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Methodological Characterization and Computational Codes in the Simulation of Interacting Galaxies: Image Evaluation with CNN

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Abstract: Currently, technological development has exponentially fostered a growing collection of dispersed and diversified information. In the case of galaxy interaction studies, it is important to identify and recognize the parameters in the process, the tools, and the computational codes available to select the appropriate one in depending on the availability of data. The objective was to characterize the parameters, techniques, and methods developed, as well as the computational codes for numerical simulation by implementing Convolutional Neural Network; with information retrieval, image and video analysis and pattern recognition. From the bibliography, it was reviewed how various authors have studied the interaction, presence of gas and star formation, and then the review of computer codes with the requirements and benefits, to analyze and compare the initial and boundary conditions. With images, the convolutional neural network (CNN) method programmed in python was applied to identify the differences and their possible accuracy. Smoothed Particle Hydrodynamics systems use more robust algorithms with invariance, simplicity in implementation, flexible geometries, but do not parameterize artificial viscosities, discontinuous solutions, and instabilities. In the case of adaptive mesh refinement, there is no artificial viscosity, resolution of discontinuities, and suppression of instabilities but with complex implementation, mesh details, and resolution problems, and they are not scalable. It is necessary to use indirect methods to infer some properties or perform preliminary iterations. The availability of observable data governs the behavior of possible numerical simulations, in addition to having tools such as a supercomputer, generating errors that can be adjusted, compared, or verified, according to the techniques and methods shown in this study, in addition to the fact that codes that are not so well known and used stand out as those that are currently more applied. Thus, CNN enables pattern recognition, based on the recovery and analysis of images and videos, as well as simulations of interacting galaxies.

Keywords: galaxy pairs, numerical simulation, computer code, spectroscopy

The increasing technological innovation and the development of new computational codes, has led to an increasing use in the generation of numerical simulations with the use of supercomputers, to determine behaviors, processes, and systems revision, as well as prediction of results, including the results, cosmological, such as the interaction of galaxies. In this way, identifying and recognizing available parameters, techniques, and methods help to choose based on the availability of data and tools to generate results that are closest to the observations and to be able to compare or adjust to other conditions.

However, it is important to start by recognizing a process, identifying the availability of data, and reviewing the packages or codes developed that represent the phenomenon through a model to be able to generate simulations, with which this leads to a visualization of results, very important in decision-making decisions, generally predictive, although the time scale plays an important role in the case of cosmological processes.

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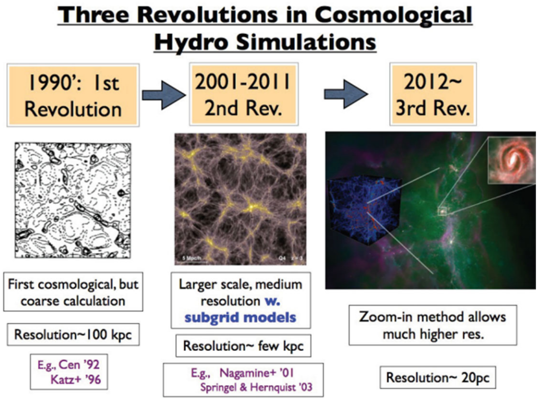
1. Introduction

In the last century, scientific and technological advances were slow and little applied, due to the scarcity of tools such as computers and the use of telescopes and satellites to obtain data from planets, satellites, stars, galaxies, and clusters of galaxies. In the 90s, the evolution of the computational field led to two great revolutions in the last two decades and currently for a third (Figure 1), according to Nagamine [1].

In this way, a great variety of astrophysical and cosmological processes have been studied in recent years, for which collaborative groups, research centers, and technological and computational development have been created, to generate projects such as COAST, AGORA, EAGLE, ILLUSTRIS, SIMBA, and MUFASA, among others [2–7].

Currently for the study of the universe, the observational cycles are the basis of the information to describe the processes, with it the graphic tools such as images are an excellent tool for the interpretation of galaxy interactions combined with the use of artificial intelligence AI. This process is common in the universe;

Figure 1
Development over time of cosmological hydrodynamic simulations [1]



it is a consequence of disturbances, where the trajectory, speed, and gravity have a significant influence on the bodies that make up the system, which distorts the distribution of particles generating new dispersions. For the treatment of these cases, it is necessary to have adequate spatial resolution, for example, from 30 to 100 pc [8], suitable angular size, and declination that allows to distinguish air masses, in order to generate an ideal reduction of data.

Thus, they have been compared with populations in HII regions, where the luminosity Hα and the radius are clearly different from the low luminosity regions [9], in such a way that in bright populations the interaction of galaxies is more frequent, in addition to the existence of turbulence and star formation, associated with gas flows giving rise to clouds that are affected by gravity, where galaxies with masses greater than 106.5 $M_{\odot}$ tend to accumulate mass by gas flows induced by the interaction.

As a result of the interaction of galaxies, there is star formation, Weistrop et al. [10] who redescribe that stellar rotation tends to reduce the Hα star formation rate by about 40%, although the gas phase may differ due to different methods used to estimate abundance. Tonnesen and Cen [11] state that if there is a merger of galaxies, this will cause an increase in the mass of galaxies for star forming, there is an impulse towards dead and red galaxies, in addition, the merger is not responsible for the color–density relationship, the environment is responsible.

But it is also to recognize that visualization plays an important role, since adequate and correct interpretations are derived from it. The evaluation with algorithms such as the Convolutional Neural Network (CNN), since it allows in order to recognize objects, classes and categories. Bickley et al. [12] used CNN for automated merger classification. Miranda [13] classified images from the light curves of simulated data, where the application of the CNN method describes differences between real data, but this is explained due to the small number of data when training with the classifiers.

