshold (i.e., ≥68) that would compromise the reproductive and productive soundness of Holstein cows in northern arid Mexico. Based on a total of 1,475,319 THI analyzed, our main research outcomes are aligned with such original statements; so, our working hypothesis is not rejected. In fact, on average, HS arose more than 300 d yr^{-1} with at least 1h-HS as well as during 31 d yr^{-1} with THI > 80 units. The results obtained from this study offer solid evidence that dairy farming under arid–hot–dry conditions must be supported with the development of mitigation strategies designed to counteract HS insults throughout more than 2/3 of the year.

The importance of the early forecasting of heat stress risk was previously highlighted by Herbut et al. [27], who stated the possibility to limit its negative impact on cow welfare. Thus, highly-milk-producing cows must be protected against any heat insult that would compromise milk productivity; the design of mitigation strategies is therefore a fundamental task for maintaining global milk production. Certainly, one of the main external factors that negatively affect the performance of dairy cows is the thermal environment in which they live [28]. High-yielding animals with high dairy-genetic merit are particularly sensitive to HS, since they produce more body heat due to their higher metabolic rate [29,30]. According to Becker and Stone [31], with increases from 35 to 45 kg/d in milk yield, the HS temperature threshold can be decreased by 5 °C, meaning that cows will become heat stressed earlier. Moreover, HS conditions in the US represent a noteworthy financial burden, which is estimated up to 1500 million USD. Such economic losses occur as animals face environmental insults when located outside their thermoneutral comfort zone [29].

4.1. Days with Heat Stress Based on THI

According to our results, dairy cows in the CLAG are exposed to HS conditions more than 75% all year-round. Dairy cows in the southeastern United States face nearly 50% of all annual hours under thermal stress, leading to an annual milk loss up to 2072 kg cow^{-1} [32]. Our results show that THI 72–76, 77–79, and ≥80 can be a serious problem for the dairy cow industry. The observed THI trends in our study, >68 and subclasses, made it evident that cows in the CLAG are subjected to continuous heat stress, depicting an interesting "heat wave profile" [32]. The last is dramatic in that dairy cows may require weeks to fully adapt to HS conditions [31], generating concomitant economic losses. Such HS insult has promoted the death of 25,000 dairy cows and a reduction in milk production close to 1.1 million liters per day [33].

4.2. Effect of Geographic Site, Month, Season, and Year upon Variability of THI Levels ≥ 68

4.2.1. Differences by Geographic Point (Farm)

The CLAG can be defined as a homogeneous area in terms of the THI ranges. Interestingly, even small areas across the CLAG, such as those near the Nazas River, occasionally with running water, can be considered as the area with the lowest regional temperatures, where the Madero dairy farm is located. Yet, the THI among geographical sites did not show important differences. Theusme et al. [34] reported climatic differences in another region of northern Mexico (i.e., Baja California). As previously proposed [35], the measurement of thermal parameters can be performed at four levels: regional, farm (outside), building (inside), and at animal levels. In the CLAG, those dairy farms without meteorological measurement devices can make use of different stations of the federal meteorological system, having the required information to define specific strategies to mitigate HS. Nevertheless, it is key to consider that different locations with automated weather stations may differ from each other; the closeness of the farm to the weather stations, the better [16].

4.2.2. Differences across Years, Seasons and Months

The results obtained from the regression analysis between HS days and year show a trend to an increase in the days with HS in the region. The last denotes a quite complex scenario, which potentially may compromise both the health and productivity of dairy cows. Certainly, under subtropical climatic conditions, little or non-alleviation from HS occurs at night. Unquestionably, since no nightly reductions in ambient temperature and humidity occur as compared to the daytime, cows are unable to lose internal heat generated throughout the day, causing these animals to be in a constant HS status [36]. At any TOE-HS subclass, spring and summer had an increased THI ≥ 68 as compared to fall and winter, while summer averaged more days per month than spring. According to Hempel et al. [24], the most HS events and largest financial losses occur in summer, proposing that such an annual increase in HS day number is related to the effect of climate change. Hence, in the CLAG, not only an increase in HS days, which occurs in the summer practically every day, but also the greatest number of days with TOE-HS with a longer exposure time and higher THI levels would also be observed. While such a scenario can negatively impact future milk yield in summer months, a carry-over effect may extend its consequences throughout the fall months, despite cows perhaps no longer be experiencing HS in Fall. From April to October, the largest number of HS days occurred. In addition, while the largest period of TOE-HS1h occurred from May to September, the TOE-HS4h arose from April to October at THI 68–71. Interestingly, during June, July, and August, the THI ≥ 68 ascended practically in a daily fashion. In agreement with our results, dairy cattle were very vulnerable to HS during July and August in the valley of Baja California, Mexico [34].

4.3. Relationship among THI Levels, Days with Heat Stress, across Years

Theusume et al. [34] predicted the impact of global warming using several bioclimatic indicators as a function of the year of study, and they concluded that most of the indicators, including the THI, showed a positive relationship across years in northern arid Mexico; such a trend was also observed in our study. In line with the previous findings, Herbut et al. [27] proposed an increasing trend toward the systematic warming of the Earth's climate. Unexpectedly, in our study, we found at THI ≥ 80, a decrease of 5.66 d yr^{-1}. We hypothesize that this may be due to slight increases in environmental temperature in the CLAG across years but without the proportional increases expected in the relative humidity of the air. Moreover, environmental temperatures have increased by 1.0 °C since the 1800s, and they are expected to continue to increase 1.5 °C between 2030 and 2052 [37]. In relationship to THI values, Cincović et al. [14] report that the mean maximal THI value (2005–2016) showed a trend of increasing in every month except January, October and November. Such increases in the environmental temperature and consequently in THI are the most noticeable environmental stressors, which are expressed by both an increased number of consecutive hot days and an augmented frequency of extremely hot days [38].