Currently there are algorithms for reading data, such as those developed with Python, which require basic programming knowledge, or software such as VisIT, ParaView, HDFView, TopCat, Blender or ResInsight that have evolved in recent years, with availability of various versions. But, even between applications there are several variations, such as the reading of the input, handling of the package, and resolution of mappings or iterations.

From the use and application of computational tools, software, codes, databases, and observational records, the objective of this research was to characterize the parameters, techniques, and methods developed, as well as the computational codes for numerical simulation, by implementing Convolutional Neural Network (CNN); with information retrieval, image and video analysis and pattern recognition.

According to the bibliographic review, cosmological hydrodynamic simulations have evolved in the last two decades, such that there is a lot of information. In this research, the techniques, methods and parameters of galaxies associated with interaction processes were reviewed, along with the recognition of the codes used in computational simulations, their general considerations, and initial and border conditions, since that some are not so well known and used. In addition, it is shown how they evaluate the presence of gas in the interaction according to visualizations from 2008 to 2022, and the CNN method is applied to evaluate images from publications and repositories with different codes and to be able to compare general differences. The methods and techniques that have been developed have interacted in the resolution of predictive problems, the evolution of programming languages, and data reduction prior to simulations, hence the resolution of the visualizations taking into account that even between different techniques and methods there is a relative error. In this way, there are very robust techniques, but they require specific parameters and are often not available or are restricted, it is necessary to recognize as shown in this article prior to generating simulations, since this also gives rise to compare, adjust, validate, improve, or create new techniques and methods from existing ones such as, a) information retrieval, b) image and video analysis, and c) pattern recognition.

2. Methodology

2.1. Techniques and methods used: Images for CNN

In the current era, the use of computers and supercomputers has given rise to the treatment of a large amount of observable information, so it was necessary to review the bibliography related to the interaction of galaxies such as NGC1/NGC2, NGC6726/NGC6727, NGC5857/NGC5859, NGC7284/NGC7285, NGC7838/NGC7837, NGC2672/NGC2673, NGC7541/NGC7537, NGC750/NGC751, NGC3395/NGC3396, NGC3893/96 (KPG 302), NGC3695/NGC3700, NGC3754/NGC3753, NGC6621/NGC6622, NGC5734/NGC5743, NGC5258/NGC5257, NGC5018/NGC5022, NGC5022/MCG-03-34 013, CPG165/CPG410, IC1727/NGC672, and even triple galaxies like NGC2807/NGC2809/NGC2807A, NGC90/NGC91/NGC93, NGC4778/NGC4759/NGC4761, NGC1625/NGC1622/NGC1618 y NGC1728/NGC1725/NGC1721.

There are also multiple galaxy interactions as NGC2872-74/NGC2875 /NGC2874/ NGC2873/ NGC2871, the UGC6741/UGC6741_B, ShaSS 622-073, or from the Arp catalog (1996). With this, the parameterization of the use of techniques and methods was carried out, shown in Table 1a and 1b, in the case of interaction, fusion, collision, shock, harassment, or even galactic cannibalism, distinguishing the presence of gas, dust and stars, geometry related to the disk, halo, and dynamic mechanisms associated with speed, rotation, and particle density, mass, and its distribution.

Building on previous techniques and methodologies, Figure 2 recovers galaxy images in various cases such as paired galaxy interaction, where the analysis can be based on images such as those provided by Sloan Digital Sky Survey (SDSS), observations, or review publications. Data reduction makes it possible to generate fields and velocity distributions, locate star-forming regions,

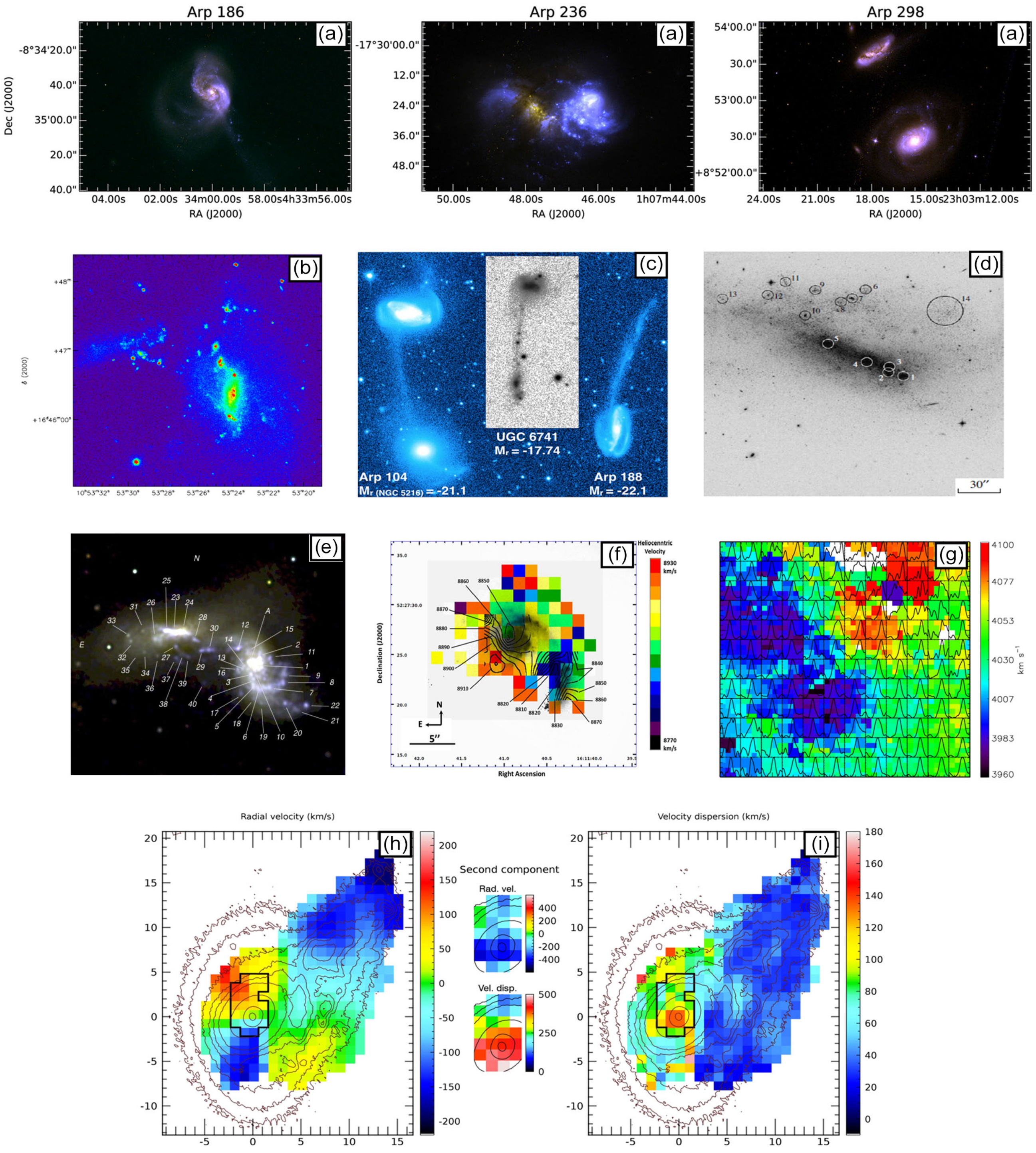
Table 1a
Parameterization as input data (own elaboration)