4.4. Effect of THI Level on Milk Production

While HS causes milk production losses in dairy cattle [29,30,39], HS during the dry period also exerts a substantial negative effect upon dairy farm profitability, which is similar to that of HS during lactation [40]. Such a trend indicates that HS is a disrupting factor upon the productivity of dairy cows even in non-lactating animals. St-Pierre et al. [29] established that dairy cows in the southeastern United States spend nearly 50% of all annual hours under thermal stress, leading to a loss of milk production up to 2072 kg cow^{-1} yr^{-1}. Our data indicate that the dairy cattle of the CLAG spend an average of 69% of their annual time (251 h) under HS conditions when facing a THI of 68–71; with THI values of 72–76, an average of 53% (192 h) occurred. Such figures generate respective average losses of 2.4 L and 4.2 L d^{-1} cow^{-1} compared with not HS conditions. This decrease in milk production is associated with a failure to rescue milk yield because shifts in energy metabolism, protein catabolism, alterations in lipid metabolism due to endocrine alterations, and immune response due to oxidative stress and inflammation are the major factors in this physiological complex [41]. Dairy farms equipped with technical systems for meteorological and health data are important for inferring associations between THI and responses in cow traits, especially in early lactation, detrimental effects of HS on test-day production and female fertility [42]; both big data and sensor-satellite intelligent approaches will help to better counteract risky environmental impacts.

5. Conclusions

The CLAG is a region with high THI levels that, on average, reach more than 300 d yr^{-1} with at least 1 h of HS, and 31 d yr^{-1} having THI values higher than 80 units. Our results offer solid evidence that dairy farming under arid–hot–dry conditions must be supported with mitigation strategies to counteract HS insults throughout more than 2/3 of the year. The research approach used in our study, not only from yearly-to-season, but monthly-to-seasonal, and even minute-to-minute quantifications, makes available sound information to support the design of wide-ranging mitigation strategies. Our research outcomes are crucial to define specific strategies not only at specific windows of action but using different time-scale approaches to lessen the negative influences of HS. Future studies must address the possible interactions among HS, THI levels, milk yield, reproductive and productive efficiency, as well as immunology soundness, which are aligned with possible thermal mitigation mechanisms to reduce HS, especially in high yielding dairy cows; the last being an unavoidable assignment.

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ESTUDIO 2

Articulo 2: Effect of ITH on Milk Production, Percentage of Milking Cows, and Time Lying in Holstein Cows in Northern-Arid Mexico.

animals

MDPI

Article

Effect of THI on Milk Production, Percentage of Milking Cows, and Time Lying in Holstein Cows in Northern-Arid Mexico

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Simple Summary: The main dairy area of the country is in the arid central north of Mexico (25° NL). It is characterized by a dry climate with high temperatures, where dairy cattle are subject to prolonged periods of heat stress (HS). Due to this, through the THI and the year's seasons, the effect of HS upon milk production, feed-to-milk efficiency, and cow comfort was evaluated in 2467 Holstein–Friesian cows between 2016 and 2019 in an intensive dairy management system. Total milk production decreased as THI increased, while milk composition also suffered changes due to HS. The percentage of cows in production and cows' lying time exhibited a visible drop from a THI of 68–71. Differences were also observed across seasons, with the highest milk production values in Winter and Spring and the lowest in Summer. In the same way, lying time differed among seasons, with a longer resting time in Winter and less time in Summer. Finally, the potential economic burden that HS caused at the producer and industry-market levels and its impact on nutrient and alimentary security at the societal level were also quantified.

Abstract: The possible effect of heat stress (HS), measured with the temperature–humidity index (THI) across seasons of the year (SY) upon milk production (MP), feed-to-milk efficiency (FME), and cow comfort (CC) was assessed in Holstein–Friesian cows in northern-arid Mexico. Data from 2467 cows (2146 milking and 321 dry) were recorded across SY [spring (SP), summer (SM), autumn (AT), and winter (WN)] between 2016 and 2019 in an intensive dairy farm located in the Comarca Lagunera (25° NL) with large fluctuations regarding ambient temperature and solar radiation. The THI was stratified into four classes: non-HS, <68; light HS, 68–71; moderate HS, 72–76; and intense HS, ≥77. The considered response variables were Milk production: both on a farm basis (totMP) and on a cow basis (cowMP); Nutritional efficiency: dry matter intake (DMI, kg); Feed conversion efficiency (FCE, kg) and energy-corrected milk (ECM, kg); Percentage of milking cows: (MC%); and Cow comfort: lying time (LT, h). Analyses of variance for unbalanced data were performed through "R". Both totMP and cowMP differed ($p < 0.05$) as HS increased; the largest values (i.e., 77,886 L and 35.9 L) occurred at lower THIs (i.e., <68 and 68–71) while the milk production fell (i.e., 66,584 L and 31.7 L) with the highest THIs (i.e., ≥77). Not only feed-to-milk efficiency (i.e., DMI, FCE, and ECM) but also the MC% exhibited a similar trend; a visible drop ($p < 0.05$) occurred from a THI of 68–71 onwards. Furthermore, the LT declined as the THI augmented, from 10.6 h at <68 to 8.5 h at ≥77. Moreover, differences ($p < 0.05$) also arose across seasons; TotMP, cowMP, DMI, FCE, and ECM revealed their largest ($p < 0.05$) values in WN and SP, halfway ones in AT, with the lowermost figures in SM. In the same way, cow comfort differed ($p < 0.05$) among seasons, with diverse lying times (h); WT, 10.5; AT, 10.20; SP, 9.3 h; and 8.8 in SM. Finally, the potential economic burden that HS caused at the producer (USD 233.2 million) and industry-market levels (USD 311.1 M), as well as its impact upon nutrient and alimentary security at the society level (i.e., 311 M milk liters and 195,415.82 Gcal), were also quantified.

Keywords: heat stress; dairy cows; arid North Mexico; milk production; milk composition; economic losses

1. Introduction

One of the main external factors that can negatively affect the performance of dairy cows is the thermal environment in which they live [1]. In fact, high performance animals with high genetic merit are particularly sensitive to heat stress (HS) because of their augmented thermogenesis due to their higher metabolic activity [2,3]. In dairy cows increasing their milk production from 35 to 45 kg/d, the HS temperature threshold may be decreased by 5 °C, meaning that cows will become heat stressed earlier [4]. HS conditions represent a significant financial burden, estimated in the US to be between USD 897 and 1500 million annually; such economic losses occur because most of the animals are raised in places where environmental temperatures are outside the thermoneutral comfort zone [3].