Process	Parameter	Technique/method	Reference
Interaction	Oxygen abundance, presence of standard star flows, gas flows, metallicity distribution.	Spectroscopy with Gemini MultiObjet Spectrograph, use of IRAF, GBIAS, GFLAT y GSRDUCE, Hα Fabry-Perot.	Torres-Flores et al. [14]
Interaction and rate of star formation	Gas phase gradients and oxygen, metallicity, excitation mechanisms.	Multi-object spectroscopy system, IRAF (Image Reduction and Analysis Facility).	Zhang et al. [15]
Interaction	Position, morphology, masses, velocity, luminosity, ionized gas, trajectories, flow inlets and outlets, scattering fields.	Observations and scanning Fabry-Perot interferometer PUMA, use of software ADHOCw[3], application of ELLIPSE, IRAF, IMEXAMINE, MSCSETWCS and Word Coordinate System and parsing with Python.	Sardaneta et al. [16]

Table 1b
Parameterization as input data (own elaboration)

Process	Parameter	Technique/method	Reference
Interaction	Morphology, asymmetry, tails, extraplanar emission, star formation.	ESO-VST ugri filters and ESO-VISTA k band k band images (Mappings 5.0).	Merluzzi et al. [17]
Interaction and rate of star formation	Scattering speed, size, luminosity Hα, radius, density, mass of ionized gas.	Fabry-Perot interferometer GHαFaS (Galaxy Hα Fabry-Perot System).	Zaragoza-Cardiel et al., [9]
Interaction	Observations of particles, coordinates, mass transfer, gravity, density, entropy, temperature, radius, sound speed, rotating in the grid.	Octo-Tiger code, HPX parallelization, linear conserved and angular momentum, stationary simulations and transients, effective potential, energy equation for the gas energy.	Marcello et al. [18]
Interaction/ collision	Gas semigravity, stars, radiative cooling, hydrodynamic pressure, shock heating, viscosity, star formation.	Fabry-Perot 2D, UV swift UVOT and SDSS, SPH-CPI.	Mazzei et al. [19]
Minor interactions	Stellar mass, spectroscopic redshift, color distribution, local density, dust, morphological information, velocity, star formation rate.	SDSS, spectroscopic and photometric, the Flexible Stellar Population Synthesis (FSPS) model, Galaxy Zoo, Kolmogorov-Smirnov (KS) test, the probability density functions and cumulative distribution functions.	Das et al. [20]
Interactions	Maximum separation, velocity, stellar mass, metallicity, mass ratio, radius and density, luminosity, metallicity.	Observations, THE THREE HUNDRED simulations of clusters of galaxies, AHF catalogues.	Contreras-Santos et al. [21]
Interaction and star formation rate	Velocity field of the ionized gas, kinematic asymmetry, star formation rate, stellar mass.	SDSS-IV MaNGA IFU survey, kinemetry package, simples an subsamples, the bar and non-bar classifications of Galaxy Zoo Project.	Feng et al. [22]
Interaction and ionized gas	Rotation fields, free spectral range, brightness, scattering velocity maps, star formation rate, density, temperature, and metallicity.	Fabry-Perot Interferometer Roque de los Muchachos Observatory, ALMA, ASTRODENDRO of Python.	Zaragoza-Cardiel et al. [23]
Interaction	Ascension and declination, stellar mass, luminosity, morphology, radial velocity, gas metallicity, oxygen abundance.	Photometry UV GALEX (Galaxy Evolution Explorer), spectroscopy, SDSS.	Paudel et al. [24]
Stellar content and interaction	Morphology, speed, apparent deformation, metallicity, color index, luminosity, density distribution.	Filter images F606W y F814W of Hubble Space Telescope ASC/WFC, photometry, TRGB method for distances, population correlation.	Tikhonov et al. [25]

Figure 2
Examples of images in static processing: (a) color composite images using F435W and F814W HST filters in Arp 186, Arp 236, and Arp 298 [23], (b) SDSS r-band image of NGC 3447/3447A [19], (c) comparison of the optical r-band of the SDSS between Arp 104 and Arp 188 with UGC 6741 [24], (d) HST image of IC 1727 in the F606W (V) filter, the circles mark the brightest star-forming regions [25], (e) Combined U, V, R image of NGC 3395/3396, 40 Blue regions phothometry [10], (f) Velocity field of NGC 6090 with the Hα data cube observation with the scanning FP Interferometer [16], (g) residual-velocity fields, difference between the observed and modelled velocity fields [14], and (h–i) gas velocity fields of the ShaSS 073-622 with [O III] λ5007 emission line were fitted using the package LZIFU [17]



behavior of gas and dust or just compare how the taking of images has evolved, aspects of relevance for astrophysics, where the mechanisms of visual interpretation play an important role for the generation and presentation of results and implementing CNN as artificial intelligence for recognition substantially improves pattern recognition.

2.2. Computational codes in numerical simulations implemented in CNN

Two approaches have been used: (i) Lagrangian represented by the smoothed particle hydrodynamics method (SPH) such as GADGET, Hydra, and GrapeSPH, among others and (ii) Eulerian with adaptive meshes or adaptive refinement (AMR) such as FLASH, ZEUS, RAMSES, and ATHENA to solve non-stationary 3D astrophysical problems [26]. The development of computational codes, based on the governing equations (continuity, Euler, and energy), has revolutionized the study of cosmology due to the possibility of numerically simulating processes that have taken billions of years, with the use of supercomputers that only require thousands of hours of processing, thus necessary to review how these codes have been used and what contributions or requirements are necessary (Table 2a, 2b, 2c, 2d).

Figure 3 shows how these codes and algorithms have been used to simulate physical processes, and with the use of CNN, pattern recognition is facilitated by the replication of information and analysis of images and videos resulting from transient simulations that use numerical codes, highlighting the chronological order in the evolution of time and the same perfection that each code has generated to be able to represent astrophysical processes with the best refinement. Currently, there is varied information which has allowed comparing the benefits for the same case, such as those presented by Volker Springel at a conference on hydrodynamic simulations in 2020. It is possible that new codes are still being developed and continue to be created and with the use of supercomputers to analyze systems that take billions of years in thousands of hours of processing, for a better resolution of results.

To CNN in visual studio code with python and the libraries tensorflow, numpy, and matplotlib, of 100 images of repositories of codes and publications, classes were labeled and generated, the process was trained and validated galaxies interactions.

Table 2a
Codes and computational routines in cosmological simulations (own elaboration)

Code	Considerations	Reference
RAMSES	Refined adaptive Lagrangian mesh, particles in a cell (dark matter or stars), exceeded baryonic density, uniform metallicity. Hydrodynamic solution of second-order Godunov scheme for perfect gases, refinements in high-density regions, uses: particle mesh, Poisson solver and hydrodynamics. It has been used to study structure formation in a low-density universe, as well as gas behavior, cooling, star formation, and supernovae. In the N-body solution, the code is similar to the ART code, whose resolution is not uniform.	Renaud et al. [27], Teyssier, [28]
FLASH	In Fortran, input/output in C, capacity to simulate problems for predictions that can be directly compared with observations, provide a variety of methods for solving Euler equations of hydrodynamics, based on the Godunov approach and Riemann solvers, flux computation, extended 2T Helmholtz EOS. Refined adaptive meshes, Poisson solver, resolution of the Navier–Stokes equations, implementation of mappings. Discretization by blocks, for simulation of gravitational fields with Lagrangian, for individual elements an Eulerian mesh. Rayleigh–Taylor and Richtmyer–Meshkov instabilities.	Daley et al. [29], Chatzopoulos & Weide [30]
VEGAS	Is a deep multi-band imaging survey, carried out with the ESO VLT Survey Telescope, it is possible to generate samples and select groups and clusters of galaxies. It allows us to explore the structure of galaxies down to the faintest level of surface brightness. Light distribution mapping, halo studies, tidal tails, stellar streams and shells, reconnaissance of satellite galaxies, and photometry. Studies of small star systems, galaxies ensemble for analysis of diffuse light properties, brightness fluctuations, galactocentric radio, evolution and transformation, acceptable integration time, with observational plan, positions, and sizes, coupling of optical data in the infrared band to reduce contaminant effects less than 5%.	Iodice et al. [31], Spavone et al. [32]
WOMBAT	The code is object-oriented and hybrid-parallelized with MPI and OpenMP, is part of the regression testing, fidelity on 1D, 2D and 3D. Euleria, non-relativistic, Mach number, momentum transport, energy changes out of shocks, diffusive shocks, non-oscillatory scheme for constrained-transport magnetohydrodynamics. Written in Fortran 2008, for uni-grid simulations with complex conditions that require load-balanced, uniform meshes, it subdivides the problem into completely independent parts, which include their necessary boundaries and metadata, no relativistic, electrical resistance, viscosity and non-adiabatic processes such as thermal conduction. Investigation of cosmological turbulence and evolution in galaxy clusters.	Donnert et al. [33], Nolting et al. [34]

Table 2b
Codes and computational routines in cosmological simulations (own elaboration)