Heat stress affects the ability of animals to thermoregulate and augments thermogenesis while decreasing feed intake, fertility, and milk production [5–11], causing significant and adverse implications for livestock productivity [12]. This can greatly decrease in such a way that it is considered that HS represents a significant financial burden, estimated in the US as between USD 897 and 1500 million annually [3]. However, not only is milk yield loss observed, but there are associated changes in milk components, including protein [13], fat, solid non-fat, casein and lactose contents, milk urea, and somatic cell score [14]. Besides productive and reproductive impairments, animal well-being has also been described, such as lying time, a very important behavioral characteristic that is a key marker of dairy cows' physiological and health status [15,16]. Therefore, the cow's lying time can be used as an indicator of the cow´s well-being [17]. Another interesting indicator, although not commonly used when evaluating the effect of HS on farm productivity, is the percentage of cows milking with respect to dry cows across a defined period, usually on an annual basis [18].

The Temperature Humidity Index (THI) is a useful tool to measure the productive response as a function of climate [19–22]. It is based on air temperature and relative humidity, serving as a measure of the sum of external forces on the animal that acts to displace body temperature from its homeostatic point [22]. Although it was common to place the THI threshold at 72 as the point where milk synthesis begins to decline, and other indicators such a milk composition and feed intake are altered [19,23], other data indicate that high-yielding dairy cows reduce their milk production with a THI of around 68 [24,25], or for other conditions [26].

We recently carried out a study [27] on HS conditions (THI) and seasonal performance in the region that produces the largest amount of cow's milk in Mexico, the Comarca Lagunera, using climatic Big Data obtained from five farms inside the regional area and for a period of 5 years, observing that HS conditions occur in the region during most of the year (305 d). The results generated the need to investigate how HS affects the dairy industry and consumers. Therefore, this study aimed to quantify the possible effect of different THI levels on milk production and milk composition, feed-to-milk efficiency, and animal comfort of dairy cows in northern-arid Mexico. Moreover, we aimed to quantify the potential economic burden that HS would cause at farm, regional, and societal levels.

2. Materials and Methods

The Comarca Lagunera (CL), a very important agro-industrial region located in central northern-arid Mexico, generates 21% of the Mexican national milk volume. Nonetheless, it is characterized by low precipitation (i.e., 200 mm yearly) and significant fluctuations in monthly average temperatures (i.e., 12.7 °C in January, 28.5 °C in June), with extremes from −5 °C to 41.5 °C, with extensive solar radiation.

2.1. Study Design

This was an observational, retrospective, longitudinal, and comparative study. The observational unit were farm daily liters of milk. The data, both climatic and productive, were obtained from an intensive dairy farm (25° 89′ NL and 103° 22′ WL).

2.2. Dairy Farm, Population Cows, and Climatic Data

The period of data analyzed was 2016–2019, and the average cow population during the period of study was 2467 Holstein cows (2146 milking and 321 dry ones), housed in pens for 120 animals and with 11 m^2 of shaded area per cow, and fed twice a day with a total mixed ration (TMR). The observational unit was the daily milk production of the farm. Years were divided into seasons: spring (21 March–20 June), summer (21 June–20 September), autumn (21 September–20 December), and winter (21 December–20 March).

Ambient temperature (°C) and relative humidity (%) data were obtained from the meteorological station situated in an intensive dairy farm (25° 89′ NL and 103° 22′ WL) in the CL. The THI was calculated as $(1.8 \cdot T + 32) - [(0.55 - (0.0055 \times RH)) ((1.8 \times T) - 26)]$ [27] and classified into four levels: without HS (WoHS = <68 THI); light HS (LHS = 68–71 THI); moderate HS (MHS = 72–76 THI), and intense HS (IHS = ≥77). Categorized THI and seasons were the independent variables.

The effect of the levels THI and season on the performance and comfort variables were compared on the next dependable variables:

Milk performance: The volume of daily milk produced at the farm (totMP) was calculated using Afi Farm 5.5™, Afimilk, Afikim, Israel, and average daily milk performance was calculated at cow level (cowMP).

Milk composition: percentages of fat and protein in milk and amount of urea in milk were obtained by infrared spectroscopy (LactoScope™ 300 FT-IR Analyzer Perkin Elmer, Waltham, MA, USA).

Feed-to-milk efficiency: The diet's average dry matter intake (DMI) was determined through daily weighing of the feed offered and orts in the following days. The amount of feed offered was adjusted weekly so that there were approximately ten per cent orts [28]; Feed conversion efficiency (FCE) was calculated as kg of milk/kg of DMI [29]; and Energy-Corrected Milk (ECM) was calculated as $(12.82 \times \text{kg fat}) + (7.13 \times \text{kg protein}) + (0.323 \times \text{kg milk})$ [30].

Economic values: Based on the annual average of the economic input received by the producer (i.e., EIP), we also projected the financial burden (i.e., EB) generated by the HS not only at the farm-producer level (i.e., EBT) but also at the regional level (i.e., CL; EBCL) expressed as USD. We also projected the loss that said thermal insult generates with respect to the reduction in the milk supply to society, expressed not only as milk volume but also as kg of fat and protein. Moreover, to quantify the concomitant impact of HS upon milk performance, the chemical values proposed by Nayak et al. [31] were considered to escalate such HS insult from an animal viewpoint up to farm and regional levels. The following milk chemical information involved in the performed analyses considered water (87.8%), fat (3.6%), protein (3.2%), lactose (4.7%), and energy (64.0 kcal) as suggested by Nayak et al. [31].

Percentage of milking cows: (MC% = cow milking × 100/total of cows).

Cow comfort: Defined as the number of daily hours at rest; lying time (LT, h; measured through a pedometer Afi Act II™, Enosburg Falls, VT, USA).

2.3. Statistical Analyses

The effect of HS level and season of the year on milk performance, milk composition, digestive efficiency, and comfort variables were evaluated by R (R Core Teams, Vienna, Austria, 2022) using the base program for the Analysis of Variance (ANOVA), considering a $p < 0.05$ as a statistical difference for all the results obtained, and the library emmeans [31] to obtain estimated marginal means (EMMs) as suggested, by Searle, Speed, and Milliken [32] for pairwise comparisons. The results are presented as lsmeans ± standard error, and the statistical difference was considered at $p < 0.05$.