Code	Considerations	Reference
BAHAMAS	Can build a correction function to study the impact of baryons on the power spectrum of matter in halo models, simulations can be run with the Lagrangian TREEPM-SPH code GADGET3, may contain extensions to the Standard Model, may generate small differences at high masses as a result of cosmic variation and relatively poor statistics (Poisson errors) in the analysis volume. Simulations of baryon physics, run with a modified version of GADGET-3, an extension of the method based on Bayesian hierarchical modeling, it fits systematic errors, possible redshift correlations and corrected intrinsic magnitudes empirically.	Robertson et al. [35], Acuto et al. [36]
CIGALE	Python Code Investigating GALaxy Emission, to study the evolution of galaxies by comparing the modeled galaxy spectral energy distributions, to observed ones from the far ultraviolet to the far infrared and radio, flexibility allows working with data from observations, catalogues and archives, calculates the dot product of the star formation history with grids, and time steps. Based on energy balance estimate physical properties of galaxies, star formation, independent modules for unique physical components or processes, in the modeling of nebular emissions. Balance between absorbed energy in UV and optical, dust emission, different heating intensities, combination of dust attenuation curves can be assumed.	Zaragoza-Cardiel et al. [9], Boquien et al. [37], Kompaniiets [38]
GIZMO	Hydrodynamics Lagrangian finite volume free meshes of the Godunov or SPH method or Eulerian fixed mesh schemes, dust and gas analysis, turbulence diffusion. Flexible and arbitrary (Stokes, Coulomb), similar to ATHENA and ZEUS. Use of Galerkin's method for nonlinear and discontinuous flows for conservation equation, no artificial diffusion required, fluid elements move with flow, cosmological integration, star formation, radiative cooling, similar to GADGET-3, free surface handling, without diffusion in vacuum, the solution is not limited by the convergence or precision of the numerical integration.	Hopkins [39], Hopkins [40]
HYDRA	Hybrid retrieval code HyDRA-H, capable of simultaneously retrieving low-resolutions and high-resolution emission spectra of transiting exoplanets, atmospheric recoveries, spectral emissions for exoplanets, can be combined parametrically, with Bayesian statistical inference algorithm and modules to constrain deviations in equilibrium, temperature profiles are verified for a parameterized minimum effect, chemical and radiative-convective equilibrium are adjusted, apply synthetic data to extract parametric values known a priori.	Gandhi and Madhusudhan [41], Gandhi et al. [42]
STARLIGHT	Stellar population, spectral synthesis model as a linear combination of elements from a base of different ages and metallicities, stellar kinematics in galaxies and information derived from the SDSS database. Written in C++, capable of simulating photonuclear interactions accompanied by Coulomb excitation, and vector mesons, which decay to generate a spin state, it can calculate cross sections, in addition to simulating collisions of two different nuclei with a mass distribution, simulation of narrow or wide resonances (highs and lows), kinematic distributions and stores lookup tables, simulate, many events quickly, linearly interpolating between the closest values.	Barua [43], Klein et al. [44]

Table 2c
Codes and computational routines in cosmological simulations (own elaboration)

Code	Considerations	Reference
AREPO	Collision and hydrodynamics in space time of Friedmann–Lemaitre–Robertson–Walker in plane and uniform expansion, dynamic discretization, in gravitational cases it allows periodic and non-periodic conditions (vacuum), it also admits conditions of boundary for inflow and outflow, the time integration is explicit, so every dark matter particle is gravitationally constrained. Written in ANSI-C, mobilized grid method, simulates semigravity, stellar fluids, dark matter without gravity, simulates in Newtonian space as in the universe in expansion, time lapses can be individual adaptive for gas or dark matter particles, it has been compared with ATHENA and GADGET output files similar to GADGET.	Springel [45], Weinberger et al. [46]
AstroPhi CosmoPhi	Performance, scalability and energy efficiency, checking the quality of the numerical solution on test problems. Galaxy collision, cosmological expansion, filament structures, galaxy cluster, voids, cell-fluid method combination, scalability, computational level efficiency.	Kulikov et al. [47], Sapetina et al. [48]

(Continued)

Table 2c
(*Continued*)