3. Results

3.1. Descriptive Statistics

Table 1 shows the descriptive statistics for the analyzed variables in the study.

Table 1. Descriptive statistics.

Variable	Mean	SD	Min	Max
Milk performance at farm level (L)	74,128.55	8652.31	54,752.00	90,787.00
Milk performance at cow level (L)	34.24	2.63	27.19	39.58
Dry Matter Intake (kg)	22.86	1.59	17.61	27.93
Feed-to-Milk Efficiency (units)	1.55	0.08	0.00	1.82
Energy-Corrected Milk (kg)	34.14	2.66	26.71	51.52
Milking Cows (%)	86.85	4.92	75.90	95.18
Lying Time (h)	9.72	0.99	6.30	11.87
Milk fat (%)	3.42	0.12	3.08	3.77
Milk protein (%)	3.14	0.07	2.97	3.33
Milk urea (mg)	10.78	1.79	6.41	17.37
THI (units)	72.76	5.42	35.46	83.23

3.2. Effect of HS Level

3.2.1. Milk Performance, at either the Farm Level or the Cow Level

TotMP was affected by THI. No differences were found ($p > 0.05$) in TotMP between <68 and 68–71 levels, with a daily average of 77,500 L. However, a decline in milk production occurred as the THI increased ($p < 0.05$) in the different THI classes, 72–76 and ≥77 (78,886 ± 985.5 L, 75,095 ± 586 L, and 66,584 ± 870 L), respectively (Table 1). A similar trend occurred with CowMP; the highest ($p < 0.05$) milk production occurred at <68 and 68–71 THI levels with an average of 35.9 L, while the CowMP decreased ($p < 0.05$) at THIs 72–76, and ≥77 levels, with milk production of 34.37 ± 0.17 L, and 31.79 ± 0.26 L, respectively (Table 2).

3.2.2. Feed-to-Milk Efficiency

According to the DMI, no differences ($p < 0.05$) were observed in cows at THIs < 68 and 68–71 (i.e., avg = 23.7 kg). The lowest DMI ($p < 0.02$) occurred at 68–71 THI (22.76 ± 0.11 kg) and at ≥77 THI (21.59 ± 0.16 kg) (Table 1). Concerning the FCE (Table 1), no differences ($p > 0.05$) arose among the THIs < 68, 68–71, and 72–76 (i.e., DMI-avg. 1.57 units], while the ≥77 groups had the lowest ($p < 0.05$) FCE, with 1.51 ± 0.01 units). The ECM was higher ($p < 0.05$) at both <68 and 68–71 THIs (i.e., avg. 35.66 kg), registering a noticeable drop as the THI increased from 68–71 onwards (Table 1).

3.2.3. Percentage of Milking Cows (%MC)

In the case of milking cows (Table 1), a negative ($p < 0.05$) relationship between THI and milking cows occurred. As the THI increased, the proportion of milking cows declined (THI 68–71 and 89.1 ± 0.61%; THI 72–71, 87.11 ± 0.36 %, and THI ≥ 77, 84.0 ± 0.54%).

Table 2. Least-square means ± standard error for daily volume of milk produced at farm (totMP) at cow level (cowMP); dry matter intake (DMI); Feed-to-Milk Efficiency (average Dry Matter Intake [DMI]; Feed Conversion Efficiency [FCE] and Energy-Corrected Milk [ECM]); Percentage of Milking Cows (MC%); Cow Comfortness (Lying Time; LT); milk fat; milk protein; and milk urea according to the THI level in a dairy farm from northern-arid Mexico (from 2016 to 2019).

Variables	Stress Level				
	<68 THI	**68–71 THI**	**72–76 THI**	**≥77 THI**	***p*-Value**
		Milk performance			
totMP (L)	76,114 ± 1038 [ab]	78,886 ± 502 [a]	75,095 ± 299 [b]	66,584 ± 443 [c]	<0.05
cowMP (L)	35.96 ± 0.30 [a]	35.88 ± 0.15 [a]	34.37 ± 0.09 [b]	31.79 ± 0.13 [c]	<0.05
		Feed-to-milk efficiency			
DMI (kg)	23.58 ± 0.19 [a]	23.77 ± 0.90 [a]	22.76 ± 0.05 [b]	21.59 ± 0.80 [c]	<0.05
FCE (units)	1.575 ± 0.01 [a]	1.562 ±.01 [a]	1.558 ± 0.003 [a]	1.514 ± 0.005 [b]	<0.05
ECM (kg)	35.54 ± 0.30 [a]	35.77± 0.15 [a]	34.23 ± 0.09 [b]	31.63 ± 0.13 [c]	<0.05
		Percentage of milking cows			
MC (%)	86.75 ± 0.64 [b]	89.08 ± 0.31 [a]	87.11 ± 0.18 [b]	84.00 ± 0.27 [c]	<0.05
		Cow comfort			
LT (h)	10.71 ± 0.15 [a]	10.53 ± 0.07 [a]	9.46 ± 0.04 [b]	8.52 ± 0.06 [c]	<0.05
		Milk composition			
Milk fat (%)	3.33 ± 0.02 [a]	3.42 ±.01 [b]	3.42 ± 0.004 [b]	3.44 ± 0.01 [b]	<0.05
Milk protein (%)	3.19 ± 0.01 [a]	3.15 ± 0.003 [b]	3.13 ± 0.002 [c]	3.09 ± 0.003 [d]	<0.05
Milk urea (mg)	10.9 ± 0.38 [ab]	10.4 ± 0.15 [b]	10.8 ± 0.09 [ab]	11.0 ± 0.13 [a]	<0.05

Different letters between columns show difference ($p < 0.05$). Data are presented as mean ± standard error of the mean.

3.2.4. Cow Comfort (Daily Average Lying Time per Cow)

Regarding the LT (Table 1), the greater the THI, the less time a cow lies down. The lying time observed values along with the THIs were: <68, and 68–71 THI, the average lying time was 10.62 h; with THI 68–71, we observed 10.53 h, while with THI 72–76 it was 9.46 h and, for THI ≥ 77, the lying time was reduced to 8.52 ± 0.13 h.

3.2.5. Milk Composition (Milk Fat, Protein Fat, Fat/Protein Milk Ratio, Milk Urea)

Milk fat was affected by HS level, showing the lowest percentage of fat content (3.33 ± 0.02 at <68 THI), while the other HS levels had an average of 3.42% of fat. Concerning protein milk, while the THI levels were increasing, the percentage of milk protein descended (from 3.19 ± 0.01 at <68 THI to 3.09 ± 0.003 at ≥77 THI). The fat/protein milk ratio was higher at ≥77 THI, and the lowest value was found at 68–71 and 72–76 THI (1.08 ± 0.003). The highest milk urea value (11.0 ± 0.13) was also found at ≥77 THI (11.0 ± 0.13), with the lowest one at 68–71 THI.

3.3. *Effect of THI and Season*

3.3.1. Milk Production at the Farm Level and per Cow

The TotMP and cowMP showed differences ($p < 0.05$) across seasons; differences were quantified in both variables where the highest values occurred in winter and spring, while an intermediate production occurred in autumn, with the lowest production observed in summer; the last was true for both TotMP and cowMP (Table 3).

3.3.2. Dry Matter Intake, Feed Conversion Efficiency, and Energy-Corrected Milk

The DMI denoted differences ($p < 0.05$) across seasons (Table 2); the highest value occurred in winter (24.23 kg), intermediated values were observed both in spring (23.29 kg) and autumn (22.79 kg), while the lowest value was detected in summer (21.18 kg), all of them with a SE of 0.06. As for the FCE, differences across seasons were also detected, with the highest values ($p < 0.05$) observed in spring and winter (1.56 units, SE 0.01), while the lowest ones ($p < 0.05$) occurred in summer and autumn (1.53 units, SE 0.01; Table 2). Moreover, the ECM (Table 2) denoted different lsmeans across seasons, showing corresponding values for winter, spring, autumn, and summer of 36.4, 34.9, 34.0, and 31.2 ± 0.20 kg respectively.

Table 3. Least-square means ± standard error for volume of milk produced at farm (totMP), at cow level (cowMP), dry matter intake (DMI), Feed-to-Milk Efficiency (average Dry Matter Intake [DMI]; Feed Conversion Efficiency [FCE] and Energy-Corrected Milk [ECM]), Percentage of Milking Cows (MC%), Cow Comfortness, (Lying Time; LT), milk fat, milk protein, and milk urea, according to the season in a dairy farm from northern-arid Mexico (from 2016 to 2019).

Variables	Season				
	Spring	Summer	Autumn	Winter	*p*-Value
		Milk performance			
totMP (L)	78,438 ± 307 [b]	64,462 ± 305 [d]	72,732 ± 305 [c]	81,091 ± 309 [a]	<0.05
cowMP (L)	35.20 ± 0.09 [b]	31.37 ± 0.09 [d]	33.80 ± 0.09 [c]	36.65 ± 0.09 [a]	<0.05
		Food-to-milk efficiency			
DMI (kg)	23.29 ± 0.06 [b]	21.18 ± 0.06 [d]	22.79 ± 0.06 [c]	24.23 ± 0.06 [a]	<0.05
FCE (units)	1.56 ± 0.004 [a]	1.53 ± 0.004 [b]	1.53 ± 0.004 [b]	1.56 ± 0.004 [a]	<0.05
ECM (kg)	34.9 ± 0.10 [b]	31.2 ± 0.10 [d]	34.0 ± 0.10 [c]	36.4 ± 0.10 [a]	<0.05
		Percentage of milking cows			
MC (%)	90.96 ± 0.12 [a]	80.82 ± 0.12 [c]	84.63 ± 0.12 [b]	91.12 ± 0.12 [a]	<0.05
		Cow comfort			
LT (h)	9.34 ± 0.05 [c]	8.76 ± 0.06 [d]	10.20 ± 0.05 [b]	10.53 ± 0.06 [a]	<0.05
		Milk composition			
Milk fat (%)	3.41 ± 0.006 [b]	3.42 ± 0.006 [b]	3.49 ± 0.006 [a]	3.38 ± 0.006 [c]	<0.05
Milk protein (%)	3.105 ± 0.003 [b]	3.116 ± 0.003 [b]	3.167 ± 0.003 [a]	3.158 ± 0.003 [a]	<0.05
Milk urea (mg)	10.9 ± 0.12 [b]	11.4 ± 0.11 [a]	10.6 ± 0.11 [b]	10.1 ± 0.13 [bc]	<0.05

Different letters between columns show difference ($p < 0.05$). Data are presented as mean ± standard error of the mean.

3.3.3. Percentage of Milking Cows

Apropos, the response variable milking cows denoted that the better ($p < 0.05$) values occurred during spring and winter (avg. 91.05 ± 0.20%); an intermediate value was registered in autumn, while the lowest value was recorded in summer; 84.63% and 80.82%, ± 0.23, respectively (Table 2).

3.3.4. Cow Comfort and Wellness Expressed as the Average Lying Time per Cow

The comfort values unveiled differences ($p < 0.05$) across seasons. The values obtained were 10.53 h in winter, 10.20 h in autumn, 9.34 h in spring, and 8.76 h, in summer, ± 0.11 h (Table 2).

3.3.5. Milk Composition (Milk Fat, Protein Fat, Fat/Protein Milk Ratio, Milk Urea)

The highest value for milk fat percentage ($p < 0.05$) occurred in autumn (3.49 ± 0.006), while the lowest value was observed in winter (3.38 ± 0.006), and intermediate and similar percentages were registered in spring and summer. Milk protein showed a biphasic behavior in relation to the season, with the highest values ($p < 0.05$) in autumn and winter (average = 3.163%) and the lowest ones ($p < 0.05$) in spring and summer (average = 3.111%). The highest value for the MF/MP ratio occurred in spring (1.10 ± 0.03 units), while the rest of the seasons showed the lowest values and were similar between them (from 1.07 to 1.08 units). Finally, milk urea also showed differences because of season, with the highest value ($p > 0.05$) in summer (11.4 ± 0.11 mg) and the lowest one ($p < 0.05$) in winter (10.1 ± 0.13 mg).