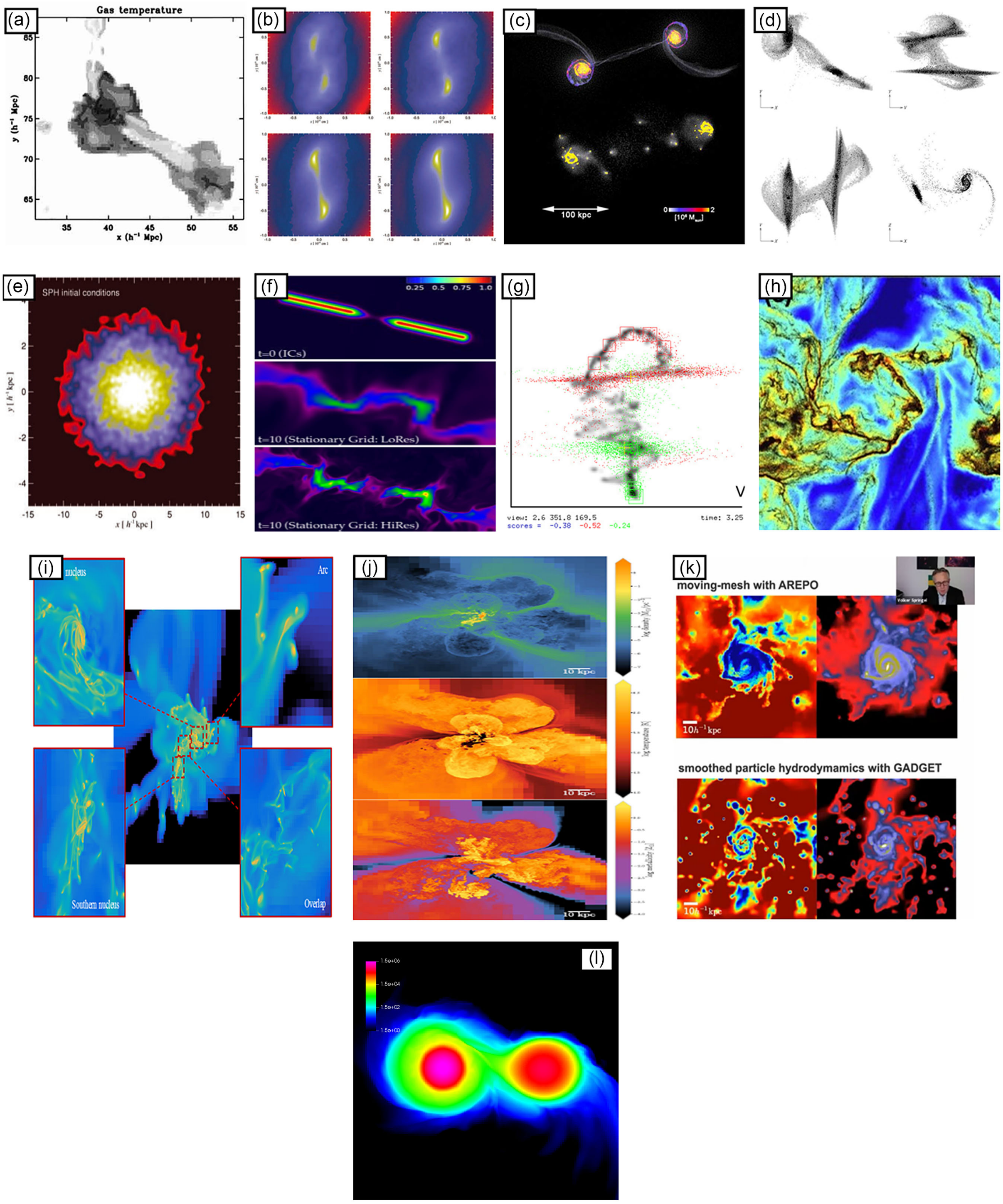
Code	Considerations	Reference
	Lagrangian, dynamic simulation in hybrid supercomputers with accelerators, with maximum cell size of 10243, incorporates Boltzmann equation without collision, to increase the scalability of the numerical method of the potential gradient; it is necessary to abort the solution of the Poisson equation and evaluate the field using the Cauchy–Kovalevskaya equation.	
ENZO	Refined adaptive meshes, high spatial and temporal resolution in hydrodynamic modeling, solution of equation of conservation of mass, momentum, energy and magnetic induction. Implementation of the high-order piecewise parabolic method, as well as second-order finite differences, each piece or element is treated as an individual object with observational data or as a particle, each grid is solved as an independent problem with Dirichlet boundary conditions, the code behaves similar to GADGET SPH within 5%. Adaptability in structural blocks, portions of density, temperature and metallicity, as well as high resolution turbulence, star formation. Compatibility with completion routines and resolution scalability in the output.	Teófilo-Salvador et al. [49], Peeples et al. [50]
SPAM	Python routines based on an astronomical image processing system, which allow simulations to be calibrated, several self-calibration waves can be included iteratively, it corrects for lack of coplanarity. The calibration imposes an additional correlation factor based on assumptions and extrapolations.	Benaglia et al. [51], Shamir et al. [52]
	Using images, potential of static galaxies and massless particles to produce tidal interactions does not reproduce gas dynamics or tail formation. They allow modeling orbital interactions and morphology. High computational speed for thousands of executions. Initial conditions not only of observed data.	
ZEUS	Speed of solution, multidimensional robustness and ability to adapt viscosity (artificial for shocks, artificial von Neumann–Richtmyer), radiation, self-gravity without hydrodynamic algorithm, implements entropy waves and stabilizes fast and slow compressional waves. It is almost acceptable for gas dynamics in cartesian, cylindrical or spherical polar coordinates.	Clarke, [53], Stone [54]
	It uses finite difference method, non-conservative mass. Solve dynamic equations in echelon meshes with a high-order method in the solution of advection.	
Identikit	Simulations for interacting self-gravitating dark halos, it is necessary to perform a simulation when changing the configuration of the disks in the halos, even if the configuration of the two halos remains unchanged, the force field of the interacting halos cannot be easily found using a tree code. If the self-consistent field code is incorporated, it is possible to find the observed morphology of interacting disk galaxies. Morphology and kinematics modeling, easy simulation in disk fusion, tidal queues with sensitivity to boundary conditions, fast scanning of multidimensional parameters of space.	Hozumi et al. [55], Mortazavi et al. [56], Barnes and Hibbard [57]

Table 2d
Codes and computational routines in cosmological simulations (own elaboration)

Code	Considerations	Reference
ATHENA	The boundary conditions for the dependent variables in each mesh block are applied by means of ghost zones, the mesh blocks are distributed more uniformly for the same computing expense. There are new higher order reconstructions on curvilinear and/or non-uniform meshes, with time integrators based on the fuzzy lines approach using the Runge–Kutta method.	Stone et al. [58], Stone et al. [59]
	Static meshes, with finite element method, based on the Godunov method not directionally split ideal for use in AMR and SMR, capturing impacts and evolving rotational and contact discontinuities, adaptable and maintainable, includes extension of upwind transport integration algorithms, solves in hydrodynamic or magnetohydrodynamic with an ideal gas or barotropic equation of state.	
GADGET	Written in C, it uses parallelization and the Tree-Particle mesh algorithm, the root is the main node and behaves like a mesh that extends to subsequent nodes, the initial conditions must be created with other codes and resources such as GalIC and N-GenIC for galaxies and large structures.	Chacón et al. [60], Kapferer et al. [61]
	Smoothed particle hydrodynamics (SPH), moving baryonic and non-baryonic components, star formation, collision trajectories, tidal tails, gas bridges and distributions, turbulent effects and Kelvin–Helmholtz instabilities, heat conduction and ram pressure.	
	Gravitational interactions the N-body method to represent a fluid without collisions.	