3.4. Milk Performance, HS, and Economic Impact at Animal, Farm, and Regional Levels

Based on the information generated in this study, if the average daily milk production by dairy cattle in the CL, in the comfort zone, was 35.9 L, and the said level of production was reduced to 31.8 L when dairy cows faced a high HS (i.e., >77 THI) when projecting such reduction (i.e., 4.1 L) to a lactation of 305 d per year, an annual reduction of 1250.5 L per cow will be expected.

4. Discussion

Our working hypothesis proposed that high THI levels will decrease milk production due to a depressed voluntary feed intake while a reduced feed conversion efficiency affects, in parallel, the comfort status of dairy cows in the CL. According to our research outcomes, milk yield, feed efficiency, and animal welfare were compromised as the environmental temperature increased (i.e., increased THIs). Therefore, our working hypothesis is not rejected. Such findings are of particular importance because the dairy cattle industry represents a significant economic activity in the CL, located in semi-desert northern Mexico. In fact, Mexico has one of the main clusters producing bovine milk in the American continent, specifically in the CL. Certainly, the dairy cattle production system not only generates a significant economic profit for dairy cow producers, but the system is also characterized because of its highly technical, up-to-date, and intensive production scheme, perfectly linked to a dairy industrialization structure, with national and international ramifications.

Being in a dry-hot semiarid region, however, marked differences are observed concerning the level of milk production because it is generated under an environment of thermal stress, affecting animal productivity, and with great discrepancies across seasons. The last is mainly generated by the increased proportion of days that those cows are outside the thermoneutral zone, characterized by more than 300 days with HS per year, and with a tendency to increase such environmental insult over time [26]. Therefore, as initially hypothesized, such HS decreased milk performance as well as fat and protein availability at the regional and national levels. In addition to such a productive scenario perfectly aligned with the significant economic importance generated by dairy cattle in this region, our results picture the massive challenge for dairy producers to guarantee the welfare and sustainability of the dairy cattle production system in the CL.

4.1. Milk Production either at the Farm Level or the Cow Level across THI and Seasons

Although the THI threshold for cows with high levels of production was relocated to 68 units [22], such a scenario did not occur in our study. Certainly, the highest milk production at either the farm level or the cow level was registered at 68–71 THI. The effects of HS on milk yield were observed from 72–77 THI onwards. According to Liu et al. [23] observing a 68 or 72 THI to declare an HS scenario is not required because of animals' extremely diverse compensatory responses to face HS. Varied strategies to avoid or diminish the effects of HS by the farm managers could help to explain our study's unaffected milk production level at 68–71 THI. Among the most plausible strategies are the adequacy of the facilities like providing sufficient and suitable shade [4,33–38] and evaporative cooling systems [4,34,39–44] which are, as stated by Roth [45], the most common strategies to lessen the effect of HS, especially in dry-hot arid environments. Other strategies consider nutritional modifications through the inclusion of dietary fiber, dietary fat, dietary microbial additives, vitamins, minerals, metal ion buffers, plant extracts, and other anti-stress additives. Both fiber and fats are easily available macronutrients that can lessen the negative impact of HS in dairy animals [23] as well as the reduction of very fibrous forages [46], the use of yeast in the diet [47,48], the inclusion of fats in the total mixed ration [49], the manipulation of the degradable protein [50], and the inclusion of K in cows' diets [51]. It is important to point out that several of the above strategies are conducted on the farm under study to diminish the HS effects.

Another possible factor to explain our research outcomes involves the acclimation capacity of cattle born and raised in the region by the special synthesis of heat shock proteins

(Hsps) when they were calves or heifers. The Hsps allow the animals to face HS when adults, promoting a better physiological response to environmental thermic challenges. According to Collier et al. [52], heat acclimation is a process that leads to a widening of the thermoregulatory range, enhancement of metabolic and signaling pathways, as well as protection against stressors other than heat by switching protective pathways to an alert state. Certainly, the process of acclimation involves changes in all levels of body organization, including the reprogramming of gene expression. Furthermore, although Hsps are primarily considered as being intracellular, Kristensen et al. [53] identified the presence of Hsp72 in plasma from Holstein–Friesian cows, concluding that, although Hsp72 is believed to be strictly stress-inducible, the finding of Hsp72 in plasma indicates that even apparently healthy individuals may experience extrinsic and (or) intrinsic stress.

In relation to the season of the year, the highest production was yielded in winter and the lowest in summer, both in TotMP and cowMP production. Ageeb and Hayes [54] reported that Holstein cows in Central Sudan had a loss of 2.7% in their production, while Imrich et al. [55] found a negative correlation between THI and milk yield ($r = -0.65$; $p < 0.01$). Besides, when dairy cows are exposed to HS for nearly 50% of all annual hours, a yearly depression in milk production of around 2072 kg/cow occurs [3]. As in our study, Becher et al. [56] reported diminished milk production due to HS associated with the summer months, although the negative consequences can continue during autumn. While Ageeb and Hayes [54] reported a noticeable milk reduction at the onset of the summer season, Du Preez et al. [57] commented that milk yield showed a decrease (i.e., 10% to 40%) in summer regarding winter. In our study, the annual losses per cow with respect to winter were 132.0 L in spring, 480.5 L in summer, and 259.4 L in autumn, for a total of 871.78 L.

4.2. Dry Matter Intake, Feed Conversion Efficiency, and Energy Corrected Milk across THI and Seasons

High THIs generate a DMI reduction; in our study, a reduction of DMI around 0.92 kg per cow occurred with 72–76 THI, while increases greater than 77 decreased up to 2.09 kg DMI as compared with THIs from <68 and 68–71. West et al. [58] reported a depressed DMI of 0.51 kg per unit of increase in THI beyond 72; Liu et al. [23] mention that DMI decreased by 4.0 kg/d when THI increased from 68 to 80. Regarding seasons, DMI varies across the seasons of the year; if considering the winter daily average DMI in our study (i.e., 24.2 kg) as 100% of DMI, spring, autumn, and summer registered a loss of 4%, 6%, and 13%, respectively (i.e., 0.9, 1.4, and, 3.1 kg). As environmental temperature increases in summer, the cow´s body temperature also increases, reducing their DMI to mitigate HS [59]. As in DMI, a similar trend occurred for the response variable FCE; as the THI augmented, the FCE was reduced (i.e., from 68–71 (1.62 units) to $\geq$77 (1.51 units). This is one of the most relevant variables to define milk production efficiency [59]. Under elevated environmental temperatures, DMI and milk yield decrease, but FCE is further depressed in heat-stressed cows than in cows kept in thermoneutral temperatures consuming the same amount of feed. Therefore, it is crucial to avoid large THI values since animals exposed to HS use a significant amount of energy to maintain body temperature and, consequently, less energy is diverted for milk production. The ECM also was affected for THI; the largest ECM occurred at the <68 and 68–71 levels, intermediate ECM values at 72–76 THI, while the lowest values were $\geq$77 THI. As expected, the best ECM occurred in winter, intermediate values in spring, with the lowest ECM values in summer and especially in autumn. An adequate intake of metabolizable energy is necessary to avoid milk depression in cows under HS [54]; any failure to maintain milk yield will occur with unbalances in the energy, protein, and lipid metabolism, depressing—in parallel—the immune response due to oxidative stress and inflammation [60].

4.3. Percentage of Milking Cows

The percentual reduction in lactating cows as the THI level increases will compromise the productive efficiency of the herd. As expected, the season also affected this variable, with the highest observed values in winter and spring. In well-managed herds, 85% of the cows are expected to be milked; any decrease in the proportion of milking cows denotes a lack of calving homogeneity across the year, which has been related to infertility problems due to increased HS [18]. A similar trend occurred regarding seasons; winter and spring had the highest value (i.e., 91.04%), while autumn and summer had the lowest values (i.e., 84.6 and 80.8%, respectively).

4.4. Dairy Cow Comfort

As the THI increases, a reduction in the resting time per cow was registered; the THIs <68 and 68–71 showed a similar ($p > 0.05$) lying time (i.e., 10.6 h). The LT decreased by 9.5 h and 8.5 h at THIs 72–76 and ≥77, respectively. Moreover, LT also differed among seasons ($p < 0.05$); the highest LT occurred in winter and autumn, regarding spring and summer. According to Tucker et al. [16], on average, lactating cows lie down daily for 8 to 13 h, within the range of our study. According to Heinicke et al. [61], LT decreased as the average daily THI increased; such LT decrease was even greater above the heat load threshold of 67 THI. According to Hut et al. [62], lactating cows spent, on average, 11.5 h/d lying; this value decreased by 6 min daily once the THI reached 56 and decreased gradually to 10.45 h/d when the THI ≥ 72. Also, Cook et al. [63] reported that LT decreased from the year's coolest season to the hottest season. The LT is important in that it reflects animal welfare [64]; the less the LT, the more depressed the milk production, mainly due to a drop in DMI [65]. In general, the larger proportion of the rumination occurs while standing [16].

4.5. Milk Composition (Percentages of Fat and Protein in Milk and Quantity of Milk Urea)

Our results show that the milk fat percentage was low at <68 THI and higher at the other THI levels, and that, with respect to seasons, the highesst value was in autumn, and the lowest was in winter. These outputs do not agree with the results of several authors [9,19,66], who found a significant decrease in the levels of fat with increasing the THI, and [9] and [66] report a significantly lower fat content from spring to summer in the first case and in summer in the second one. However, other authors have reported inconsistent responses of fat content's reaction to HS, with increasing, decreasing [67], or no change reports of fat percentage [22].

With respect to the protein milk percentage, we found an inverse relationship between protein milk and THI levels; in other words, the percentage diminishes conform the THI level increased. These results have correspondence with other reported early [9,19,66,68]. As ambient temperature increases and as body temperature concomitantly increases, cows decrease their feed intake to mitigate HS, thereby leading to a gradual decline in milk production and a change in milk content [23], then, failure to rescue milk yield and the changes in milk composition due to shifts in energy metabolism; protein catabolism; alterations in lipid metabolism due to endocrine alterations and immune response due to oxidative stress and inflammation are the major factors in this context [60]. However, Cowley et al. [68] attribute the reduction on milk protein concentration to specific downregulation or mammary protein, rather than a general reduction in milk synthesis.

Our results show that milk urea was higher at ≥77 THI and lower at 68–71 THI, with intermediate values at <68 and 72–76 THIs. Regarding season, the higher value was in summer and the lowest in winter, then, the quantities of milk urea are affected by THI and their seasonal distribution, as suggested by Muroya et al. [69]. Regarding the fact that HS and high humidity conditions have negative effects on the production of milk true proteins and increase the urea-N content in milk, the former agrees with Gernand et al. [70] who found that milk urea was quite constant within the THI range from THI 40 to 70, but when THI was higher than 70, milk urea substantially increased. Similarly, Cowley et al. [68] found increasing milk urea under HS conditions; they suspected that this increase is due to catabolized muscle tissue, a process that is intensified under HS conditions. Subsequently, in our results, the increase in milk urea as a consequence of a higher THI and season associated with THI could be the effect (not measured in our study) of plasma urea concentrations which are increasing, especially in cows at early lactation exposed to HS, as mentioned by Koch et al. [71].

At this point in the discussion, a reasonable question arises: How can we align our research outcomes to measure the impact of HS from the perspectives of the producer, the market, and the society? Unquestionably, this is a difficult undertaking. Nevertheless, projecting the said HS impact from an economic standpoint is a sensible way of sizing up the problem faced by the dairy cattle industry in the CL. Between 2020 and 2021, bovine milk production in the CL increased by 4% (i.e., 2613.58 to 2730.75 million (M) liters), generated by a daily increase in milk production from 7.16 to 7.48 M liters in those years. Interestingly, such an increase in the production level occurred despite the observed decrease in the CL milking cow census (i.e., 250,877 to 248,719). According to these results, while a 1% decrease in the number of milking cows occurred, a 4% increase in the volume of milk produced was observed [72]. The last occurred despite the significant thermal insult faced by dairy cattle in the CL, which exist for more than 300 days of the year [27].