Figure 3

Examples of images in dynamic processing: (a) gray scale images of the gas temperature (T > 10^5 K) of the computational volume of 256^3 particles in 5 levels of refinements with RAMSES [28], (b) resolution study for the "standard isothermal collapse" simulation of the gas density in a slice GADGET2 [62], (c) in the lower panel the interaction takes place in an ambient medium with a constant ram pressure acting face-on at the system, whereas in the upper panel no ambient gas with GADGET2 [61], (d) a pair of merging galaxies with Identikit [57], (e) gas density in the original smoothed particle hydrodynamics (SPH) particle distribution in an isolated galaxy of 30,000 particles [45], (f) disc rotated the with gas, the Lagrangian particle-based methods (Traditional SPH, Modern SPH, Meshless Finite Mass, Meshless Finite Volume) are invariant to such rotations, t = 0 in equilibrium, t = 10 LoRes stationary-grid at lower resolution and t = 10 HiRes higher resolution in [40], (g) the cold gas is shaded grey, and the best-fitting Identikit galaxy models are the red and green points, simulation GADGET [56], (h) dust grains moving in a super-sonically turbulent cloud with GIZMO [39], (i) gas density map of the 12 kpc × 12 kpc of the merger with RAMSES [27], (j) slices of density (top), temperature (middle), and metallicity (bottom) through central halo in the 78 pc resolution simulations at z = 2.5 with ENZO [50], and (k) conference of Volker Springel hydrodynamical simulations of galaxy formation in 2020, (l) Orbital density slice, ideal gas with code [18].



Since the use of supervised CNN allows estimating morphological properties of galaxies from global morphology to more detailed properties [63].

3. Results and Discussion

According to the previous review, the required parameters are position, morphology, symmetry, masses, luminosity, color, trajectories, density and its distribution, gravity, pressure, viscosity, rotation, dispersion speed, presence of oxygen, gas flow zone, metallicity distribution, scattering fields, transfer, trajectories and gas concentrations, star formation rates, and possible deformations.

The most widely used technique is based on spectroscopy, the use of interferometers, and the digitization of SDSS images, with which the methodologies select a set or pairs of galaxies in a region to generate structural analyses, these studies are complemented with codes developed to adjust correlations under certain conditions.

In hydrodynamic studies, images and a composition of these can be used, for which a reduction is necessary using appropriate filters according to the band used, the same image composition can allow the identification of star formation regions, but with it the determination of trajectories of speed within a field of speeds, which is influenced by the distribution of the particles and the same speed with which they move with respect to each other and with respect to the center in the case of galaxies. Velocity fields can be generated between the observed and modeled data, and with a focus on the application of gas hydrodynamics, the behavior deduced from the radial velocity and the distribution velocity, being more noticeable in areas with higher density of according to the reviewed publications.

The imminent need implemented in CNN for the codes has led to some presenting more attributes derived from the needs in recent years and others with improvements. For example, according to Kulikov et al. [26], the advantages of SPH are that it is more robust in the structure of the algorithm, invariant solutions, simplicity in implementation, and flexible geometries, but it is necessary to parameterize artificial viscosities, some discontinuous solutions, and instabilities, some of which are not scalable.

In the case of AMR, the benefits are appropriate numerical methods, there is no artificial viscosity, resolution of discontinuities, suppression of instabilities, but with disadvantages such as complex implementation, mesh details, and resolution problems, and the methods are not scalable.

The Fortran and C programming languages are among the most widely used in planning, organization, and development of algorithms for solving numerical simulation problems. The standard test in these codes is the Godunov scheme, necessary for parallelization and the development of new routines and subroutines, which are verified with analyzes such as Raleigh–Taylor instabilities, Richtmyer–Meshkov, Mach number, some codes have similarities with some preliminary source code, adding improvements and version updates which allow restricting cosmological parameters allowing hierarchical modeling.

In the application case, according to the readings and illustrations observed in the publications, the greater the relations between galaxies in the interstellar or intracluster medium, the greater the instability in the scales due to the high mass regime, with the previous considerations, the reduction part of identifying tidal tails in nearby galaxies. Other parameters such as the nature of gravity, orbital velocities, distribution velocity, rotation curve, baryonic mass and dark matter, the effect of luminosity and energy produced, influence cosmological studies, such that it has suggested analyzes as smoothed particles, that is to say homogeneous, uniform and continuous. The descriptions of such situations require mathematical conviction for numerical calculations, for which data reduction is necessary in the generation of particular conditions when space systems are invariant to directional and density changes, in order to reduce the dependence on time.

The development of computational codes has increased and with it the need for supercomputers to generate cosmological simulations, since thousands of particles are required in a simple test, each particle has a relative position and velocity with respect to the position of the galaxy itself, in addition to the presence of gas and dust, dark matter, and its distribution in the same galaxy. In the case of interaction of paired galaxies, the presence of a second one, with particles of different conditions.

At the beginning of the year 2000, the resolution of the output images of the codes did not have the same resolution as today, for example, it was more difficult to identify variations in gas temperature or density, but this improvement has already evolved that codes like GADGET and ENZO have generated simple tests to determine the behavior of the same gas due to the fineness in the resolution.

When evaluating with the CNN method on a personal computer, it was found that it is necessary to homogenize the images, with it the long pixel width. In a first attempt with 10 images (weight of 24 MB), the accuracy obtained was 74% for three color channels (red, green, blue), and the set reaches a validation of 81%, but for 100 images the accuracy increased, weighted to 196 MB, and the programmed algorithm showed an accuracy of 84%. Finally, with a 2.4 GB dataset with images, the computer did not show output, losing the output image, so this led to the need for a supercomputer with the necessary characteristics to process large amounts of data for the analysis of large amounts of data. These factors must be reviewed beforehand to generate efficient results, from considering performance metrics and computational cost, memory usage, and classification speed, which influences an ideal architecture based on the available computational resources [64]. Thus, even networks trained on visually classified SDSS images achieve an accuracy of 91.5 %, and networks trained by simulation reach 65.2 %, for example, EAGLE, and the classifications of SDSS images by simulation are less successful, reducing accuracy to 64.6%, while the classification of EAGLE images with the observation network is even lower, up to 53.0 % [65]. This is consistent with what was obtained in this work, since most of the images collected for CNN did not have visible interaction features, and the visually identified interaction catalogs could be incomplete and biased towards certain types of interaction, in addition to the high resolution of current images when compared to images from 20 years ago.

It is important to highlight the features needed to process large amounts of data, and artificial intelligence AI enables; a) information retrieval, b) image and video analysis, and c) pattern recognition, and need to compare codes such as AREPO and GADGET, as well as ATHENA or FLASH, under the same initial and border conditions, being codes commonly used in order to determine benefits on particular cases, since the passing of the years has led to obtaining more observational information.

Several revised models consider dissimilar or similar objects as input data, to reduce differences in large samples analyzed and that the proposed models fit the observed data. Because galaxies are a structural set of matter and energy, masses that move around a center or nucleus due to gravity. In this way, it is difficult to compare the massiveness as a function of the masses in the interaction of galaxies, due to the available astronomical data, and the access to them. However, the CNN application allows determining the fundamental parameters that govern the dynamic modeling of interacting galaxy pairs, such as the relative inclination between their disks and the viewing angle [66], although images of interacting galaxy pairs, or in approximation published or reported in databases, have been used.

Cavanagh and Bekki [67] report high validation accuracy of up to 98% and 99% as a function of time, well above the expected minimum uncertainty of 5% inherent to the training set, with a probable degree of overfitting, even for batches of 200 images of a single galaxy model.

In this context, it is important to highlight that there is some uncertainty about processes outside the visible range; therefore, being consistent with Merluzzi et al. [17] there will always be some ignorance in the hidden parts in galaxies, in addition to the fact that the observable data, their reduction, and treatment are compared even in relatively large intervals (14%) to find consistency with the reported numerical simulations [32]. It is difficult to reproduce the interaction of the observed galaxies, due to the absence of complete coordinates in a wide space of parameters, of initial conditions and multiple solutions, so it is necessary to use indirect methods to infer them, in addition to performing iterations to measure the centers of galaxy mass, as well as final positions and velocities, which can lead to relative errors of up to 10%, or higher, to interpret the images related to the output display.

Simple and fast solutions can be deduced if initial and boundary conditions are imposed, such as isolating the system, assuming geometries, velocities, morphologies and mass ratios of gas, dust, and baryonic matter, which may suggest the formation of a pattern parameter in the interaction, so iteration will be one of the benefits of numerical simulation to achieve convergence.

This research does not assess which is the best or worst code (this would lead to a conflict of interest or possible bias), it shows characteristics of the computational codes so that, from a set of codes, the user can evaluate which is appropriate according to their interests, so even the most used present a margin of error as various authors report without giving precise data. Despite the drawbacks that limit the use of CNN in astronomical research currently, such as the download of large quantities of heavy images, obtained in remote observatories and the computational and hardware resources necessary to train a CNN [68].

From the research, the limitations found where: there is no single case study of galaxy interaction where various codes are applied, additionally having observable data requires belonging to a collaborative group or having the means and resources for data processing in the case of research centers. The main disadvantage was not being part of a research center, with which the data are more controlled and only what is published or public data from large projects already reported that are used to review from other approaches are available.

4. Conclusion

The updating and implementation of techniques and methods in the study of cosmological processes such as the interaction of galaxies has made it possible to compare, verify, and adjust these processes between observed, simulated, and published data.

The more robust the code for the numerical simulation, the mathematical, physical, and computational knowledge is necessary for the initial and boundary conditions, in addition to the fidelity of databases or observational data.

The position, morphology, symmetry, masses, luminosity, color, trajectories, density and its distribution, gravity, pressure, viscosity, rotation, dispersion velocity, presence of oxygen, gas flow zone, metallicity distribution, dispersion fields, transfer, gas trajectories and concentrations, star formation rates, and possible deformations are some of the most outstanding parameters required in the study of galaxy interaction.

Ramses, Flash, Vegas, Wombat, Bahamas, Cigale, Gizmo, Hydra, Starlight, Arepo, AstroPhi, Enzo, Spam, Zeus, Identikit, Athena, and Gadget, recently Octo-Tiger code, are some of the codes, routines, or software currently developed, modified, or adjusted in several versions to generate numerical simulations.

Analysis of millions of particles in the codes has led to improvements in the resolution of output images, with it a better interpretation and deduction or prediction of processes in cosmological environments. But the capture of observations translated into images has led to a diversity of predictive models.

Each technique and/or method applied in the study of the interaction of galaxies depends on the initial and boundary conditions, on the availability of observable, reported, published, or registered data, and is complemented with simulation codes, to verify or adjust processes that have taken billions of years and that with these codes and powerful supercomputers is reduced to thousands of hours.

In order to analyze large amounts of data from simulation and visualization, it is necessary to have a supercomputer, time progresses, codes and algorithms evolve, requiring greater memory, processor, and graphical interface capacity, among others.

There is a wide heterogeneity of methods, techniques, and tools in the study of galaxy interaction, which leads to certain codes or algorithms being more used, as well as visualization packages, some have outstanding advantages such as it is in the reading and writing of certain extensions over others and this depends to a large extent on financial resources, collaborative groups and academic level where they are developed and improved.

In summary, images were obtained from repositories, records, simulations and publications and by implementing CNN, the attributes of fidelity and representativeness of the galaxy interaction process were identified. With this, artificial intelligence favors a) information retrieval, b) image and video analysis, and c) pattern recognition.

Recommendations

Implementation of an astrophysical code requires reconnaissance, review of input and output data, as well as the initial and boundary conditions, have observational or repository data, as well as data from a supercomputer or remote servers, and from this generate a reduction or filtering, follow the simulation and visualization. It is necessary to have knowledge of data science, of astrophysical interpretation associated with hydrodynamic processes.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Eduardo Teófilo-Salvador: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Funding acquisition. **Patricia Ambrocio-Cruz:** Visualization, Project administration. **Margarita Rosado-Solís:** Writing – review & editing, Supervision.

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