When dimensioning, from an economic stance, how significant this thermal insult is at the regional level, some features related to the inventory and level of the regional dairy production must be considered. The CL concentrates 248,719 milking cows; based on the milk reduction observed in our study, an annual regional potential decrease of around 311 M liters of milk would be projected. Moreover, if the average payment to the producer is 0.4 USD per liter of milk, thermal stress potentially generates an annual economic loss for the producer of the CL equivalent to USD 233.2 M. Then, amplifying such projection at market value (i.e., 1 L = 1 USD), a critical but perilous stance, the potential annual economic loss in the industry and market for bovine milk in the CL, would be as high as USD 311 M.

Nevertheless, even more serious, albeit sensible, is to try to dimension such milk losses from the social and ethical points of view. While the right to food is recognized since 1948 in the Universal Declaration of Human Rights, thereafter, in the Millennium Declaration approved by the United Nations Assembly, a compromise was reached to halve the number of people suffering from hunger by the year 2015 [73]. Furthermore, the right to adequate food in the context of national food security was also agreed [74]. In this regard, Mexico does not produce enough milk to match national demand; more than 30% of the total milk consumed must be imported [75]. When projecting the economic and social impacts of the annualized loss of 311 M liters of milk due to HS in the CL, besides the detriment in the volume of milk available to society through the different market channels, we must also consider the significant loss of key nutrients, which similarly declines the national alimentary and nutritional security. Certainly, such loss in the milk volume generated by HS in the CL is more straightforwardly dimensioned when bearing in mind the associated losses, expressed in annual metric tons, of the following milk nutrients: fat (10,892.03), protein (10,251.32), lactose (14,415.92), minerals (2562.83), and vitamins (320.35). Interestingly, a total of 195,415.82 Gcal would not be available to society.

These numbers and trends undeniably highlight the massive challenge that—from environmental, biological, productive, economic, and social standpoints—the dairy cattle industry faces in the CL. Irrefutably, it is essential to intensify mitigation strategies to lessen the effects of HS on the regional dairy herd, such as the redesign of diets, the modification of infrastructure to increase the amount of shade and air circulation and, also, to improve the use of evaporative cooling, among others; however, other strategies in relationship with environment sustainability must be considered [76]. Still, these mitigation strategies have an essential requirement to hold an enhanced understanding of the main trends of the THI across years, seasons, months, and even throughout the day. Indisputably, a Big Data and Artificial Intelligence approach will increasingly become a constant to face the challenges from HS. Indeed, real-time capture systems (i.e., Big Data, minute-by-minute) of environmental information are essential to accomplish such a goal. Likewise, remote sensors (i.e., Artificial Intelligence) that quantify the body temperature of a lactating cow facing a thermal insult, together with other physiological and behavioral constants generated by the HS through wireless devices for continuous measurement, will certainly be essential to improve, modify, and expand HS mitigation strategies.

5. Conclusions

Despite the highly significant environmental challenge faced by dairy cows, the Comarca Lagunera in the arid north of Mexico produces more than 20% of the nation's bovine milk volume. Said HS occurs for more than 300 days a year; such an environmental insult promotes the animal compensatory responses from both physiological and ethological standpoints. According to our research outcomes, HS provoked a lower feed-to-milk efficiency, reducing milk production both at the herd and cow levels, endangering not only animal welfare by reducing the resting hours but also decreasing the percentage of lactating cows, impacted by the effect of low fertility caused by HS. Even more critical, not only the economic losses at both the producer and the dairy industry levels but the accompanying nutritional losses at the society level undoubtedly impact the massive challenge that the dairy cattle industry in the Comarca Lagunera faces, from environmental, biological, productive, economic, and social standpoints. Finally, the proposal of measures to mitigate the thermal insult caused by HS on the bovine milk production and industrialization systems, in parallel with the quantification of how and when HS affects the chemical composition of milk in the region are, undeniably, pending assignments.

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CONCLUSIONES GENERALES

Estudio 1

La comarca lagunera es una región con niveles altos de ITH que, en promedio, alcanzan más de 300 días al año, con al menos una hora de HS y 31 días al año con valores de ITH superiores a 80 unidades. Nuestros resultados ofrecen evidencia sólida de que la producción lechera en condiciones áridas, calurosas y secas debe apoyarse con estrategias de mitigación para contrarrestar los ataques de EC durante más de 2/3 del año. El enfoque de investigación utilizado en nuestro estudio, no solo de año a temporada, sino también de mes a temporada, e incluso de minuto a minuto, pone a disposición información sólida para respaldar el diseño de estrategias de mitigación de amplio alcance. Los resultados de nuestra investigación son cruciales para definir estrategias específicas no solo en ventanas de acción específicas, sino también utilizando diferentes enfoques de escala de tiempo para disminuir las influencias negativas del EC. Los estudios futuros deben abordar las posibles interacciones entre el EC, los niveles de ITH, la producción de leche, la eficiencia reproductiva y productiva, así como la solidez inmunológica, que están alineados con los posibles mecanismos de mitigación térmica para reducir el EC, especialmente en vacas lecheras de alto rendimiento; el último es una asignación ineludible.

Estudio 2

A pesar del gran desafío ambiental que enfrentan las vacas lecheras, la Comarca Lagunera en el árido norte de México produce más del 20% del volumen de leche bovina del país. Dicho estrés calórico ocurre más de 300 días al año; tal insulto ambiental promueve en el animal respuestas compensatorias tanto desde el punto de vista fisiológico como etológico. De acuerdo con los resultados de nuestra investigación, el EC provocó una menor eficiencia de la alimentación a la leche, reduciendo la producción de leche tanto a nivel de rebaño como de vaca, poniendo en peligro no solo el bienestar animal al reducir las horas de descanso, sino también disminuyendo el porcentaje de vacas lactantes, seguramente motivado por un efecto de baja fertilidad como consecuencia de dicho insulto térmico. Aún más crítico, no solo las pérdidas económicas tanto a nivel del productor como de la industria láctea, sino las pérdidas nutricionales que las acompañan a nivel de la sociedad, sin duda dimensionan el enorme desafío que, desde el punto de vista ambiental, biológico, productivo, económico y social, enfrenta la ganadería lechera en la Comarca Lagunera. Finalmente, la propuesta de medidas para mitigar dicho insulto térmico sobre los sistemas de producción e industrialización de la leche bovina, paralela a la cuantificación de cómo y cuándo afecta el EC a la composición química de la leche en la región son, indiscutiblemente, asignaturas pendientes.